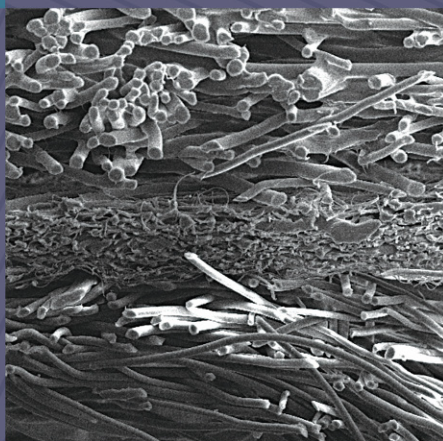


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Composite Nonwoven Materials

Structure, Properties and
Applications

Edited by Dipayan Das and Behnam Pourdeyhimi



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Dipayan Das and Behnam Pourdeyhi



The Textile Institute



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Introduction to composite nonwovens

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Abstract: This chapter gives an introduction to composite nonwovens. It begins with the definitions of composites and nonwovens and continues to discuss how these definitions are used to define composite nonwovens. It then classifies composite nonwovens according to the materials used or manufacturing processes employed for the creation of composite nonwovens. Each class of composite nonwoven is described and discussed with numerous practical examples. The chapter then proceeds to discuss the scope, markets and applications of composite nonwovens. The final section highlights the challenges and promises of composite nonwovens.

Key words: composite, nonwoven, definition, classification, scope, market, application.

1.1 Introduction

The term ‘composite nonwoven’ has an interesting etymology. Impressionistically, it appears to mean a category of nonwoven materials which is prepared by a combination of different nonwoven preforms or different nonwoven fabrics. In the past, the members of the nonwoven industry used the terms ‘composite nonwoven’ and ‘nonwoven composite’ sometimes synonymously and sometimes differently. Those who preferred to use them differently would mean composite nonwoven as a material combining nonwoven preforms or nonwoven fabrics with at least one other material such as yarn, cloth, knit, braid and film, and nonwoven composite as a material consisting of a resinous matrix reinforced by an embedded nonwoven fabric (Das *et al.*, 2012). Though composite nonwovens prepared by various combinations of materials and processes are well established, the definition of composite nonwovens has been a topic of debate in the nonwoven and allied industries. In the following sections, the definitions of the term ‘composite’ and ‘nonwoven’ are given and how they are used to define the term ‘composite nonwovens’ is discussed.

1.1.1 Definitions of composite

The term ‘composite’ comes from the Latin word *compositus*, which means ‘put together’ indicating something made by putting together different parts or materials. Nevertheless, the definition of the term ‘composite’ has been continued to be confusing to the members of the nonwoven and allied industries.

Holliday (1990) suggested a definition of composite for the nonwoven industry as a material comprising two or more different parts or elements in which each material has its own unique characteristics. These materials may include fibre, fabric, plastics, superabsorbents or other materials that effect and become a homogeneous part of, and are nonseparable from, the total structure.

Holliday made an attempt to differentiate composites from laminates by stating that a laminate is a material which is formed by uniting or bonding two or more distant layers that may be similar or different in composition, with heat, adhesive or pressure. These layers may include fabrics, foam, sheets, webs or films such that each layer retains a substantial portion of its original characteristics and therefore does not become homogeneous in the structure. Further, a laminate can be theoretically delaminated, i.e. the layers can be separated from one another.

The North American Association of the Nonwoven Fabrics Industry (INDA) and the European Disposables and Nonwovens Association (EDANA) (2005) jointly define a composite material as a macroscopic combination of two or more distinct materials, having a recognizable interface between them. This definition of composite has not been accepted by the allied industries, however. The textile industry, which is closely associated with the nonwoven industry, follows another definition of composite. As per the Textile Institute Textile Terms and Definitions, composite is defined as a product formed by intimately combining two or more discrete physical phases, usually a solid matrix and a fibrous material (McIntyre and Daniels, 1995). The textile industry therefore thinks of composites as fibre-reinforced-composites only.

The man-made fibre industry, which is closely associated with the nonwoven industry, follows a similar definition of composite. As per the dictionary of man-made fibres, composites are materials with plastics as matrix and high tenacity fibres or short fibres as reinforcement; without this reinforcement, plastics would be insufficiently rigid, solid and impact resistant (Koslowski, 1998). Thus the man-made fibre industry thinks about composites as fibre-reinforced and plastic-matrix composites only. The polymer industry however typically follows another definition of composite. The *Encyclopaedia of Polymer Science and Technology* (Mark, 1970) defines composites as combinations of materials differing in composition or form on a macroscopic scale in which all of the constituents in the composites retain their identities and do not dissolve or otherwise completely merge into each other.

The composite industry uses a different definition of composite. As per the ASTM (Committee D-30 on Composite Materials) standard D3878-07, a composite material is defined as a substance consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents. Further, a composite material is inherently inhomogeneous on a microscopic scale, but can often be assumed to be homogeneous on a macroscopic scale for certain engineering applications. The constituents of a composite retain their identities:

they do not dissolve or otherwise merge completely into each other, although they act in concert.

Each industry thus follows its own definition of composites. It appears that each of these industries have different circumstances and motivations so it is no wonder that they have pushed their own criteria for defining composites.

1.1.2 Definitions of nonwoven

The definition of nonwoven has had an interesting history. A chronological description of the definitions of nonwoven has been given by Batra and Pourdeyhimi (2012). It can be observed that nonwoven has been defined differently from time to time by different authors, standardization agencies and industry associations. Nevertheless, the following definitions of nonwoven are generally found acceptable worldwide. As per ISO 9092, nonwoven is defined as:

a manufactured sheet, web or batt of directionally or randomly oriented fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments or felted by wet-milling, whether or not additionally needed. The fibres may be of natural or man-made origin. They may be staple or continuous filaments or be formed in situ. Note that the wet-laid nonwovens are distinguished from the wet-laid papers by a clause that a material shall be regarded as a nonwoven if more than 50% by mass of its fibrous content is made up of fibres (excluding chemically digested vegetable fibres) with a length to diameter ratio greater than 300; else if more than 30% by mass of its fibrous content is made up of fibres (excluding chemically digested vegetable fibres) with a length to diameter ratio greater than 300 and its density is less than 0.40 g/cm^3 .

This definition of nonwoven by ISO 9092 has been adapted by CEN (EN 29092) and consequently by DIN, AFNOR, and all standardization offices in the EU.

ASTM prefers to define nonwoven as ‘a textile structure produced by bonding or interlocking of fibres, or both, accomplished by mechanical, chemical, thermal, or solvent means, and combinations thereof. Note that the term does not include paper, or fabrics which are woven, knitted, tufted, or those made by wool or other felting processes.’ This definition is available in many ASTM standards including D 123, D 1117, D 2646, D 3786, D 3787, D 5684, D 5732, D 5733, D 5734, D 5735, and D 5736.

There are currently two leading associations of nonwovens producers in the world, namely EDANA (the European Disposables and Nonwovens Association) and INDA (the North American Association of the Nonwoven Fabrics Industry). They have been the voice of the nonwoven industries in Europe and North America, respectively. Nonwovens are defined by them as well. Though EDANA has adopted the definition of nonwoven given by ISO 9092 or CEN 29092, INDA

prefers to define nonwovens in another way. According to INDA, ‘nonwoven fabrics are broadly defined as sheet or web structures bonded together by entangling fibre or filaments (and by perforating films) mechanically, thermally or chemically. They are flat and porous sheets that are made directly from separate fibres or from molten plastic or plastic film. They are not made by weaving or knitting and do not require converting the fibres to yarn.’ It is quite interesting to note that everybody has their own definition of nonwoven and there is no unique definition of nonwovens existing in the world.

1.1.3 Definitions of composite nonwoven

There are also definitions available for composite nonwovens. Bikales (1976) classified nonwoven fabrics into four categories:

- 1 fabrics produced by chemical and mechanical finish
- 2 fabrics produced by wet processes using modified papermaking techniques
- 3 spunbonded fabrics
- 4 composite fabrics produced from laminates of scrims, fibres, or foams with tissue, films, or other nonwoven fabrics.

An example of the fourth category of nonwoven fabric is as follows. Continuous-filament yarns were coated with a phenolic resin and converted into a cross-laid nonwoven scrim to which layers of tissue were applied to each side and finally the composite was exposed to heat to allow the adhesive to set. Holliday (1990) cited interesting examples of composite nonwovens as a combination of carded webs and other webs or fibrous materials by means of water jet entanglement, or a combination of webs, fabrics, yarns, scrims, foam and other materials, or a combination of a highloft of fibrefill nonwoven and a meltblown nonwoven such that the meltblown fibres are blown between the fibres of the fibrefill and penetrate into the structure. It was further added that a foam laminated nonwoven for making wipes and a needle-punched felt bonded to a film and embossed cannot be considered an example of composite nonwoven, but can be considered as an example of laminated nonwoven.

The definition of composite nonwoven, as given by INDA/EDANA (2005), is widely discussed by the nonwoven industries worldwide. According to it, the term composite nonwoven is used when the essential part of a composite material can be identified as a nonwoven material; if the essential part cannot be identified, the term composite nonwoven is used when the mass of the nonwoven content is greater than the mass of any other component material. Further, EDANA added that a composite nonwoven may be an unbounded nonwoven preform to which filaments or spun yarns have been incorporated.

However, there is a different description available for composite structure as given by Hutten (2007). According to him, for a medium to be fit for the definition of composite structure it must be layered. In this connection, he cited a few

structures that, according to him, cannot be considered as composite structures. For example, a single-layer structure, when combined with activated carbon particles or coated or impregnated with some chemicals for exhibiting additional properties, remains as a single-layer structure, hence cannot be considered as a composite structure. He further added that all the layers of a composite structure need not necessarily be nonwoven, that is, one or more layers could be a woven material or membrane material or plastic material or metal mesh material to provide necessary support to the structure. However, McIntyre (2008) describes composite nonwovens as a marriage of two different technologies in one process line or combination of multiple substrates (combination of different types of nonwovens or combination of nonwoven with another type of fabric like a woven or a film) made on entirely different lines. Examples include nonwovens prepared by employing a multi-beam spunmelt line, nonwovens prepared by bonding air-laid and wet-laid nonwovens or woven fabric and nonwoven fabric, etc. However, Batra and Pourdeyhimi (2012) reported that the nonwoven trade uses the phrase 'composite' for those nonwovens which are either produced by combining laminates of fibres of different types/species (or fibres blended with particulates), or combining laminates of different fibre species with layers of different fibres produced by employing the same technology or different technologies, to obtain a new unified or integrated structure. It is thus clear that there are many definitions available on composite nonwovens. But, whatever definition is chosen, there are enormous possibilities existing for creation of these materials.

1.2 Classification of composite nonwovens

Composite nonwovens can be classified under the aegis of raw materials used and process technologies employed for their creation. According to the materials constituting composite nonwovens, they can be classified as multi-fibre composite nonwoven, multi-filament composite nonwoven, combined fibre and filament composite nonwoven, particulate composite nonwoven, and hybrid composite nonwoven. Needless to say, there are numerous ways to prepare each of these composite nonwovens. They can be prepared by employing multi-forming processes, multi-bonding processes, or a lamination process. Then, according to the manufacturing processes employed, composite nonwovens are classified as multi-formed composite nonwoven, multi-bonded composite nonwoven, and laminated composite nonwovens. All of these classes of composite nonwovens are described below.

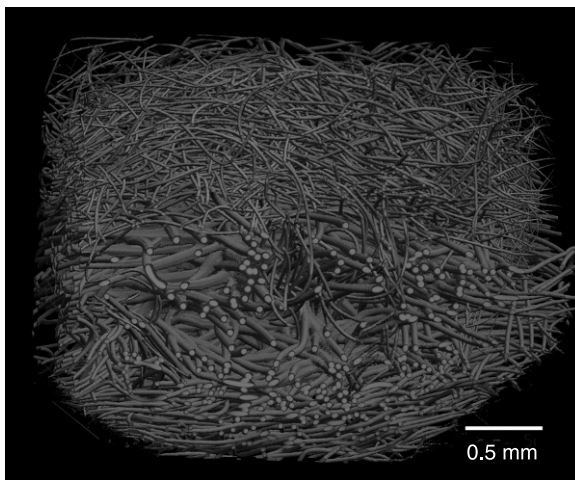
1.2.1 Multi-fibre composite nonwovens

The multi-fibre composite nonwovens are comprised of fibres of different types or species or characteristics or a combination thereof, where the fibres can be mixed intimately or each layer can add different fibres to the fibreweb. Examples include

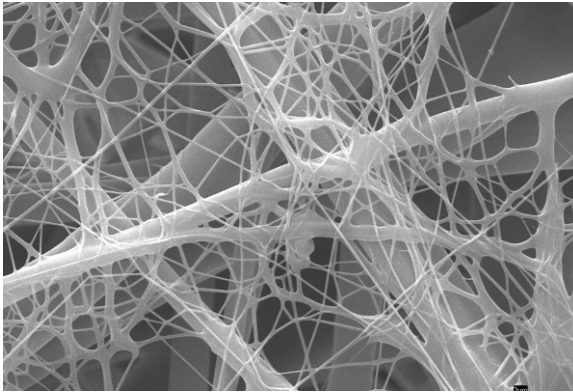
composite nonwovens comprising of natural and synthetic fibres, composite nonwovens consisting of natural or synthetic fibres of different types or species or characteristics, and composite nonwovens with gradient structures prepared by a combination of a large-fibre-layer to a small-fibre-layer. Figure 1.1 displays a digital volumetric image of a needlepunched nonwoven material consisting of two layers, one made up of finer fibres and the other made up of coarser fibres. Figure 1.2 shows a scanning electron microscopic image of a composite nonwoven consisting of electrospun nanofibres and meltblown microfibers.

It is believed that by combining the characteristics and performance features of different fibres the composite nonwovens are putting a new twist on the versatility, high performance and quality that have come to be expected from nonwovens (Wuagneux, 2006). There are several embodiments of such composite nonwoven materials available. In an exemplary embodiment, Liu *et al.* (2008) termed an electrospun web of poly(L-lactic acid) and poly(vinyl alcohol) as composite nonwoven material. Duello *et al.* (2010) disclosed a multi-layered composite nonwoven prepared by combining two webs comprising of staple fibres of different finenesses for the use as a fluid filter.

Holliday (1990) illustrated composite nonwoven with the help of a practical example where highloft or fibrefill structures with large areas of openness between fibres was impregnated with the micro fibres from the meltblown process. As a result, the meltblown fibres penetrated into the fibrefill structure and a composite nonwoven fabric was thus formed. Jeambar (2009) developed a composite nonwoven fabric prepared by combining two webs, one made up of synthetic fibres and the other made up of natural fibres. Smithies *et al.* (2008) disclosed a



1.1 Image of a nonwoven fabric comprising finer fibres laid on coarse fibres.



1.2 SEM image of composite nano- and microfibre nonwoven.

composite nonwoven material wherein microfibres were combined with nanofibres for the use in filtration application. Welch *et al.* (2000) disclosed a composite nonwoven fabric made up of one layer consisting of wood pulp fibres and another layer comprising of polyolefin staple fibres for the use in absorbent products.

Bergholm *et al.* (2005) disclosed a composite nonwoven fabric for the use as a wet wipe which was formed from fibrous layers bonded together by entanglement of fibres of the first and second outer layers each comprising a mixture of hydrophobic and hydrophilic fibres, as well as an intermediate layer of hydrophobic fibres sandwiched between the first and the second outer layers.

1.2.2 Multi-filament composite nonwovens

The multi-filament composite nonwovens consist of filaments of different types or characteristics or a combination thereof, where each layer adds different filaments to the web. Examples include composite nonwovens prepared by combining two spunbonded layers each consisting of different filaments. There are numerous descriptions available for such structure.

Bansal (2006) disclosed a patent of stretchable composite nonwoven which was formed by mechanically needling a crimped spunbond web to an elastomeric spunbond web. Boscolo (2008) invented a hydroentangled composite nonwoven fabric comprising of an absorbent pulp layer sandwiched between two layers of spunbond nonwovens. Ferrira and Rieger (2004) fabricated a composite nonwoven material by combining unpulped vegetable fibre webs with spunbond filaments for the use as thermoformed vehicle interior trim products.

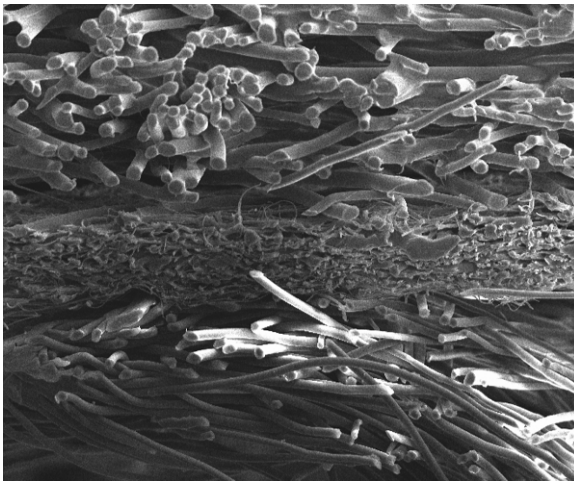
Boscolo and Maltese (2009) reported a spunbond nonwoven material made up of a plurality of multi-component filaments which was thermo-bonded with polyolefin-based nonwoven layers in order to make a composite nonwoven

fabric, particularly suitable for hygiene application. Ferencz (2002) developed a composite nonwoven fabric comprising one or more fine denier spunbond layers and one or more barrier layers. Newkirk *et al.* (2002) disclosed a composite nonwoven fabric with areas of different basis weights prepared by combining different layers of spunbond nonwovens for the use in hygiene products.

1.2.3 Combined fibre and filament composite nonwovens

These composite nonwovens consist of a combination of fibres and filaments such that one layer can add fibres and another layer can add filaments. Examples are SMS/SMMS/SSMMMSS composite nonwovens where relatively small but weak meltblown (M) fibres are sandwiched between large and strong spunbond (S) filaments. Figure 1.3 displays a scanning electron microscopic image of an SMS nonwoven. There are several descriptions available for fibre and filament combined composite nonwovens.

Brock and Meitner (1977) of Kimberly Clark disclosed the first patent on SMS structure. Damaghi *et al.* (2010) disclosed a composite nonwoven consisting of at least one nonwoven layer of staple fibres and an SMS web layer for the use as a wipe. Rudisill *et al.* (2003) developed a composite nonwoven fabric by including spunbonded filaments and meltblown fibres. Quantrille and Zimmerman (1995) described a composite nonwoven fabric that combined a fibrous layer consisting of staple fibres and an elastic layer comprised of filaments in such a way that it showed low extensibility in machine direction but substantial elastic properties in cross-machine direction. Angelini and Haley (2006) developed a composite nonwoven material by combining a wet-laid layer of staple fibres and a



1.3 Image of composite SMS nonwoven.

spunbond layer of continuous filaments. Homonoff *et al.* (1992) described a hydroentangled composite nonwoven fabric comprising of a combination of spunbond web consisting of continuous synthetic filaments and wet-laid wood pulp fibrous web consisting of staple fibres.

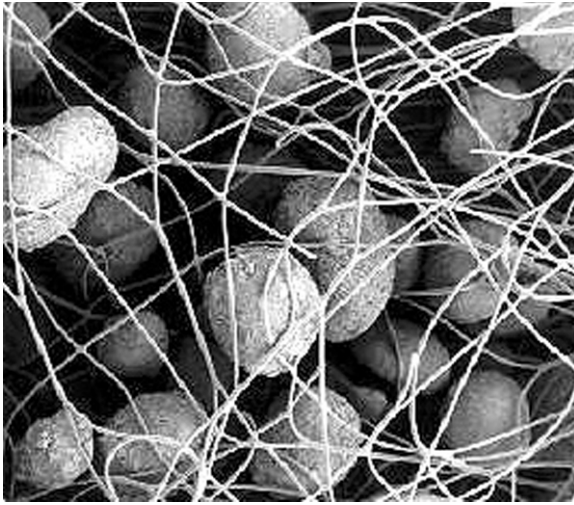
Jones and Lim (2010), in an exemplary embodiment, disclosed a composite nonwoven material comprised of nanofibres and spunbonded filaments for the use in filtration applications. Bonneh (2006) developed a composite structure consisting of a spunlaid continuous filament layer and a meltblown staple fibre layer, which, upon subjected to water jet treatment, resulted in the breaking of meltblown fibres and caused the broken ends to extend through the spunlaid layer, thus forming a composite nonwoven fabric for use in absorbent products. Smithies *et al.* (2010) disclosed a patent on composite nonwoven material that included a nanofibre layer deposited onto a spunbond layer consisting of continuous filaments for the use in air filtration application.

Everhart *et al.* (1994) filed a patent on high pulp content composite nonwoven fabric which was prepared by hydroentanglement of a pulp fibre layer to a continuous filament substrate. Griesbach *et al.* (1996) described a composite nonwoven fabric prepared by hydroentanglement of two filamentous web layers and a cellulosic layer containing cellulosic fibres. Vuillaume and Noelle (2007) disclosed an invention on a composite nonwoven fabric prepared by hydroentangling a cellulosic fibre layer sandwiched between two webs of spunbonded filaments. Stralin *et al.* (2011) reported a hydroentangled integrated composite nonwoven material including a mixture of randomized continuous filaments and synthetic staple fibres. Duncan *et al.* (2003) disclosed a composite nonwoven fabric manufactured by joining a fibrous web that was comprised of wood fibres or a mixture of wood fibres and synthetic fibres to a spunlaid nonwoven by means of hydroentanglement.

In a US patent entitled 'composite nonwoven fabrics', Gessner and Trimble (1998) described a composite nonwoven fabric prepared by laminating two oxidatively degraded spunbond nonwoven webs of thermoplastic filaments to a meltblown web of microfibres, thus forming a spunbond/meltblown/spunbond composite nonwoven fabric for numerous applications, including medical garments and disposable absorbent products. Stranqvist (2005) disclosed an invention of hydroentangled composite nonwoven material prepared by combining layers of continuous filaments, synthetic staple fibres and natural fibres.

1.2.4 Particulate composite nonwovens

The particulate composite nonwovens are prepared by embedding particulate matters into nonwoven structures. The particulate matters of interest are activated carbon, super absorbent powders, metal ions, biocides, antimicrobials, abrasive particles, preservative agents, wetting chemicals, etc. Examples include composite nonwoven with immobilized particulate matter, composite nonwoven with one



1.4 Image of activated carbon and microfibre based composite nonwoven.

partially densified web, composite nonwoven with two partially densified webs, and composite nonwovens with different functional particulate matters immobilized and microfibre webs in contact. Figure 1.4 displays a scanning electron microscopic image of activated carbon-particle-embedded microfibre composite nonwoven. Nowicka (2003) reported a series of composite nonwoven materials prepared by incorporating powder-sorbent particles such as carbon, chitosan and aluminium oxide in meltblown nonwovens. Kalayci *et al.* (2008) disclosed a composite nonwoven fabric consisting of elastomeric nanofibres and at least one type of active particle for the use as protective garments.

1.2.5 Hybrid composite nonwovens

The hybrid composite nonwovens are prepared by combining nonwovens with other materials such as woven, knitted and braided fabrics, films, scrims, foams with tissue, etc. Qian (2007) developed a novel three-layer composite material by hydroentangling a woven fabric layer sandwiched between two nonwoven layers for the use as synthetic leather. Recently, Gensheimer *et al.* (2011) developed a polymer/bacteria composite nanofibre nonwoven by electrospinning of living bacteria by hydrogel microparticles for manifold new applications, including microbial fuel cells, biotechnical synthesis and environmental remediation.

Nakamae and Shima (1984) described a hybrid composite nonwoven for acting as a substrate for artificial leather, which was prepared by hydroentangling three layers among which the first layer was a meltblown web of very fine fibres, the

second one was made up of staple fibres, and the base layer was made up of woven or knitted fabric. Langley (1989) reported a multi-layered composite chemical barrier fabric, which was prepared by adhesive bonding of a nonwoven polypropylene fabric sandwiched between two layers of polymer multi-layered films. Paul and Kumar (1995) described a composite carpet-backing material consisting of a fibreglass scrim reinforced into two layers of nylon nonwoven fabric. Prodoehl *et al.* (2006) disclosed a multi-layer scrub pad comprising a spunbond scrubbing layer, an air-laid absorbent core layer and a laminated thermoplastic/cellulosic wiping layer.

1.2.6 Multi-formed composite nonwovens

These can be manufactured by employing more than one forming section adding different fibres or filaments to the web. The processes include multi-card, multi-forming box air-lay, multi-forming box wet-lay, multi-beam spunbond, and multi-beam meltblown process, or combinations of various forming processes. Examples are SMS/SMMS/SSMMMSS composite nonwovens, CoForm composite nonwovens, prepared by a combination of carded, air-laid, and carded layers and bonded by the through-air bonding process. As known, the benefits of combining spunbond and meltblown webs are observed in surgical gowns, respirator filter, etc. (Russel, 2007).

Manning (1993) described a composite nonwoven material prepared by combining an air-laid nonwoven pulp web and a wet-laid bicomponent web layer by means of heat or chemical treatment. Angelini and Haley (2006) disclosed a composite nonwoven material which was prepared by combining a spunbond layer and a wet-laid layer and laminating thereafter for the use as a semipermeable membrane support. Jeambar (2009) disclosed a composite nonwoven fabric which was prepared by combining a carded web comprised of synthetic fibres and a wet-laid web of short natural fibres and then bonding by employing the hydroentanglement process. Homonoff *et al.* (1992) described a composite nonwoven fabric which was prepared by combining a spunbond web and a wet-laid fibrous web and bonding by employing the hydroentanglement process. Boscolo (2008) disclosed a composite nonwoven fabric prepared by hydroentangling a pre-consolidated spunbonded web, an absorbent pulp layer, and a carded or spunbonded cover layer.

In another embodiment, Collins (1995) disclosed a composite nonwoven material prepared by hydroentanglement of a carded web and a series of spunbonded nonwovens. Bonnef (2006) developed a composite nonwoven fabric by combining a spunlaid continuous filament layer and a meltblown staple fibre layer and bonding them by means of hydroentanglement. Crainic (2005) disclosed a highbulk composite nonwoven prepared by combining a hydro-entangled binder fibre layer to a nonwoven layer issued from forming heads also consisting of binder fibres by means of the through-air bonding process.

Tai (2001) reported a continuous process for producing a composite nonwoven fabric by employing carding and air-laying processes of web formation. Also, it was claimed that a carded/air-laid/carded/carded composite nonwoven fabric can be produced by using the same process line. Doherty (2003) disclosed a composite nonwoven media for gas filtration application which was comprised of an electrically charged air-laid fibrous layer and a wet-laid fibrous layer. Manning (1993) developed a composite laminate including airlaid nonwoven pulp web layers reinforced by a wet-laid bicomponent web layer with or without addition of adhesive material in-between a bicomponent layer and the air-laid pulp web layer.

1.2.7 Multi-bonded composite nonwovens

These composite nonwovens are prepared by a combination of nonwoven bonding processes. Examples include a composite nonwoven prepared by employing a combination of needle-punching and hydroentanglement or a composite nonwoven prepared by employing a combination of thermal bonding and adhesive bonding, etc. Orlandi (2005) reported a composite nonwoven fabric where a pulp layer was deposited onto a consolidated carded nonwoven before being coated with the super absorbent material and all these layers were finally thermo-bonded. Parikh *et al.* (2006) observed that a set of nonwoven fabrics bonded by a combination of needlepunching and hydroentanglement showed higher basis weight uniformity as compared to similar nonwoven fabric bonded by employing needlepunching only. It was reasoned that the hydroentanglement process redistributed the fibres near the holes created by needlepunching, thus improving uniformity.

Kumehara (2003) made a patent disclosure of a composite nonwoven fabric of high strength and superior printability which was developed by intertwining the filaments of a stretched unidirectionally aligned nonwoven fabric and a dry nonwoven fabric by a needlepunching process, following which the two fabrics were unified by a thermal calendaring process. Neely and Oran (1995) disclosed a composite polyester nonwoven fabric for the use as a recyclable bale wrap prepared by employing combined thermal and needlepunching bonding technology.

1.2.8 Laminated composite nonwovens

These can be manufactured by laminating many nonwoven substrates consisting of fibres or filaments of different types or species, or nonwoven substrates with other substrates, including woven fabric, knitted fabric, braided fabric, films and other materials. Gessner and Trimble (1998) disclosed a preferred embodiment where two outer nonwoven webs, comprised of oxidatively degraded spunbonded filaments, were laminated to a web of meltblown microfibres, thus forming a

spunbond/meltblown/spunbond composite nonwoven. Koczab (2001) developed a composite nonwoven material for the use in making absorbent hygiene products by assembling a synthetic fibre lap in-between two fluid-permeable nonwoven materials by means of thermal fusion.

Howey and Martin (1996) described a laminated multi-layered composite nonwoven material that provided a liner for the magnetic recording medium in a computer diskette with superior wiping and hygroscopic dimensional stability and low debris characteristics. Manning (1993) disclosed a laminated composite nonwoven material comprised of an air-laid nonwoven pulp web reinforced by a wet-laid bicomponent web layer. Angelini and Haley (2006) described a laminated composite nonwoven comprised of a spunbond layer and a wet-laid layer and claimed that the resulting semi-permeable membrane provided an advantageous balance of properties, including smoothness, interlaminar adhesion and flux properties.

Rudisill *et al.* (2003) disclosed a laminated composite nonwoven fabric comprised of a spunbond web consisting of composite fibres and a meltblown web consisting of low density polyethylene fibres. Allgeuer *et al.* (2007) developed a composite nonwoven material by laminating propylene-based nonwoven layers made by the meltblown process. Ducker and Rangachari (2005) disclosed a composite nonwoven fabric prepared by laminating an air-laid absorbent core comprising cellulosic fibres and a nonwoven fabric layer consisting of polymeric fibrous material.

1.3 Processing, markets and applications

Composite nonwovens are produced by a modern and innovative industry by employing nonwoven technology or an integration of nonwoven and allied technologies to bring together fibres and/or filaments of different types or species or characteristics. Combinations of different nonwoven, preforms or fabrics, prepared either by employing a variety of different process technologies or by combining nonwoven preforms or fabrics with traditional textile preforms or fabrics or scrims or foams or other materials into a consolidated structure, can also result in development of composite nonwovens. Also, integrating an embedded phase of particulates to a matrix phase of fibres or filaments forming a three-dimensional network around the particulates can lead to creation of composite nonwovens. Thus prepared composite nonwovens are providing engineered solutions by creating multi-functional products as well as economical solutions by eliminating many manufacturing processes and replacing two or more products by one product.

Composite nonwovens are proving that innovative substrate, fibre combinations, and integration of process technologies are an increasingly beneficial option for new product developers (Wuagneux, 2006). By combining the characteristics and performance features of different fibres and/or filaments and/or substrates,

composite nonwovens are putting a new twist on the versatility, high performance, and quality that have come to be expected from nonwovens.

Composite nonwovens are finding numerous applications including, but not limiting to, hygiene, wiping, medical, filtration, insulation, geotechnical, automotive, agriculture, apparel, home furnishing and packaging. The common products made with composite nonwovens include baby diaper, sanitary pad, adult diaper, household and personal wipes, absorbent pad, sterile wrap, wound care, face mask, surgical gown, drape, wound dressing, bandage, respirator filter, vacuum cleaner filter bag, HVAC filters, HEPA filters, automotive headliners, carpet, cabin air filter, agricultural coverings and seed strips, apparel interlining, footwear, bed mattress, wall coverings, window shades, carpeting and upholstery fabrics, etc.

Composite nonwovens are already being used significantly in many markets, including hygiene, wipe, medical, filtration, automobile, geotextile, and agriculture. Wuagneux (2006) reported very interesting information on the usage of composite nonwovens in many of these markets. Hygiene has been the focus of composite nonwoven research for many companies looking to diversify in this market. Composite nonwovens are used in numerous hygiene products including baby care, feminine care, and adult incontinence products. In this direction, a significant amount of research, development, and commercialization has been taking place on combining nonwovens with films to meet the market's increasing demand for softness, comfort and production, or developing three-dimensional perforated laminate with aloe and cotton ingredients to meet the market's ever-increasing demand for better functionality.

Besides hygiene, the wipes market has also seen increased usage of composite nonwovens. It has witnessed composite nonwovens prepared from a combination of webs made up of synthetic and natural fibres such as pulp or cellulose through hydroentanglement, needlepunching, thermal bonding or other technologies. The use of natural fibres resulted in enhancement of eco-friendliness and sustainability of the final product while multi-layer technologies can add benefits such as controlled absorption and release of lotion. Beyond hygiene and wipe, the medical market is known to be one of the significant users of composite nonwovens. They have played an important role in the medical market's quest to achieve a balance between comfort and protection. Besides, many industry experts believe that the EU regulations for drapes and gowns have driven the growth of multi-layered composite structures in Europe. The medical market has witnessed the success of many composite nonwoven materials which were produced by SMS technology, or combining multiple nonwovens (layers of different nonwoven technologies), or by combining nonwovens to films by using lamination technology. Another major contribution made to the usage of composite nonwovens is due to filter products. The filter market is aware of many developments of nano and micro-fibre based composite nonwovens for creation of novel air filter media, and it believes that these materials will play a major role in all segments of filtration in

years to come. A composite nanofibre filter media consisting of nanofibres from electrospinning in combination with a wet-laid substrate material has already been found in a wide range of industrial, consumer, and defence filtration applications.

Researchers are currently exploring additional nanofibre composite nonwovens for several new uses including providing a highly permeable aerosol barrier in protective gear such as facemasks, respirator filters, surgical gowns, drapes, and protective clothing applications. Also, composite nonwovens prepared by a combination of multiple layers of nonwovens with structured nets by employing ultrasonic bonding to create a set of interesting pleatable alternatives for liquid filtration applications are introduced into the filtration market.

The automotive industry also represents a significant market for application of composite nonwovens. In addition to industrial and residential markets, composite nonwovens appear to be used in protective applications. As a substitute of woven combat uniform, a multi-layer composite nonwoven fabric was developed with an aim for excellent performance, high tear strength, durability, comfort, breathability, water absorbency and water repellency, all the while reducing life cycle costs. This fabric reportedly incorporated activated carbon, molecular sieves within multi-layer nonwovens to remove biological or chemical agents. Composite nonwovens are also found to be used in geotextile and agriculture markets. As known, the most common composite nonwoven used in geotextile is a nonwoven mat that has been bonded by needlepunching to one or both sides of a woven scrim. Further, it is known that the waterproof but breathable composite nonwoven fabric is available for the agriculture market.

1.4 Conclusion and future trends

Composite nonwovens are considered as advanced technical materials which are created by a modern and innovative industry by combining different materials, technologies and substrates. While designing composite nonwovens, nonwoven scientists and engineers are ingeniously combining various fibres and filaments, different processes and technologies, and various substrates and structures to produce a new generation of nonwoven materials. These materials are offering engineering solutions by creating multi-functional products as well as economical solutions by eliminating many process steps and replacing two or more products by one product.

With the advancement of polymer and fibre materials and manufacturing technologies it is possible to select appropriate materials and suitable process technologies or a combination thereof to develop tailor-made composite nonwoven products for a variety of applications. They are found to offer superior properties as compared to traditional nonwovens and this establishes a promising future for composite nonwovens. They are proliferated in many directions to find numerous applications and will continue to do so well in the days to come. Nevertheless,

like any industry, the nonwoven industry is not left without any challenge. As indicated by O'Dell (2009), the price pressure is growing as mass markets are extending in certain areas. Therefore, an appropriate price-performance ratio is certainly needed in the entire industry. Also, consumers are demanding long-lasting products that are high-performance, cost-conscious and environmentally sound. A large number of nonwoven scientists and engineers worldwide are working towards newer combinations of materials, processes and structures for development of novel composite nonwoven materials. As the nonwoven industry continues to invest wholeheartedly in continuing research and development, it is poised for great success.

As reported by O'Dell (2009), the combination of several layers or composite constructions with appropriate after-treatment option allows nonwoven manufacturers to create interesting product novelties. As predicted, there will be an interesting and exciting future of composite nonwovens for technical applications (O'Dell, 2009). It would therefore be worthwhile to look for further innovations directed towards combinations of materials or coupling of process technologies for creation of novel composite nonwoven materials.

1.5 Sources of further information and advice

Composite nonwoven is considered to be an advanced technical material which is continuously gaining interest among the nonwoven scientists and researchers worldwide. Several interesting inventions on composite nonwovens have already been reported to date, mainly in the form of patents. But, at the same time, it is felt that there are many more excellent possibilities remaining for creations combining nonwovens for a variety of applications. A close watch on patents is therefore required in order to get to know the latest inventions on composite nonwoven materials. Besides, there are several trade journals which continually publish latest information on the nonwovens industry, nonwovens market, and newer nonwovens products and processes. These include *Nonwovens Industry*, *Nonwovens World*, *Nonwoven Markets*, *Nonwovens Reports International*, etc. These journals can therefore be of interest for the latest information on composite nonwovens. Further, the publications of professional bodies such as INDA and IDANA, and research scientists worldwide, can also be the source of further information on composite nonwovens.

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Natural and synthetic fibres for composite nonwovens

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Abstract: This chapter reviews the use of natural and synthetic fibres in composite nonwovens. It begins by reviewing the use of natural fibres including the most widely used: cotton, jute, kenaf and flax. Most nonwoven fibres are still, however, synthetic. The rest of the chapter discusses the use of polypropylene, polyester, polyethylene and nylon. The chapter concludes by reviewing the use of bicomponent fibres to combine the properties of different fibre types in maximising the functionality of nonwovens.

Key words: natural fibres, synthetic, bicomponent.

2.1 Introduction

This chapter reviews the use of natural and synthetic fibres in composite nonwovens. It begins by reviewing the use of natural fibres including the most widely used: cotton, jute, kenaf and flax. Most nonwoven fibres are still, however, synthetic. The rest of the chapter discusses the use of polypropylene, polyester, polyethylene and nylon. The chapter concludes by reviewing the use of bicomponent fibres to combine the properties of different fibre types in maximising the functionality of nonwovens.

2.2 Natural and biodegradable fibres for nonwovens

The environmental impact of disposable products such as baby diapers, adult incontinence and feminine hygiene products has meant that there is growing interest in the use of natural or biodegradable fibres. Natural fibres for nonwovens include cotton, jute, kenaf and flax as well as smaller quantities of hemp, coir, sisal, milkweed, wood and some animal fibres. Synthetic biodegradable fibres that have also been used for nonwoven applications include:¹

- regenerated cellulosic fibres such as cellulose acetate, rayon and lyocell;
- synthetic fibres such as polylactic acid (PLA), poly(caprolactone) (PCL), poly(hydroxybutyrate) (PHB), poly(hydroxybutyrate-co-valerate) (PHBV), polytetramethylene adipate-co-terephthalate (PTAT) and poly(vinyl acetate) (PVA).

Among natural fibres, cotton is most widely used for nonwoven applications² and it has been estimated that cotton accounts for 8% of the global market in

nonwoven fibre products.³ The advantages of cotton include biodegradability, superior wet strength and a quick drying surface which is particularly useful for wipes. Bleached cotton fibres are used because of their superior appearance and high levels of absorbency as well as being soft to the touch and breathable.⁴ Uses of cotton nonwovens include disposable products such as swabs, wipes, filters, wadding, personal care products such as babies' diapers and feminine hygiene products as well as semi-durable products such as bedding, pillow fillers and household furnishings. An area of recent growth is spunlaced cotton fibres for cosmetic wipes. Typical production techniques involve web formation using one of three techniques:

- dry laid process
- wet laid process
- polymer laid process (involving spun laid and melt blown web formation).

Bonding is achieved through needle punching, hydroentangling, stitchbonding and chemical or thermal bonding techniques. Cotton has been combined into bicomponent fibres for nonwoven applications using fibres such as lyocell and cellulose acetate. Biocomponent fibre technology is discussed later in this chapter.

Useful properties of jute fibres for nonwoven applications include high strength, modulus and dimensional stability as well as good moisture absorption and breathability.⁵ Jute fibres are typically pretreated to improve properties such as crimp to aid further processing. Manufacturing techniques for jute include stitch bonding, hot calendering, needle punching, thermal bonding and hydroentanglement. Needle punching is particularly suitable for developing nonwovens with properties such as good acoustic insulation. Applications of jute nonwovens include floor coverings (where they provide thermal and acoustic insulation), filters, composites and geotextiles. A particularly important application of jute nonwovens is automotive interiors (e.g. door, floor and boot lining materials) due to the combination of light weight, durability, low flammability and other mechanical properties such as drapability, tensile strength and impact performance.

Kenaf fibres are typically pretreated to reduce stiffness,⁶ while they may be blended with cotton, polyester and polypropylene.⁷ Nonwoven mats are typically formed by the air laid process followed by needle punching and thermal bonding. Kenaf nonwoven mats are used in composites and geotextile applications as well as automotive interiors.⁸ The high cellulose content and length of flax fibres also makes them a good substitute for synthetic fibres in disposable nonwovens.⁹ Fibres are prepared by pulping and bleaching. They can then be processed using wet laying followed by hydroentangling or spunlacing. The wet laid process can result in poor fibre formation in the web which can be corrected through good control of fibre length and the use of appropriate fibre finishes. Dry laid jute nonwovens have been shown to have more consistent properties. Applications of jute nonwovens include filters.¹⁰

2.3 Polypropylene and polyester fibres

Polypropylene fibres account for 60% of all the fibres used for nonwoven production. They come under the general category of polyolefins. Filaments are produced from the polymer by melt-spinning. Generally, the polypropylene used in filaments is of the isotactic variety while 65% of polypropylene fibre nonwovens are used for hygiene applications. Its oleophilic nature makes the nonwoven fabric efficient in absorbing and retaining oil from oil–water mixtures. Polypropylene fibres have the advantages of being lightweight, dry (due to low moisture absorption) with good strength, good abrasion resistance, high modulus and good resistance to deterioration from chemicals and microorganisms as well as having a soft feel. Wettability can be improved by various treatments such as plasma treatment. Polypropylene has a major limitation in terms of its thermal properties – its low glass transition temperature and melting point restricts some potential applications.

Polyester is the second most widely used fibre next to polypropylene in nonwoven production. Polyester is used in quilted fabrics, bedspreads and other home furnishings. The term polyester generally refers to polyethylene terephthalate or PET. There are also other polyester fibres available such as polybutylene terephthalate (PBT) and polytrimethylene terephthalate (PTT). However PET is still the most widely used polyester fibre. Polyester is mainly produced by melt spinning. Fibres are relatively strong and have between 60% and 85% crystallinity. The high crystallinity of polyester and the presence of the aromatic ring in the fibre structure makes fibres low in water absorption and resistance to acids and alkalis. The diameter of polyester fibres most widely used to produce nonwovens and composite nonwovens varies from 0.38 to 50 μm and a cut length of 0.9 to 150 mm.

The advantages of polyester fibres include high strength, high modulus, high toughness, good abrasion resistance, good resilience, very low moisture absorbency, high melting temperature and heat distortion temperature, resistance to hazardous chemicals, oxygen barrier, inertness and biocompatibility. They can be processed using any of the main methods of nonwoven manufacture. The wettability of polyester fibres can be improved by plasma treatment.¹¹

In a study on geotextiles by Abdelmalek *et al.*¹² the in-plane and cross-plane water-retention characteristics of polyester geotextiles was studied. The materials used in the investigation were continuous filaments nonwoven needle punched polyester geotextiles varying in their apparent opening size. It was found that cross-plane water-retention data demonstrated their hydrophobic nature, with both specimens being essentially non-conductive to water beyond suction heads of 0.2–0.3 kPa. Both specimens exhibited significant hysteresis in their water-retention function, such that at a given suction a geotextile contained more water when drying than when wetting.

2.4 Polyethylene and nylon fibres

Polyethylene (PE) is the second type of polyolefin which is also used in nonwoven applications. Depending on the kind of structure, they are classified as HDPE (high density polyethylene), LDPE (low density polyethylene) or LLDPE (linear low density polyethylene). There has been limited research on polyethylene nonwovens, but the pre-irradiation induced emulsion graft polymerisation method has been used to introduce acrylonitrile onto PE nonwoven fabrics.¹³ In another study, Ma *et al.*¹⁴ studied impregnation of nonwoven HDPE fibrous samples with a nonionic surfactant (N,N-dimethyldodecylamine N-oxide) using supercritical carbon dioxide as the solvent. The results showed that although the supercritical fluid (SCF) was absorbed into the polymer, no structural changes or loss of mechanical strength was observed. The wetting properties of this highly hydrophobic material were significantly improved.

Nylon is a polyamide. The most common types are nylon 6 and nylon 66. Nylon 6 is polymerised from caprolactam whereas nylon 66 is produced from hexamethylene diamine with adipic acid as the starting material. Both polymers are meltspun to form continuous filaments. The most commonly used nylon fibres have a diameter of 15 to 25 μm . Nylon fibres have low heat resistance and show poor conduction of heat. Their advantages in practical terms include high durability, relatively high glass transition and melting temperatures, high tensile and tear strengths, good elastic recovery and low static electric charge generation. Disadvantages include poor resistance to exposure to light and poor wet strength.

The physical properties of nylon 6 nonwoven mats produced from solutions with formic acid have been studied.¹⁵ Nonwoven electrospun mats from various solutions with different concentrations were examined regarding their morphology, pore size, surface area and gas transport properties. Each nonwoven material with average fibre diameters from 90 to 500 nm was prepared under controlled electrospinning parameters. From the results, the authors observed that fibre diameter was strongly affected by the polymer concentration (polymer viscosity). In addition, the results showed that the pore size and gas transport property of electrospun nylon 6 nonwoven mats were affected by fibre diameter.

Saraf *et al.*¹⁶ created a superhydrophobic/superoleophobic surface by preparing a metastable Cassie–Baxter (CB) surface. To create a CB surface it was essential to have low surface energy and properly constructed surface morphology. The researchers explored three different techniques to achieve superhydrophobicity and superoleophobicity using hydroentangled nylon nonwoven fabric: pulsed plasma polymerisation of 1H,1H,2H,2H-perfluorodecyl acrylate (PFAC8), microwave-assisted condensation of 1H,1H,2H,2H-perfluorodecyltrimethoxysilane (FS), and FS condensation through wet processing. Nonwoven fabric materials prepared using these three techniques were superhydrophobic and superoleophobic as shown by their very high contact angles for both water (contact angles of 168–174°) and dodecane (contact angles of 153–160°).

2.5 Bicomponent fibres

The objective of spinning bicomponent fibres is to overcome the limitations of conventional single component spinning. The principal purpose of blending polymers to produce bicomponent fibres is to achieve improved processing and functional properties for a specific end use.

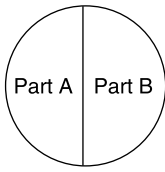
Bicomponent fibres can be mainly classified into three types:

- *Side by side (S/S)* – where each polymer is divided along the length into two or more distinct regions of the cross-section.
- *Core sheath type (C/S)* – as the name suggests, in this type of fibre one of the components is completely surrounded by another component. The core sheath type fibres can be self bonding (e.g. two components with varying melting points with the lower melting point polymer on the sheath), surface tailored fibres (e.g. sheath containing expensive additives) or filled fibres (e.g. a core of recycled material covered by a sheath which has desired properties).
- *Matrix fibril (M/F)* – where many fine fibrils of one polymer are dispersed randomly in size and location but with axial alignment in a matrix of another component.

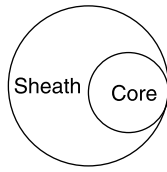
There are various variants of bicomponent fibres with varying phases (in terms of quantity and location) and tailored interfaces. Bicomponent fibre spinning is a type of blend spinning.¹⁷ Depending on the choice of constituents, they can be either compatible or non-compatible. The first category results in a homogenous single phase solution and their spinning resembles the spinning of single component homopolymers. Incompatibility between the polymers results in phase separation. The control of morphology becomes more challenging. The different cross-sections of biocomponent fibres are shown in Fig. 2.1¹⁸ including:

- citrus, wedge, or segmented pie;
- hollow or non-hollow;
- regularly round cross-section;
- irregularly non-round cross-section, including flat ribbon, multilobal, triangle, paralleled strip, etc.

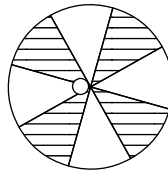
Every type of bicomponent fibre has specialised end uses. Side-by-side fibres and eccentric core/sheath fibres demonstrate self-crimping properties. C/S fibres with polypropylene sheath around a nylon core may potentially produce a fibre with the wear resistance of a nylon fibre and display the stain resistance of polypropylene fibre. Trilobal biocomponent fibres are used for speciality filtration applications. In the meltblown industry, sheath core fibres are used as a thermobonding fibre. A strong bond must be made between the two materials to prevent fibre splitting.¹⁹ A fibre made of chemically different species will require specialised treatment to enhance the strength of the interface. The splitting of fibres is done by thermal, mechanical or chemical means.



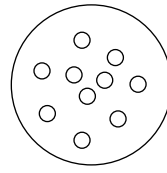
Side-by-side



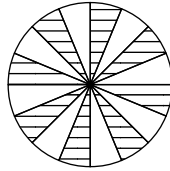
Eccentric sheath/core



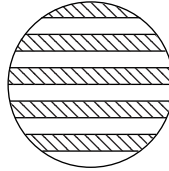
Citrus



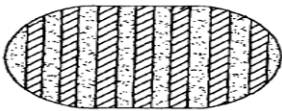
Island-in-the-sea



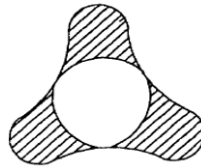
Segmented pie



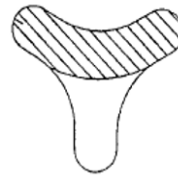
Segmented circle



Segmented ribbon



Trilobal sheath/core



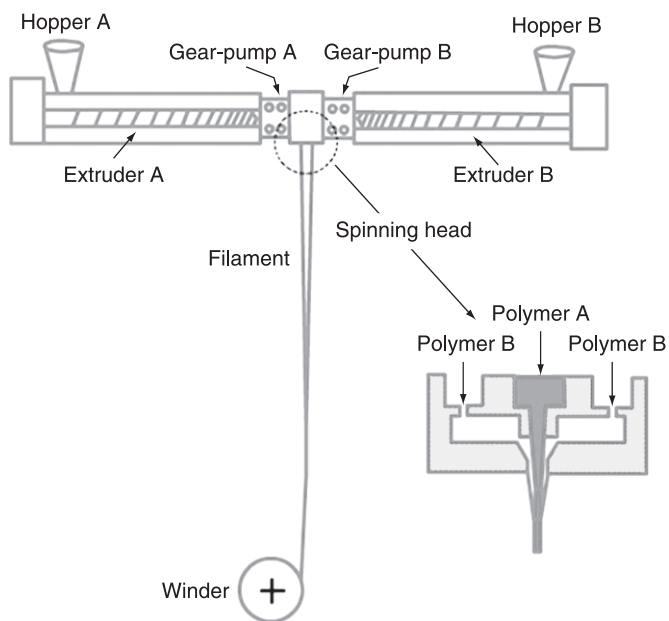
Trilobal side-by-side

2.1 Cross-sectional conformations of different types of bicomponent fibres.

The first bicomponent fibres were spun by Dupont in 1960.²⁰ Early designs include those by Okamoto and co-workers^{23,24} as well as Moriki and Ogasawara.²⁵ Extensive research by companies such as Hills Inc. and Enca Inc. resulted in the design of a modified spinning system using thin flat plates with groves and holes to conduct the polymer, making the process more flexible and effective. The basic design consists of two feeding systems to the spin packs and a distribution system to meter both the polymers to the die. The feed system may vary and is generally a combination of

- two continuous polymerisation processes;
- two extruders;
- a combination of these.

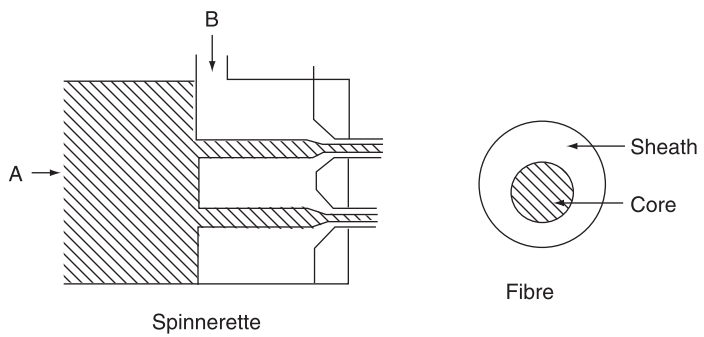
An excellent review of developments has been given by Fitzgerald and Knudsen.²¹ Bicomponent fibres have been spun from viscose by Sisson and Morehead.²² The process involved extruding two different component solutions (or dopes) through



2.2 Schematic of bicomponent spinning.⁴

the same spinnerette hole (Fig. 2.2). The two components A and B are fed to a single spinnerette hole split by a knife edge or septum which channels the two components into a side-by-side or bilateral arrangement. This same principle can be applied to multi-ring/multi-knife edge arrangements and to non-circular arrays of holes and knife edges.

Figure 2.3 illustrates a design for spinnerets required for preparing sheath core conjugate fibre. One of the component streams is fed through a narrow tube while

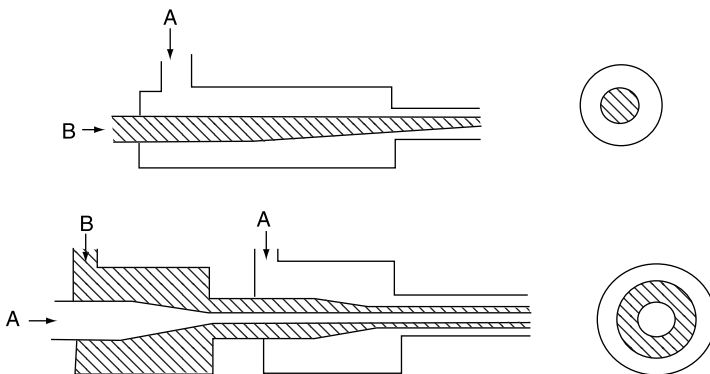


2.3 Core conjugate spinning.⁴

the second component stream supplying the sheath is fed around this narrow tube and the combined stream is emitted from a single hole. The combined material which emerges is coagulated in a sheath core arrangement. The eccentricity of the sheath core necessary for crimp development is assured in two ways. Firstly, normal variability in coagulation conditions is sufficient to ensure crimping. Secondly, a misalignment of the centre of the spinneret hole and the tube results in eccentricity. For sheath core spinning of bicomponent fibre, separate provision has to be made for merging the component streams at each spinnerette hole. Figure 2.4 illustrates the concept of a 'pipe-in-pipe' mixing element. One of the component streams envelops the other component stream at the exit end of the tube of the inner stream. The resultant stream contains in cross-section the individual streams in concentric circles. Streams can be further added by consecutive mixing elements to provide merged dope streams of concentric layers of the two components.

In 'sea-island' or 'islands-in-sea' type fibre, one portion is in a dispersed phase (called island component) and the other is in a continuous phase (sea component). Fibres are made by conjugate spinning. In the manufacturing process, one polymer is fed in individual streams inside a 'sea' of another polymer. The spun filaments typically have a total denier of 2–5 dpf (12–20 μm) after drawing. The sea polymer is generally dissolved away after the fibres are knitted or woven into fabric to leave small submicron island filaments on the surface of the fabric. Typical polymer ratios are 20% sea and 80% islands. When the island polymer is greater than 65% of the total filament mass, the island filaments become square in shape due to the packing density.

Shi *et al.*²⁶ have produced sheath-core type PBT/PBAT bicomponent fibres by extruding the melts of PBT (intrinsic viscosity of 0.88 dL/g) as the sheath and PBAT (melt volume flow rate of 3–6 ml/10 min) as the core using two different extrusion systems. The co-axially combined polymer melts were extruded through



2.4 Pipe-in-pipe mixing element.⁴

an annular-type spinneret at a temperature of 260 °C, and the mass flow rate was controlled at 3 g/min for each component. Compared with the respective single component fibres, in PBT/PBAT fibres, the molecular orientation and crystalline structure development of the PBT component was greatly enhanced, whereas the molecular orientation of the PBAT component was greatly suppressed.

The application of bicomponent fibres has been reported in various US Patents. In one patent²⁷, the manufacturing of composite elastic nonwoven fabrics was described. The composite nonwoven fabrics developed by the inventors had good strength, stretch and recovery properties. The manufacturing process involved forming a layered structure including the binder fibre-containing fibrous web and the elastomeric net, hydroentangling the layered structure and then thermally treating the hydroentangled fabric. In a patent by Newkirk²⁸, manufacturing of high loft nonwoven fabrics using bicomponent filaments for personal hygiene products was discussed. Fabrics were composed of at least two carded webs of bicomponent thermoplastic resin fibres. In another patent²⁹, two nonwoven webs were bonded using bicomponent filaments to create nonwoven disposable medical barrier fabrics such as surgical drapes, disposable gowns, etc. A patent by Anders *et al.*³⁰ describes a composite nonwoven material containing continuous filaments and short fibres in which both the continuous filaments and short fibres are evenly integrated into the matrix.

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Structure of composite nonwovens

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Abstract: This chapter reports on the structure of composite nonwoven materials. It first describes a set of basic fibre characteristics in homo-component nonwovens. It then develops the basic fibre characteristics for hetero-component nonwovens. Subsequently, it depicts fibre packing characteristics in composite nonwovens. Afterwards, it delineates fibre directional arrangement in composite nonwovens. The chapter concludes by describing the pore structure in composite nonwovens.

Key words: composite nonwoven, structure, packing, orientation, pore.

3.1 Introduction

The basic unit of construction of a composite nonwoven structure is fibre. Fibres are characterized by a long and thin configuration. A large number of fibres are organized to create the internal structure of composite nonwoven materials in a way which is influenced by the geometry of the fibres used. The geometry of fibres is generally characterized in terms of length, fineness, diameter, aspect ratio, cross-sectional shape, surface area, specific surface area, etc. Understanding the geometrical characteristics of individual fibres and their relationships in composite nonwovens consisting of homogeneous and heterogeneous fibres is essential for understanding the structure of composite nonwovens.

The organization of fibres in such materials is characterized by means of fibre packing arrangement and fibre directional arrangement. The fibre directional arrangement is often referred to fibre orientation. In addition, the geometry of pores is also considered to be another important structural characteristic of composite nonwoven materials.

3.2 Fibre characteristics in composite nonwovens

3.2.1 Fibre characteristics in nonwovens with homogeneous fibre composition

Homo-component nonwovens use fibres of the same origin and very similar characteristics. However, for the sake of simplicity, in this discussion it is assumed that all fibres are identical. Figure 3.1 shows a fibre that has mass m_f , length l ,

cross-sectional area s , volume V_f , perimeter p , and surface area A_f (Neckář and Das, 2012). Evidently, it is valid to write that

$$V_f = sl. \quad [3.1]$$

Its density ρ is defined by the ratio of its mass and volume:

$$\rho = m_f / V_f. \quad [3.2]$$

In practice, it is often necessary to specify the fineness characteristic of fibres. The fineness of a fibre is usually defined by the mass per unit length of the fibre:

$$t = \frac{m_f}{l} \quad [3.3]$$

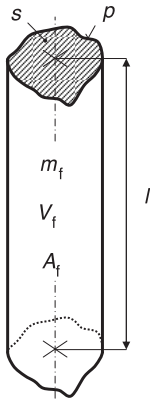
where t denotes fibre fineness.

By using Equations (3.3) and (3.2) it can be written that

$$t = \frac{V_f}{l} \rho, \quad V_f = \frac{tl}{\rho}, \quad \frac{V_f}{l} = \frac{t}{\rho}. \quad [3.4]$$

Equation (3.4) demonstrates an interesting limitation on the use of t as a measure of fibre fineness. In general, one can think about ‘fineness’ in terms of geometry, particularly ‘area of cross-section’ or ‘diameter’. As such, the use of fibre volume per unit length (the ratio V_f/l) would be a more logical way to express the fineness of a fibre. In contrast, the standard value of fibre fineness t must be divided by the value of fibre density ρ in order to obtain the value of fibre volume per unit length. Otherwise, if we compare the values of fineness t of two fibres having different densities, we may find that the ‘heavier’ fibre (higher value of ρ) is thinner than the ‘lighter’ one (smaller value of ρ).

The shaded area shown in Fig. 3.1 represents the cross-sectional area of a fibre, which is formed by intersecting a plane perpendicular to the axis of the fibre.



3.1 Schematic of a fibre.

Assuming that fibre cross-sectional area s is constant throughout its length, the volume of individual fibre can be expressed as $V_f = sl$. By substituting this expression into Equation (3.4) the expression for fibre cross-sectional area is obtained:

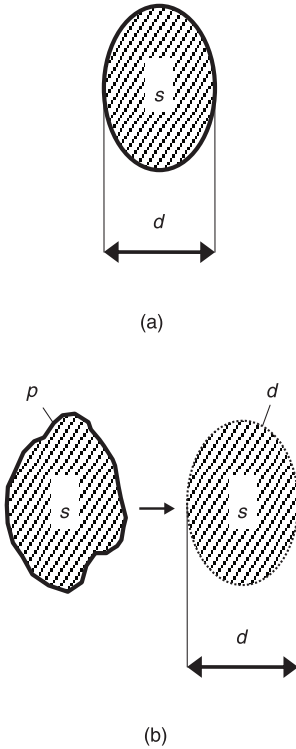
$$t = s\rho, \quad s = \frac{V_f}{l} = \frac{t}{\rho}. \quad [3.5]$$

It can be observed that the expression for fibre cross-sectional area is identical to the expression for fibre volume per unit length. Hence we realize that fibre cross-sectional area is an important measure of fibre geometry, i.e., the 'size' of a fibre.

Let us consider a cylindrical fibre as shown in Fig. 3.2(a). The fibre cross-sectional shape is circular and the fibre cross-sectional area is given by $s = \pi d^2/4$, where d is fibre diameter. By substituting this expression in Equation (6.5), we find the following expression for fibre diameter:

$$d = \sqrt{\frac{4s}{\pi}} = \sqrt{\frac{4t}{\pi\rho}}, \quad t = \frac{\pi d^2}{4} \rho. \quad [3.6]$$

Let us now consider a fibre with non-circular cross-sectional shape. Such a fibre is presented in a classical geometrical way without any defined diameter in



3.2 Fibre cross-section: (a) circular; (b) non-circular.

Fig. 3.2(b). The variable d calculated from Equation (3.6) expresses the diameter of an equivalent circular cross-sectional area, which is also shown in Fig. 3.2(b), and this diameter is known as equivalent fibre diameter. The correct value of fibre cross-sectional area can be calculated without considering the real shape of the fibre. The area of a circular cross-section is

$$s = \frac{\pi d^2}{4}. \quad [3.7]$$

By applying Equations (3.5) and (3.7), the fibre volume is expressed as

$$V_f = sl = \frac{\pi d^2}{4} l. \quad [3.8]$$

The fibre length and fibre diameter are frequently used to characterize the geometry of fibres. It is then reasonable to introduce the expression of fibre aspect ratio Λ , which is defined by the ratio of fibre length l and fibre diameter d :

$$\Lambda = l/d. \quad [3.9]$$

The real perimeter p of a fibre encloses its real cross-section as shown in Fig. 3.2(b). The perimeter of an imaginary equivalent circle of sectional area s is πd . It is well known from geometry that a circle is the shortest possible curve enclosing a given area, therefore, $p \geq \pi d$. Then $p/(\pi d) \geq 1$, and

$$q = \frac{p}{\pi d} - 1 \geq 0, \quad p = \pi d(1 + q), \quad [3.10]$$

where q is termed as fibre shape factor. It can be understood that a cylindrical fibre would show shape factor $q=0$. Morton and Hearle (1962) used another definition of shape factor and the fibre with circular cross-section showed the shape factor of one.

The fibre surface area is expressed by $A_f = pl$ (Fig. 3.1). The exact fibre surface area should include the areas of cross-sections of the two ends. Usually, these areas are negligibly small as compared to that of the cylindrical surface, and are ignored; the resulting error is negligibly small. Thus, by rearranging Equation (3.10), we find the following expression for fibre surface area:

$$A_f = pl = \pi d(1 + q)l. \quad [3.11]$$

Fibre specific surface area is expressed by surface area per unit mass of fibre. By applying Equations (3.11), (3.3), (3.5), and (3.7), we get the following expression for fibre specific surface area:

$$a = \frac{A_f}{m_f} = \frac{\pi d(1 + q)l}{\left(\frac{\pi d^2}{4}\right)l\rho} = \frac{4(1 + q)}{\rho d}. \quad [3.12]$$

An alternative expression for a is obtained by substituting fibre diameter from Equation (3.6) into Equation (3.12):

$$a = \frac{4(1 + q)}{\rho} \sqrt{\frac{\pi\rho}{4t}} = 2\sqrt{\pi} \frac{1 + q}{\sqrt{\rho t}}. \quad [3.13]$$

The ratio between fibre surface area and fibre volume is a useful measure to characterize the geometrical structure of a fibre. This is expressed by $\gamma = A_f/V_f$, where γ denotes fibre surface area per unit volume. By applying Equations (3.11), (3.1), and (3.7) we get the following expression for fibre surface area per unit volume:

$$\gamma = \frac{A_f}{V_f} = \frac{\pi d(1+q)l}{(\pi d^2/4)l} = \frac{4(1+q)}{d}. \quad [3.14]$$

By substituting Equation (3.6) into Equation (3.14), we get an alternative expression for γ :

$$\gamma = 4(1+q)\sqrt{\frac{\pi\rho}{4t}} = 2\sqrt{\pi}(1+q)\sqrt{\frac{\rho}{t}}. \quad [3.15]$$

By rearranging Equations (3.14) and (3.12) we can also find that

$$\gamma = a\rho. \quad [3.16]$$

Example 3.1: A nonwoven material of 250mg weight is prepared from polypropylene fibres of 51 mm length, 6 denier fineness, and 0.02 shape factor. The weight of one fibre is 34 μg . The nonwoven is composed of 7353 polypropylene fibres. The density of polypropylene fibre is 910 kg/m^3 . The equivalent diameter of polypropylene fibre is 30.55 μm . The surface area of a polypropylene fibre is 4.99 mm^2 . The total surface area occupied by all polypropylene fibres in the nonwoven is 0.0367 m^2 . The specific surface area of a polypropylene fibre is 146.76 m^2/kg . The surface area per unit volume is 133.55 mm^{-1} .

3.2.2 Fibre characteristics in nonwovens with heterogeneous fibre composition

Often fibres of the same origin but possessing highly different characteristics or fibres of different origins and possessing highly different properties are blended together to develop nonwoven materials. Such a fibre blend is characterized by mean characteristic values which are expressed in terms of mean characteristic values of individual components (different types of fibres). Then, the expressions derived in the previous section can be considered as the mean characteristic values of individual components.

Let us consider that a hetero-component nonwoven has n components, where each component consists of identical fibres. The fibre blend has total mass m and the mass of i -th component of the blend is m_i , where $i = 1, 2, \dots, n$ then it is valid to write that

$$\sum_{i=1}^n m_i = m, \quad m_i \leq m. \quad [3.17]$$

Let us further consider the (mean) fibre parameters of i -th component as density ρ_i , fineness t_i , length l_i , and surface area A_i , specific surface area a_i , and surface

area per unit volume γ_r . Analogously, the characteristics of the blend will be expressed without any subscript.

The mass fraction g_i of i -th fibre component is defined by:

$$g_i = \frac{m_i}{m} \quad (m_i = mg_i). \quad [3.18]$$

From Equations (3.17) and (3.18), it is valid to write that

$$\sum_{i=1}^n g_i = 1. \quad [3.19]$$

In practice, the composition of a blend is usually characterized either by mass fraction ('weight fraction') or by mass percentage of the components. In industry, the mass fraction (mass percentage of components) is preferred, because it is relatively easy to weigh the different components of the blend.

The volume of i -th component of the blend is V_i and the total volume of fibres in the blend is V , then from the definition of fibre density given by Equation (3.2) and applying Equation (3.18), we can write that

$$V_i = \frac{m_i}{\rho_i} = m \frac{g_i}{\rho_i}, \quad [3.20]$$

$$V = \sum_{i=1}^n V_i = m \sum_{i=1}^n \frac{g_i}{\rho_i}. \quad [3.21]$$

The mean fibre density of the blend is obtained from Equations (3.2) and (3.21):

$$\rho = \frac{m}{V} = \frac{1}{\sum_{i=1}^n \frac{g_i}{\rho_i}} \quad \left(\frac{1}{\rho} = \sum_{i=1}^n \frac{g_i}{\rho_i} \right). \quad [3.22]$$

It is obvious from Equation (3.22) that the mean fibre density of the blend is the weighted harmonic (not arithmetic!) mean of fibre density of individual components of the blend. (Remember that the harmonic mean is lower than the arithmetic mean.)

The volume fraction v_i of i -th component of the blend is defined by the ratio between the volume of i -th component of the blend and the total volume of fibres in the blend V . From Equations (3.20) to (3.21) we get

$$v_i = \frac{V_i}{V} = \frac{m \frac{g_i}{\rho_i}}{m \sum_{i=1}^n \frac{g_i}{\rho_i}} = g_i \frac{\rho}{\rho_i} \quad \left(\sum_{i=1}^n v_i = 1 \right). \quad [3.23]$$

The mass fraction of the individual components of the blend g_i is not a very important variable when studying the structure of the blend. This value is frequently used in industrial practice, because it is easy to determine during the blending process; on the contrary, the volume fraction v_i determines the relative

space, i.e., the 'size' occupied by the individual component, and it is an essential characteristic for predicting the behaviour of the blend.

The total fibre length L_i of i -th component in the blend is expressed from Equations (3.3) and (3.18):

$$L_i = \frac{m_i}{t_i} = m \frac{g_i}{t_i}. \quad [3.24]$$

It is evident that the total length L of all fibres in the blend is

$$L = \sum_{i=1}^n L_i = m \sum_{i=1}^n \frac{g_i}{t_i}. \quad [3.25]$$

By substituting Equation (3.25) into (3.3), we get the following expression for mean fibre fineness of the blend:

$$t = \frac{m}{m \sum_{i=1}^n \frac{g_i}{t_i}} = \frac{1}{\sum_{i=1}^n \frac{g_i}{t_i}}. \quad [3.26]$$

It is important to remember that the mean value of fibre fineness of the blend is also a weighted harmonic mean of the fineness values of individual components of the blend.

The mean fibre cross-sectional area s of the blend can be directly estimated from Equation (3.5) by using the mean fibre fineness and the mean fibre density of the blend. This can also be found from the mean fibre cross-sectional area of the individual components of the blend. Equation (3.5) can be used to express the fineness of i -th component of the blend as $t_i = s_i \rho_i$. Equation (3.23) can also be expressed by $v_i / \rho = g_i / \rho_i$. By substituting both equations into Equation (3.26), we get an alternative expression for the mean fibre fineness of the blend:

$$t = \frac{1}{\sum_{i=1}^n \frac{g_i}{s_i \rho_i}} = \frac{1}{\sum_{i=1}^n \frac{v_i}{s_i \rho}} = \frac{\rho}{\sum_{i=1}^n \frac{v_i}{s_i}}. \quad [3.27]$$

The mean fibre cross-sectional area of the blend is obtained by applying Equations (3.5) and (3.27) and rearranging them:

$$s = \frac{t}{\rho} = \frac{1}{\sum_{i=1}^n \frac{v_i}{s_i}}. \quad [3.28]$$

As shown, the mean fibre cross-sectional area of the blend is the weighted harmonic mean of the mean fibre cross-sectional area of the individual components of the blend.

The mean equivalent fibre diameter d of the blend can be directly obtained from Equation (3.6) by applying the expressions for mean fibre fineness and mean fibre density of the blend. It is also possible to calculate this value from the equivalent

fibre diameter of the individual components of the blend. From Equation (3.7), we find the mean fibre cross-sectional area of the blend is $s = \pi d^2/4$, and the cross-sectional area of the individual component of the blend is $s_i = \pi d_i^2/4$. By applying both equations into Equation (3.28) and rearranging, we get the following expression for the mean equivalent fibre diameter of the blend:

$$\frac{\pi d^2}{4} = \frac{1}{\sum_{i=1}^n \frac{4v_i}{\pi d_i^2}}, \quad d = \frac{1}{\sqrt{\sum_{i=1}^n \frac{v_i}{d_i^2}}}. \quad [3.29]$$

It is evident that the mean equivalent fibre diameter d of the blend is neither the arithmetic nor the harmonic mean of the mean equivalent fibre diameter d_i of the individual components of the blend, but the square value of mean equivalent fibre diameter d of the blend is the weighted harmonic mean of the square value of equivalent fibre diameter d_i of individual components of the blend. However, there are many empirical expressions available for the arithmetic mean of the mean equivalent fibre diameter.

The fibre length fraction of i -th component of the blend is denoted by λ_i and it is defined by the ratio of the fibre length of i -th component of the blend L_i and the total fibre length of the blend L . By applying Equation (3.24) into Equation (3.25), we find the following expression for the fibre length fraction of i -th component:

$$\lambda_i = \frac{L_i}{L} = \frac{m \frac{g_i}{t_i}}{m \sum_{i=1}^n \frac{g_i}{t_i}} = g_i \frac{t}{t_i} \quad \left(\sum_{i=1}^n \lambda_i = 1 \right). \quad [3.30]$$

Remark: The fibre length fraction of a parallel fibrous assembly (for example, continuous filament yarn) is also the relative frequency of the number of fibres of the individual component.

The (mean) length of fibres of i -th component is denoted by l_i (considering staple fibres) and the number of fibres N_i in i -th component of the blend can be estimated as $N_i = L_i/l_i$. By applying Equations (3.24) and (3.30) we find the following expression for the number of fibres in i -th component of the blend:

$$N_i = \frac{L_i}{l_i} = m \frac{g_i}{l_i t_i} = \frac{m}{t} \frac{\lambda_i}{l_i}. \quad [3.31]$$

From the above expression, we can express the total number of fibres in the blend as

$$N = \sum_{i=1}^n N_i = \frac{m}{t} \sum_{i=1}^n \frac{\lambda_i}{l_i}. \quad [3.32]$$

The mean fibre length l of the blend is obtained from Equations (3.3) and (3.32):

$$l = \frac{L}{N} = \frac{\frac{m}{t}}{\frac{m}{t} \sum_{i=1}^n \frac{\lambda_i}{l_i}} = \frac{1}{\sum_{i=1}^n \frac{\lambda_i}{l_i}}. \quad [3.33]$$

Here again we recognize that the mean fibre length of the blend is a weighted harmonic mean of the mean fibre length of the individual components.

The ratio between the number of fibres in i -th component and the total number of fibres in the blend is known as the relative frequency v_i . By applying Equation (3.31) into Equation (3.33), we find the following expression for the relative frequency of number of fibres of i -th component of the blend:

$$v_i = \frac{N_i}{N} = \frac{\frac{m}{t} \frac{\lambda_i}{l_i}}{\frac{m}{t} \sum_{i=1}^n \frac{\lambda_i}{l_i}} = \lambda_i \frac{l}{l_i} \quad \left(\sum_{i=1}^n v_i = 1 \right). \quad [3.34]$$

The mean fibre aspect ratio Λ of the blend can be found directly from Equation (3.9), by applying the mean fibre length and the mean equivalent fibre diameter of the blend. It can also be derived from the fibre aspect ratio of the individual components of the blend. According to Equation (3.9), fibre aspect ratio of i -th component of the blend is expressed by $\Lambda_i = l_i/d_i$ and from Equation (3.34) we find $l_i = \lambda_i l / v_i$. By combining both of these expressions, we find the following expression for the fibre diameter of i -th component of the blend:

$$d_i = \frac{l_i}{\Lambda_i} = \frac{\lambda_i l}{v_i \Lambda_i}. \quad [3.35]$$

The mean fibre aspect ratio of the blend is found from Equation (3.9) where $\Lambda = l/d$. By rearranging Equations (3.29) and (3.35), we find the following expression for the mean fibre aspect ratio of the blend:

$$\Lambda = \frac{1}{d} = l \sqrt{\sum_{i=1}^n \frac{v_i}{d_i^2}} = l \sqrt{\sum_{i=1}^n \frac{v_i v_i^2 \Lambda_i^2}{\lambda_i^2 l^2}} = \sqrt{\sum_{i=1}^n \left(\frac{v_i v_i^2}{\lambda_i^2} \Lambda_i^2 \right)}. \quad [3.36]$$

From Equation (3.12), it is valid that the fibre surface area of i -th component of the blend is $A_i = m a_i$. By substituting this expression into Equation (3.18) we find the fibre surface area of i -th component of the blend:

$$A_i = m a_i = m g_i a_i. \quad [3.37]$$

Accordingly, the surface area of all fibres A in the blend is obtained:

$$A = \sum_{i=1}^n A_i = m \sum_{i=1}^n (g_i a_i). \quad [3.38]$$

The mean specific fibre surface area a of the blend can be obtained by comparing Equations (3.12) and (3.38):

$$a = \frac{A}{m} = \sum_{i=1}^n (g_i a_i). \quad [3.39]$$

The mean specific fibre surface area of the blend is the summation of the product of mass fraction and the mean specific fibre surface area of the individual components of the blend.

The relationship between the specific fibre surface area and the fibre surface area per unit volume of i -th component of the blend is given by Equation (3.16) as $a_i = \gamma_i / \rho_i$. Similarly, for the blend it is valid that $\gamma = a\rho$, where γ denotes the mean specific fibre surface area per unit volume. Furthermore, according to Equation (3.23), it is valid that $g_i = v_i \rho_i / \rho$. By substituting these expressions into Equation (3.39) we find

$$a = \sum_{i=1}^n \left(\frac{v_i \rho_i}{\rho} \frac{\gamma_i}{\rho_i} \right) = \sum_{i=1}^n \frac{v_i \gamma_i}{\rho}, \quad a\rho = \sum_{i=1}^n (v_i \gamma_i), \quad \gamma = \sum_{i=1}^n (v_i \gamma_i). \quad [3.40]$$

The mean surface area per unit volume of the blend is the arithmetic mean of the fibre surface area per unit volume of the blend components.

The mean shape factor q of fibre cross-section of the blend can be found directly from Equation (3.14) by applying the expressions for mean specific fibre surface area per unit volume and the mean equivalent fibre diameter of the blend. Of course, it is also possible to derive this expression from the mean shape factor of fibre cross-section of the individual components of the blend. From Equation (3.6), the fineness of the blend is $t = (\pi d^2 / 4) \rho$ and the fibre fineness of i -th component of the blend is $t_i = (\pi d_i^2 / 4) \rho_i$. The ratio between these two expressions is obtained as

$$\frac{t}{t_i} = \frac{d^2 \rho}{d_i^2 \rho_i}. \quad [3.41]$$

From Equation (3.30), we find $t/t_i = \lambda_i / g_i$; and from Equation (3.23), we find $\rho/\rho_i = v_i / g_i$. By substituting both of these expressions into Equation (3.41) and rearranging we get the following expression for the equivalent fibre diameter of i -th component of the blend:

$$\frac{\lambda_i}{g_i} = \frac{d^2}{d_i^2} \frac{v_i}{g_i}, \quad d_i^2 = \frac{v_i}{\lambda_i} d^2, \quad d_i = \sqrt{\frac{v_i}{\lambda_i}} d. \quad [3.42]$$

From Equation (3.14), we obtain $1 + q = \gamma d / 4$ for the blend and $\gamma_i = 4(1 + q_i) / d_i$ for the i -th component of the blend. By substituting the above expression for the equivalent fibre diameter of i -th component of the blend into Equation (3.40) and applying Equation (3.42), we find the following expression for the mean shape factor of fibre cross-section of the blend:

$$\begin{aligned}
 1 + q &= \frac{\gamma d}{4} = \frac{d}{4} \sum_{i=1}^n (v_i \gamma_i) = \frac{d}{4} \sum_{i=1}^n \left[v_i \frac{4(1+q_i)}{d_i} \right] = \frac{d}{4} \sum_{i=1}^n \left[v_i \frac{4(1+q_i)}{\sqrt{(v_i/\lambda_i)}d} \right] \\
 &= \sum_{i=1}^n \left[\sqrt{v_i \lambda_i} (1+q_i) \right] q = \sum_{i=1}^n \left[\sqrt{v_i \lambda_i} (1+q_i) \right] - 1.
 \end{aligned} \quad [3.43]$$

The fibre surface area fraction of i -th component of the blend χ_i is defined by the ratio between the mean fibre surface area of the i -th component of the blend A_i and the surface area of all fibres of the blend A . This is obtained by applying Equations (3.37), (3.38), and (3.39):

$$\chi_i = \frac{A_i}{A} = \frac{mg_i a_i}{m \sum_{i=1}^n (g_i a_i)} = g_i \frac{a_i}{a}. \quad [3.44]$$

Example 3.2: Let us consider a bi-component nonwoven composed of 40% polypropylene fibres and 60% polyester fibres. The shaded boxes in Table 3.1 indicate the known parameters of the fibres. The other boxes represent the calculated parameters for the individual components and also for the whole material. The number of equations used to calculate these parameters is also mentioned in Table 3.1.

Table 3.1 Fibre characteristics in bi-constituent nonwoven

Parameters	Dimension	Polypropylene	Polyester	Blend	Equation
Length l	[mm]	51	51	51	(3.33)
Fineness t	[denier]	1.35	1.53	1.44	(3.26)
Density ρ	[kg/m ³]	910	1380	1144	(3.22)
Shape factor q	[–]	0.30	0.04	0.16	(3.43)
Cross-sectional area s	[µm ²]	164.8	123.2	141.1	(3.28)
Equivalent diameter d	[µm]	14.5	12.5	10.7	(3.29)
Aspect ratio Λ	[–]	3516	4072	4724	(3.36)
Specific surface area a	[m ² /kg]	394.3	240.6	302.1	(3.39)
Surface area per unit volume γ	[m ^{–1}]	358.85	332.08	345.54	(3.40)
Mass fraction g	[%]	40	60	–	–
Volume fraction v	[%]	50	50	–	(3.23)
Length fraction λ	[%]	43	57	–	(3.30)
Frequency fraction ν	[%]	43	57	–	(3.34)
Surface area fraction χ	[%]	52	48	–	(3.44)

Table 3.2 Fibre characteristics in tri-constituent nonwoven

Parameters	Dimension	Polypropylene	Polyester	Viscose	Blend	Equation
Length l	[mm]	51	51	51	51	(3.33)
Fineness t	[denier]	6.0	1.5	6.0	3.51	(3.26)
Density ρ	[kg/m ³]	910	1380	1500	1115	(3.22)
Shape factor q	[–]	0.30	0.20	0.09	0.13	(3.43)
Cross-sectional area s	[μm ²]	732.6	123.2	446.7	345.9	(3.28)
Equivalent diameter d	[μm]	30.6	12.5	23.9	17.6	(3.29)
Aspect ratio Λ	[–]	1669.5	4071.2	2138.0	5360.6	(3.36)
Specific surface area a	[m ² /kg]	187.1	277.7	121.9	193.4	(3.39)
Surface area per unit volume γ	[m ⁻¹]	170.2	383.2	182.8	215.55	(3.40)
Mass fraction g	[%]	50	25	25	–	–
Volume fraction v	[%]	61	20	19	–	(3.23)
Length fraction λ	[%]	29	57	14	–	(3.30)
Frequency fraction ν	[%]	29	57	14	–	(3.34)
Surface area fraction χ	[%]	45	36	19	–	(3.44)

Example 3.3: Let us consider a tri-component nonwoven composed of 50% polypropylene fibres, 25% polyester fibres, and 25% viscose rayon fibres. The shaded boxes in Table 3.2 indicate the known parameters of the fibres. The other boxes represent the calculated parameters for the individual components and also for the whole material. The number of equations used to calculate these parameters is also mentioned in Table 3.2.

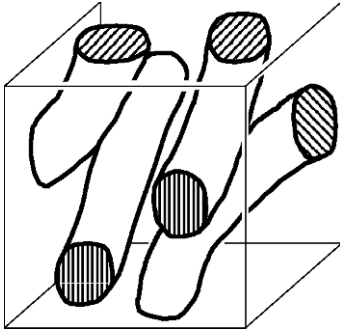
3.3 Fibre packing in composite nonwovens

3.3.1 Definition of fibre packing density

Figure 3.3 illustrates a three-dimensional section of a fibrous assembly of total volume V_c . The volume of fibres occupied by this section is V , thus $V \leq V_c$. The difference between the volumes $V_c - V$ expresses the volume of air present in the assembly, i.e., the empty spaces between fibres. The fibre compactness is measured by the ratio of the volume occupied by the fibres to the total volume of the fibrous assembly as

$$\mu = \frac{V}{V_c}, \quad \mu \in \langle 0, 1 \rangle. \quad [3.45]$$

The variable μ is termed as fibre volume fraction or fibre packing density.



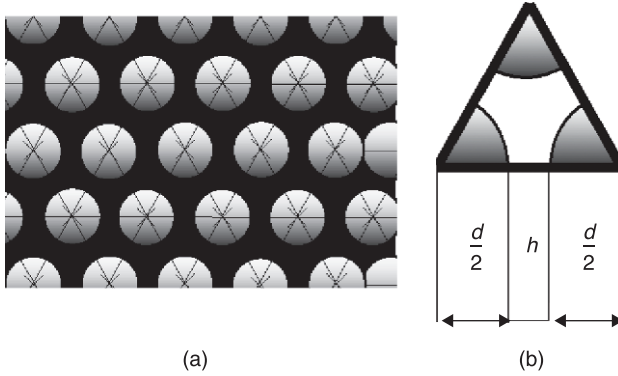
3.3 Section of a fibrous assembly in a three-dimensional plane.

3.3.2 Interpretation of fibre packing density

The fibre packing density in composite nonwovens is interpreted in terms of area packing density or packing density factor. The term area packing density is used when an infinitesimally thin section of a composite nonwoven material is cut and then kept under a microscope. This is then expressed by the ratio of the sectional area of all fibres present in the section to the area of the section itself. If it is assumed that the observed nonwoven has the same packing density in all the sections, then the value of area packing density can be taken as the value of packing density of the nonwoven.

On the other hand, the term packing density factor is expressed by the ratio of the density of nonwoven to the density of fibre. This is very much used while studying the continuum models of nonwoven media. In continuum modelling, the density of a mass element is divided by an arbitrary constant (density of fibre) to get packing density factor of the element. Actually, the packing density factor at an arbitrary point in a three-dimensional space takes either one if only fibre element occupies the space or zero if there is no fibre element in the space. The interpretation of packing density factor is also frequently used in practice. The density of a sample of composite nonwoven material can be calculated by dividing the measured basis weight of the sample to the thickness of the sample. Afterwards, the density of the sample can be divided by the density of the constituting fibre so as to determine the packing density factor of the composite nonwoven material.

Example 3.4: Consider a composite nonwoven material, made up of polyester fibre, has 2 mm thickness and 100 g/m^2 basis weight. So its density is calculated as 50 kg/m^3 . The density of polyester fibre is taken as 1380 kg/m^3 . The fibre packing density is then calculated as 0.0362.



3.4 Hexagonal structure: (a) configuration around a single core; (b) repeat of unit structure.

3.3.3 Model of fibre packing arrangement

The nonwoven fibrous assemblies are usually composed of fibres. In an idealized nonwoven fibrous assembly, the circular fibres are parallelly and uniformly distributed along the axes of the assembly. In such a fibrous assembly, the fibres are arranged in a configuration around a single core fibre as shown in Fig. 3.4(a). The repeat of the unit structure gives an equilateral triangle as shown in Fig. 3.4(b). The packing density of the triangular section of the fibrous assembly shown in Fig. 3.4(b) can be considered equal to the packing density of the whole structure. The length of each side of the triangle is $d+h$ and the height of the triangle is $(d+h)\cos 30^\circ$. Hence, the area of the triangle is obtained:

$$S_c = \frac{(d+h)(d+h)\cos 30^\circ}{2} = \frac{\sqrt{3}}{4}(d+h)^2. \quad [3.46]$$

The area occupied by the fibres in the triangular section of the assembly is equal to the summation of the areas of three equal sectors, shown by the shaded colour in Fig. 3.4(b), each is making an angle of 60° to the vertex of the triangle. This area is given by

$$S = \frac{\pi d^2}{8}. \quad [3.47]$$

The packing density is often expressed as a ratio between the sectional area of all fibres and the total area of the fibrous assembly including the empty spaces and fibres. Then the packing density of the triangle and thus for the whole structure can be expressed as

$$\mu = \frac{S}{S_c} = \frac{\frac{\pi d^2}{8}}{\frac{\sqrt{3}}{4}(d+h)^2} = \frac{\pi}{2\sqrt{3}} \frac{1}{\left(1 + \frac{h}{d}\right)^2}. \quad [3.48]$$

In the most compact type of fibre arrangement, all fibres are in contact with each other. This structure is called limit structure. In such a limit structure, the distance between fibres is $h=0$ and by applying this into Equation (3.48), we obtain the limit of packing density:

$$\mu_{\text{lim}} = \frac{\pi}{2\sqrt{3}} \cong 0.907. \quad [3.49]$$

Considering the space between fibres ($h < d/2$), the structure, where, ($h < d/2$), is called compact or tight structure. The packing density of this structure is obtained from Equation (3.48) by the following manner:

$$\mu > \frac{\pi}{2\sqrt{3}} \frac{1}{\left(1 + \frac{d/2}{d}\right)^2} = \frac{\pi}{2\sqrt{3}} \frac{1}{(1.5)^2} \cong 0.403. \quad [3.50]$$

Here we assume that the space between fibres is $h \in \langle d/2, d \rangle$. The structure, where $h \in \langle d/2, d \rangle$, is called intermediate structure. The highest packing density of this kind of structure is equal to the lower limit of packing density of compact structure, i.e., $\mu \cong 0.403$ and the lowest packing density of this kind of structure is obtained from Equation (3.48):

$$\mu = \frac{\pi}{2\sqrt{3}} \frac{1}{\left(1 + \frac{d}{d}\right)^2} = \frac{\pi}{2\sqrt{3}} \frac{1}{2^2} \cong 0.227. \quad [3.51]$$

The structure, where $h > d$, is called loose structure. The packing density of such a structure is less than the lower limit of the packing density of intermediate structure, i.e., $\mu < 0.227$. This structure has very low mechanical resistance and is significantly soft, porous, and drapable.

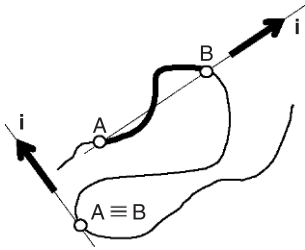
3.4 Fibre orientation in composite nonwovens

The arrangement of fibres in composite nonwovens can also be described by fibre directional arrangement. The direction arrangement of fibres is often referred to as fibre orientation. The orientation of fibres in the nonwovens is known to influence the mechanical strength of the nonwovens. The following sections deal with the definitions, concepts, and relations of fibre orientation in composite nonwovens. It starts with the concept of fibre orientation vector, then gradually proceeds to derive models of isotropic and anisotropic fibre orientation in fibrews, further continued to derive models of planar fibre orientation in multi-layered structures comprising fibrews.

3.4.1 Concept of orientation vector

Nonwovens are considered to be an assemblage of fibres. Each fibre follows different curvatures. Even the curvature of a single fibre varies widely in a nonwoven fibrous assembly. Thus, the term ‘orientation’ is not clear, but it can be intuitively thought. It is therefore required to exactly define the term ‘fibre orientation’.

Figure 3.5 displays the curvature of a single fibre. Here, a fibre segment of finite length (for example, the segment AB shown by thick black line) is designated by a suitable orientation vector \mathbf{i} . Conventionally, this is implemented according to the considerations that the orientation vector has a direction of joining the end points (A and B) of the fibre segment and the orientation vector is unitary. Then, at any arbitrary point on a fibre, a very short length (infinitely short segment) can be defined. (The curvature of fibres is considered as a smooth curve.) Then, the end points $A \equiv B$ of such segments coincide. Accordingly, the orientation vector follows the direction of the tangent to the fibre curvature as shown in Fig. 3.5.

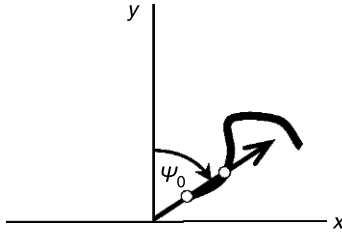


3.5 Orientation.

3.4.2 Planar fibre orientation in fibrewebs

There are a variety of fibrewebs that resembles to an ideal model of two-dimensional planar structure. Then, each fibre curvature is assumed to follow a planar curve and all such curves are lying on one plane only. Let us consider a fibre from such a plane and divide it into very (infinitely) short segments. One such fibre and its segment is shown in Fig. 3.6. The direction of fibre segments can be described by their orientation angles $\psi_0 \in (-\pi/2, \pi/2)$ taken from the y -axis. As known, in case of isotropic orientation, the fibre segments are equally distributed in all directions; therefore, we can describe their orientation by a constant probability density function $f_0(\psi_0) = \text{constant}$. It is then possible to write the following expression:

$$1 = \int_{-\pi/2}^{\pi/2} f_0(\psi_0) d\psi_0 = f_0(\psi_0) \int_{-\pi/2}^{\pi/2} d\psi_0 = f_0(\psi_0) \pi, \quad f_0(\psi_0) = \frac{1}{\pi}. \quad [3.52]$$



3.6 Direction of a fibre segment.

In practice, the air-laid webs and wet-laid webs are known to display practically isotropic orientation of fibres. Figure 3.7(a) shows the image of a wet-laid nonwoven web. A sample of this web was placed on a mirror, and the light was allowed to pass through the fleece and reflect off the mirror surface vertically back to the camera. The fibres, regardless of their position within the web, could merely block the light, appeared dark, and were in focus. The result was an image with excellent contrast and uniformity. The image was ‘thresholded’ to separate the fibres from the black and white background to obtain a binary image. This binary image was then analysed to determine the orientation of 1500 fixed 24-pixel fibre segments. Thirty such images were taken randomly from different parts of the web, thus the orientation of 45 000 fibre segments was determined. This large set of orientation data was summarized by frequency distribution in ten classes each of 18 degree width. The resulting histogram is displayed in Fig. 3.7(b). The continuous line corresponds to the probability density function of fibre orientation in fleece as expressed by Equation (3.52). This was obtained by employing the standard non-linear statistical regression technique. Evidently, the theoretical result corresponded well to the experimental one.

But, in practice, there are many fibrewebs where the orientation of fibre segments is not purely random. This occurs because of the technological methods dealing with the processing of fibres. In such cases, the fibres are found to be preferentially oriented in one particular direction. The fibres are often found to be longitudinally arranged in the direction of the material output (e.g., card web). It is then possible to derive the following expression:

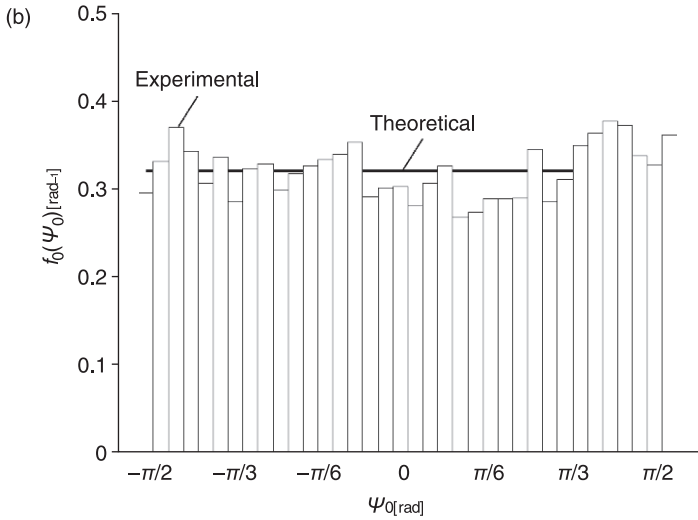
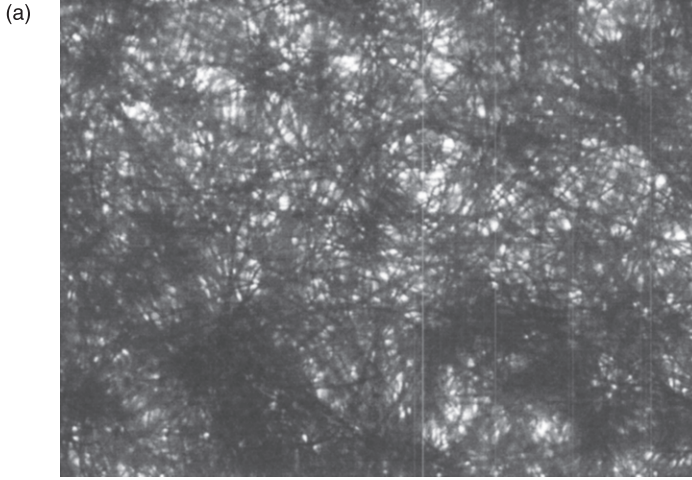
$$f(\psi) = \frac{1}{\pi} \frac{C}{C^2 - (C^2 - 1)\cos^2 \psi} \quad [3.53]$$

where $f(\psi)$ stands for the probability density function of angle of orientation ψ , and C is a measure of anisotropy of fibre orientation. The step-by-step derivation of the aforesaid expression is given by Neckář and Das (2012). The behaviour of this expression for different values of the parameter C is graphically shown in Fig. 3.8. It is evident that the maximum value of the probability density function f_{\max} is obtained at angle $\psi = 0$, and then according to Equation (3.53), we obtain

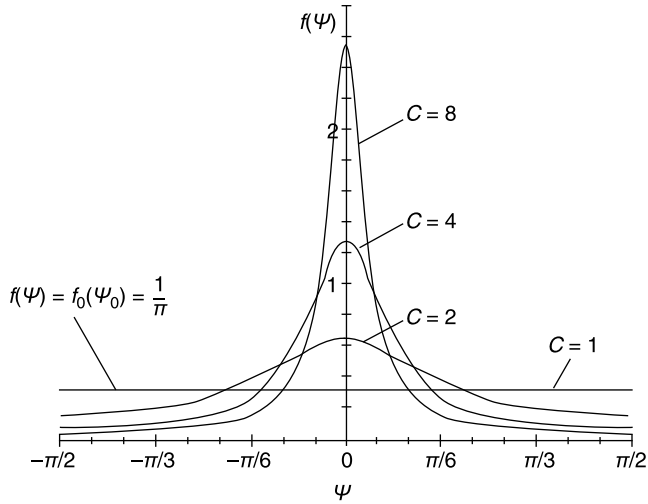
$$f_{\max} = f(0) = \frac{C}{\pi}. \quad [3.54]$$

Similarly, the minimum value of the probability density function f_{\min} is obtained at angle $\psi = \pm\pi/2$, and then according to Equation (3.53), we obtain

$$f_{\min} = f\left(\frac{\pi}{2}\right) = \frac{1}{C\pi}. \quad [3.55]$$



3.7 Image of wet-laid nonwoven fabric and fibre orientation distribution: (a) wet-laid nonwoven; (b) fibre orientation histogram.



3.8 Probability density function of orientation of fibre segments at preferential direction $\psi=0$.

Thus, we can write

$$\frac{f_{\max}}{f_{\min}} = C^2. \quad [3.56]$$

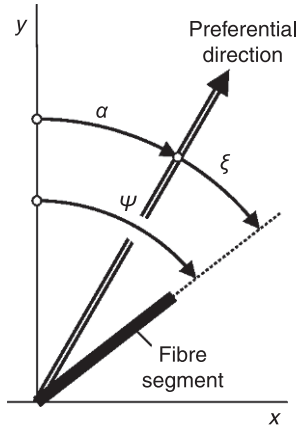
Further, when the value of C is equal to one, the fibre orientation is isotropic. The higher is the departure of value of C from one, the higher is the anisotropy of fibre orientation. The distribution function $F(\psi)$ of fibre orientation in plane can be obtained from the integration of the probability density function expressed in Equation (3.56):

$$F(\psi) = \frac{1}{\pi} \arctan (C \tan \psi) + \frac{1}{2}. \quad [3.57]$$

Sometimes, while processing, the fibre segments may tend to take a direction near to the preferential direction, because they are mechanically affected by neighbouring segments of same or other fibres and machine elements such as pins, cylinders, etc. In that case, the preferential direction of fibre segments is described by the preferential angle $\alpha \in (-\pi/2, \pi/2)$ to the y -axis (Fig. 3.9). Accordingly, the orientation angle ψ (to the y -axis) is expressed as the summation of the preferential angle α and another angle ξ , which is described by the angle that the fibre segments makes to the preferential direction as shown in Fig. 3.8. Then it is valid to write

$$\psi = \alpha + \xi \quad (\xi = \psi - \alpha). \quad [3.58]$$

The probability density function expressed by Equation (3.53) has been derived for the case where the preferential direction coincides with the direction of the

3.9 Angles ψ and ξ .

y -axis, i.e., where $\alpha=0$. It is evident that the angle ψ was earlier used with the sense of the angle ξ , i.e., the angle between the fibre segment and the preferential direction. The probability density function of the angle ψ is $g(\psi)$ and this must be equal to the function $f(\xi)$ according to Equation (3.53). Then, we obtain

$$g(\psi) = f(\xi) = \frac{1}{\pi} \frac{C}{C^2 - (C^2 - 1)\cos^2 \xi} = \frac{1}{\pi} \frac{C}{C^2 - (C^2 - 1)\cos^2(\psi - \alpha)}. \quad [3.59]$$

3.4.3 Planar fibre orientation in multi-layered structure

The multi-layered nonwoven structures are usually produced by layering of fibrewebs. There are many techniques of layering followed in practice. One of them is known as parallel-lay technique. In this technique, the card fibrewebs supplied by sequentially arranged parallel-cards are doubled on a common conveyor belt to form parallel-laid structure. In case of composite parallel-laid structure, each layer of card fibreweb can be made up of different fibres or same fibres but of different characteristics or of different basis weights. In such cases, the fibre orientation distribution of the resulting structure is expressed as

$$g(\psi) = \left(\frac{\varsigma_1}{\varsigma_1 + \varsigma_2} \right) \frac{1}{\pi} \frac{C_1}{C_1^2 - (C_1^2 - 1)\cos^2(\psi - \alpha_1)} + \left(\frac{\varsigma_2}{\varsigma_1 + \varsigma_2} \right) \frac{1}{\pi} \frac{C_2}{C_2^2 - (C_2^2 - 1)\cos^2(\psi - \alpha_2)} \quad [3.60]$$

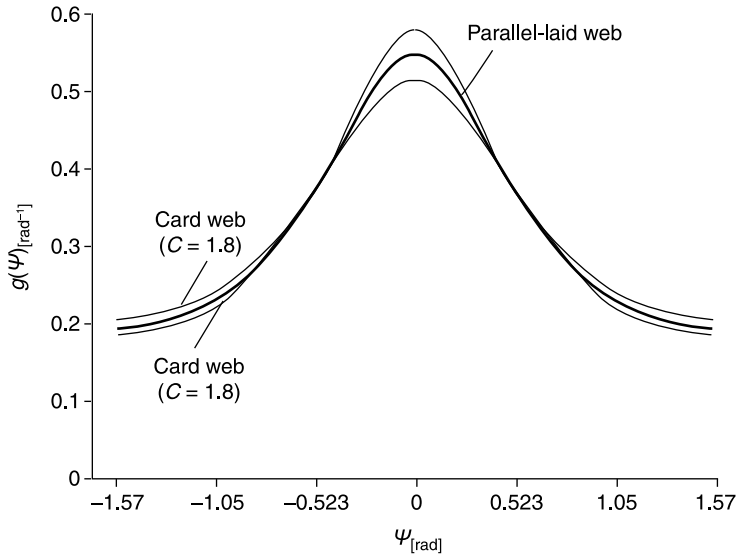
where ς_i stands for the weight of i -th type of web, C_i refers to the anisotropy parameter of i -th type of web, and α_i indicates the angle of preferential direction of the i -th type of web from y -axis.

Example 6.5: A parallel-laid fibreweb structure is formed by layering of two card webs. The fibres in the card webs are preferentially oriented along the direction of direction of the production machine. The measure of anisotropy in fibre orientation in the card webs is 1.6 and 1.8, respectively. The fibre orientation distribution in the card webs can be found from Equation (3.53) as shown in Fig. 3.10. Then, the fibre orientation distribution in the parallel-laid fibreweb can be found from Equation (3.60). This is also plotted in Fig. 3.10.

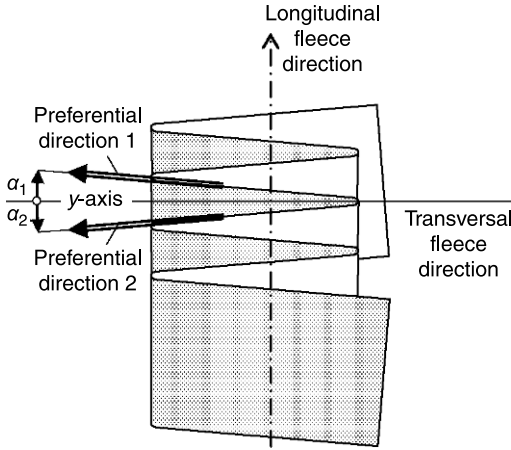
Another type of technique of layering of fibreweb is known as cross-lay technique. In this technique, the layers of fibreweb are deposited in zig-zag manner as illustrated in Fig. 3.11. Consider that the cross-laid fibreweb structure is composed of two fibreweb, one with preferential direction 1 which makes angle $\alpha_1 > 0$ to the y -axis and the other with preferential direction 2 which makes angle $\alpha_2 < 0$ to the same y -axis. Let us assume that the preferential direction of the fibres in the webs follows the technological direction of the production machine. The probability density function of orientation (angle ψ related to the y -axis) of fibres in the cross-laid fibreweb takes the following expression:

$$g(\psi) = \frac{0.5}{\pi} \frac{C}{C^2 - (C^2 - 1)\cos^2(\psi - \alpha_1)} + \frac{0.5}{\pi} \frac{C}{C^2 - (C^2 - 1)\cos^2(\psi - \alpha_2)} \quad [3.61]$$

The step-by-step derivation of the aforesaid expression is given by Hearle and Ozsanlav (1979). Usually, it is true that $|\alpha_1| = |\alpha_2|$, $\alpha_1 = -\alpha_2$. Nevertheless, it must



3.10 Fibre orientation distribution in card webs and parallel-laid web.



3.11 Formation of a fleece from two webs.

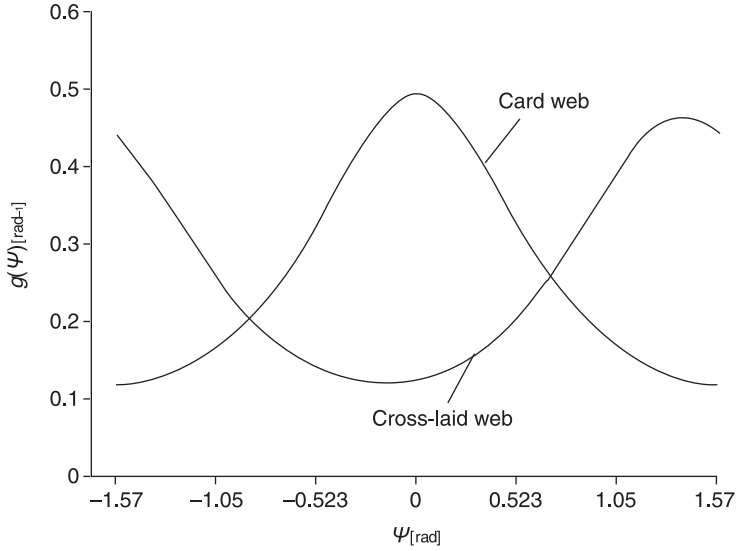
be valid for a more general case that $\alpha_1 - \alpha_2 = \beta$ and the value of β ('double α -value') must be a constant which is decided by the technological process employed to produce the fleece. The value of β can also be calculated as

$$\sin \frac{\beta}{2} = \frac{M_w H_w}{M_f H_f}, \quad [3.62]$$

where M_w and M_f denote the basis weights (mass per unit area) of the card web and the cross-laid web, respectively and H_w and H_f are the widths of the card web and cross-laid web, respectively. The step-by-step derivation of the aforesaid expression is given by Neckář and Das (2012).

Example 3.6: Consider that a cross-laid fibreweb is prepared for production of a nonwoven fabric by using polyester fibres of 51 mm staple length and 6 denier fineness and employing carding and cross-lapping technologies. The basis weight of the carded web is 18 g/m^2 and the width of the carded web is 440 mm. The measure of anisotropy of fibre orientation in carded web is determined as 1.6. The fibre orientation distribution in the card web can be obtained from Equation (3.53). This is graphically displayed in Fig. 3.11. Let us assume that the fibres in the carded web are preferentially oriented along the direction of the production machine. The basis weight of the fleece is 90 g/m^2 and the width of the fleece is 500 mm. By using Equation (3.62), the value of the angle β is found as $\beta = 0.3538$ radian. The fibre orientation distribution in cross-laid web can be obtained from Equation (3.61). This is graphically displayed in Fig. 3.12.

The theoretical fibre orientation distributions derived above can be very useful in predicting the orientation of a structure resulting from superimposition of



3.12 Fibre orientation distribution in card and cross-laid webs.

random, carded and cross-laid webs in any combinations. In deriving the distribution equations for such structures, a knowledge of the relative weight of the component webs is also essential. The general expression of distribution for a composite structure composed of n number of web types is

$$g(\psi) = \sum_{i=1}^{i=n} \left(\zeta_i / \sum_{i=1}^{i=n} \zeta_i \right) \frac{1}{\pi} \frac{C_i}{C_i^2 - (C_i^2 - 1) \cos^2(\psi - \alpha_i)} \quad [3.63]$$

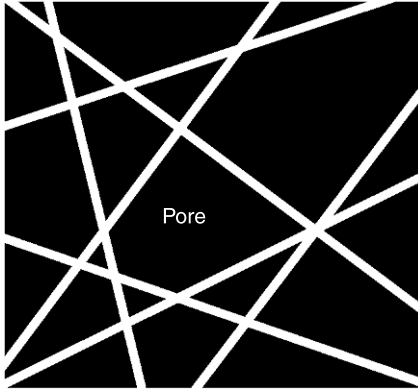
where ζ_i stands for the weight of i -th type of web, C_i refers to the anisotropy parameter of i -th type of web, and α_i indicates the angle of preferential direction of the i -th type of web from y -axis (Hearle and Ozsanlav, 1979).

3.5 Pore characteristics in composite nonwovens

3.5.1 Definition of porosity

The measure of fibre compactness in a nonwoven fabric can also be characterized by the presence of relative amounts of air in the fibrous assembly. For example, the nonwoven fabric shown in Fig. 3.13 has a total volume of V_c including fibre volume V . Then the volume of air (volume of pores) V_a between fibres in that assembly is

$$V_a = V_c - V. \quad [3.64]$$



3.13 Image of a Pore.

The relative volume of air is expressed by porosity $\xi = V_a/V_c$. By applying Equations (3.64) and (3.45) into the expression of porosity, we find the following expression:

$$\xi = \frac{V_a}{V_c} = \frac{V_c - V}{V_c} = 1 - \frac{V}{V_c} = 1 - \mu. \quad [3.65]$$

3.5.2 Interpretation of pores

Nonwovens are known to be fibrous porous material. A large volume of this material is occupied by air and the rest is occupied by fibres. If this material is projected onto a two-dimensional plane, an 'elementary plane' of this material is obtained. This is shown in Fig. 3.12. Evidently, this plane consists of many fibres and numerous air spaces surrounding the fibres. Let us call these air spaces 'pores'. One such pore is shown in Fig. 3.13.

3.5.3 Model of pore geometry

Simmonds *et al.* (2007) reported a model of pore structure in an elementary plane of a nonwoven fabric. As per this model, let the fibres be distributed randomly in an elementary plane of unit area and the probability $P(n_f)$ that any given point is covered by n_f fibres present per unit area of the plane is given by Poisson distribution of the following form:

$$P(n_f) = \frac{e^{-c} c^{n_f}}{n_f!}, \quad [3.66]$$

where c is the total projected area of fibres per unit area of the plane. Often, c is termed as coverage and it is expressed as $c = n_f l d$, where l is fibre length, and d is fibre width (diameter). According to the geometrical definition of probability, $P(n_f)$ is the area covered by n fibres per unit area of the plane, that is, $P(n_f)$ is the fraction of unit area covered by n fibres. If so then $P(0)$ is the fraction of unit area not covered by fibres, then $P(0)$ represents the open area fraction of the plane. Then, $P(0) = e^{-c}$. Clearly, $1 - e^{-c}$ is the fraction of the unit area covered by fibres. Similarly, $P(1)$ is the fraction of area covered by one fibre, $P(2)$ is the fraction of area covered by two fibres, and so on. Let us assume that a point covered by n_f fibres is covered by $n_f - 1$ crossings. Then, the total area A_c occupied by all fibre crossings per unit area of the plane can be derived by using Equation (3.66):

$$\begin{aligned} A_c &= \sum_{n=2}^{n=\infty} (n-1)P(n) = \sum_{n=2}^{n=\infty} (n-1)P(n) = \sum_{n=2}^{n=\infty} (n-1) \frac{e^{-c} c^n}{n!} \\ &= e^{-c} \sum_{n=2}^{n=\infty} (n-1) \frac{c^n}{n!} = c - (1 - e^{-c}). \end{aligned} \quad [3.67]$$

Thus, the total area of fibre crossings A_c is the difference between the total coverage c and the fraction of the unit area covered by fibres $(1 - e^{-c})$. The area a_c occupied by one fibre crossing is given by

$$a_c = \left(\frac{\pi d}{2} \right) = \frac{\pi}{2} d^2. \quad [3.68]$$

Then, for a small value of c , the number n_c of fibre crossings per unit area of the plane can be obtained by using Equations (3.67) and (3.68):

$$n_c = \frac{A_c}{a_c} = \frac{e^{-c} + c - 1}{\frac{\pi}{2} d^2} = \frac{2}{\pi d^2} (e^{-c} + c - 1) = \frac{(n_f l)^2}{\pi}. \quad [3.69]$$

The fibre-to-fibre crossings create the vertices of polygons in the plane. Each polygon simulates a pore. According to Kallmes and Corte (1960), the expression for a number of such pores n_p is

$$n_p = (n_c - n_f) e^{-c}. \quad [3.70]$$

Using the above expression, the mean cross-sectional area a_p of a pore is obtained:

$$a_p = \frac{e^{-c}}{n_p} = \frac{e^{-c}}{(n_c - n_f) e^{-c}} = \frac{1}{(n_c - n_f)} = \frac{1}{n_c \left(1 - \frac{n_f}{n_c} \right)}. \quad [3.71]$$

In general, it is valid that $n_f \ll n_c$. Then, it can be written that

$$a_p \cong \frac{1}{n_c} = \frac{\pi}{(n_f l)^2}. \quad [3.72]$$

Thus, the mean pore cross-sectional area is inversely proportional to the square of the total length of fibre deposited. If it is considered that the mean cross-sectional area a_p of pore is equal to the area of a circle of diameter d_p , then the following expression can be written by using Equation (3.72):

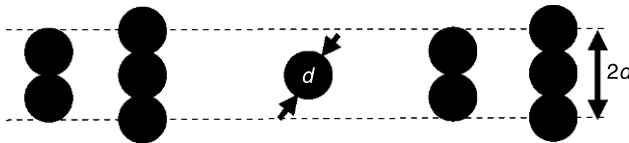
$$\frac{\pi d_p^2}{4} = a_p = \frac{\pi}{(n_f l)^2} \quad \text{or, } d_p^2 = \frac{4}{(n_f l)^2} \quad \text{or, } d_p = \frac{2}{n_f l}. \quad [3.73]$$

The variable d_p is called an equivalent pore diameter, or simply, pore diameter. Here the pore diameter is inversely proportional to the total length of fibre deposited.

3.5.4 Pore geometry in a multi-layered structure

The aforesaid relations are valid for an elementary plane. Consider that many such identical elementary planes are stacked one on the other in order to make the ultimate multi-layered structure. Further, assume that the thickness T of such a plane is equal to the thickness of two fibres, that is, $T = 2d$ (Fig. 3.14) and the centre of fibres lie on or within this plane. That means, in principle, as many as three fibres can intersect within this plane. Apparently, the pore structure of an elementary plane is decided by the pore structure of other elementary planes. One can imagine that at least two elementary planes always interact to determine the effective pore structure of a given plane. Let n_p^* be the number of elementary planes that must be taken into account together to describe the pore structure d_p^* in a multi-layered structure and we assume $d_p^* = d_p / n_{p*}$. Then, it can be written that

$$d_p^* = \frac{d_p}{n_{p*}} = \frac{\pi d}{4n_{p*}(1-\zeta)}. \quad [3.74]$$



3.14 Position of fibres in plane.

Table 3.3 Physical properties of spunbond nonwoven fabrics

Fabric code	Measured value (experiment)				Calculated values of average pore diameter (micrometer)
	Basis weight (g.m ⁻²)	Thickness (mm)	Porosity (–)	Average pore diameter (micrometer)	
A	34.20	0.3140	0.90	15.70	14.99
B	50.00	0.3430	0.87	11.70	11.53
C	65.00	0.3360	0.83	10.00	8.82
D	96.00	0.4690	0.82	8.80	8.33
E	111.00	0.5060	0.81	8.40	7.89

In order to see if the above model of pore geometry in multi-layered structures can explain the pore geometry of real nonwoven fabrics, Simmonds *et al.* (2007) developed a series of spunbond nonwovens by varying basis weight (weight per unit area), thickness and porosity. The physical properties of these fabrics are reported in Table 3.3. The fibre diameter was measured as 3.82 μm . The pore diameter was measured by using the standard image analysis technique. Table 3.3 shows the results of experiments. The pore diameter was also calculated from Equation (3.74). The theoretical results are also shown in Table 3.3. Evidently, the theoretical results correspond very well with the experimental results.

3.6 Conclusion

The characteristics of fibres in composite nonwovens are discussed and their relationships in homo- and hetero-constituent nonwovens are derived. The structure of composite nonwovens is described in terms of fibre packing arrangement, fibre directional arrangement, and geometry of pores. The theoretical models are presented from initial assumptions through mathematical derivations to final relations. Such theoretical relations are often found in good agreement with the experimental results.

3.7 Sources of further information and advice

Composite nonwovens are continuously gaining interest among the nonwoven scientists and researchers worldwide. Many attempts are being made to analyse and understand the structure of composite nonwovens. The role of structure on properties composite nonwovens is also being examined scientifically and the newer results are expected to be published in scientific journals. A close watch on such journals is required to gain new knowledge on composite nonwoven structure. Besides, the nonwoven trade journals and the publications of professional

bodies such as INDA and EDANA can also be looked at to obtain newer information on the structures of composite nonwovens.

3.8 References

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Properties of composite nonwovens

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Abstract: This chapter reports on the physical properties of composite nonwoven materials. These properties include strength and elongation, fluid permeability, thermal conductivity, liquid sorption, and particle filtration. The chapter summarizes the research progress made so far in establishing the roles of fibre materials and process technologies in determining these properties. Special attention is paid to the structure–property relationship in composite nonwoven materials.

Key words: composite nonwoven, strength, permeability, absorption, filtration.

4.1 Introduction

Composite nonwovens are considered to be advanced technical textiles. They are manufactured by combining different fibres and filaments as well as various substrates and structures using a range of process technologies. They are often characterized in terms of their physical properties including tensile strength, breaking elongation, bursting strength, fluid permeability, thermal conductivity, liquid sorption, and particle filtration. These properties are primarily determined by fibre characteristics, technological parameters, and structural features.

Understanding material–process–structure–property relationships has always been an important topic of research in composite nonwovens. This relationship is complicated due to the complex variables arising from the raw materials and the process technologies used. In spite of this, an in-depth knowledge has been gained over the years on material–process structure–property relationships in composite nonwovens. This knowledge is used by product development engineers to create novel or improved composite nonwoven products for a variety of applications.

4.2 Mechanical properties of composite nonwovens

One of the reasons for the development of composite nonwovens is related to the higher strength and other functionalities that can be achieved. Take the case of the spunbond-meltblown-spunbond (SMS) composite nonwoven, where the meltblown nonwoven imparts liquid and particulate barrier properties, whilst the spunbond nonwoven provides strength and abrasion resistance (Russel, 2007). As with any other manufactured material, the mechanical properties of composite nonwovens are primarily determined by the characteristics of the constituent

fibres and the internal structure, itself impacted by the manufacturing technologies employed.

Several studies have been carried out examining the roles of fibre characteristics, process parameters, and structural features on the tensile properties of composite nonwovens. Sun *et al.* (2002) prepared multi-layered fibrous structures by placing pre-thermally bonded cotton/polypropylene staple fibre webs on one or both sides of unbonded polypropylene spunbond webs. The resulting multi-layered structure underwent thermal calendar bonding at a variety of different temperatures and were then tested for tensile properties. It was observed that the tensile strength and breaking elongation of composite nonwovens increased with an increase in bonding temperature. Also, higher amount of polypropylene, achieved either by increasing the proportion of polypropylene in the thermally bonded cotton/polypropylene staple fibre web or by increasing the basis weight of the polypropylene spunbond web, led to an improvement in the bonding strength of the ultimate composite nonwovens. Such materials were claimed to be useful for many medical applications such as isolation gowns, hospital drapes, shoe covers, head covers, pillowcases, feminine hygiene pads, baby wipes, etc.

Tausif and Russel (2012) prepared a series of composite hydroentangled nonwovens comprising polyester and glass fibres in accordance with a two-level full factorial equipment design. A cross-laid web of polyester fibres was placed onto a parallel-laid web of 80/20 glass/polyester fibres and hydroentangled. Different water jet pressures, conveyor speeds, nozzle diameters, and number of injectors were employed in preparation. The resulting composite nonwovens were tested for their z-directional tensile strength in accordance with a modified version of BS ISO 15754. It was observed that a higher water jet pressure in combination with a lower conveyor speed produced composite nonwovens with higher tensile strength. Further, it was observed that for minimal consumption of specific energy, high water jet pressure, low conveyor speed, small nozzle diameter, and with a low number of injectors, stronger composite nonwovens were produced. The average separation point between the two layers shifted as a result of a change in the specific energy. As the tensile strength was increased, the average separation point was found to shift towards the layer comprised of polyester fibres.

Haghi and Zaikov (2012) reported on a study carried out to examine the influence of a nanofibre layer on the tensile strength of a composite fabric. The composite fabric was prepared by placing a nanofibre web between a polypropylene spunbond nonwoven fabric and a cotton woven fabric. For comparison, a composite which omitted the nanofibre web was also prepared. Both composite fabrics were tested for their tensile properties and it was observed that the tensile strengths of the composite fabrics prepared with the nanofibre layer were enhanced as compared to those without. No trend with breaking elongation was observed however.

Chattopadhyay *et al.* (2012) examined the tensile strengths of multi-component nonwovens exhibiting a multimodal fibre diameter distribution and compared with those with nonwovens showing a monomodal fibre diameter distribution. It was

observed that the tensile strengths of both multi-component and mono-component nonwoven fabrics were found to decrease with an increase in the average diameter of the constituent fibres. Further, it was observed that the mono-component nonwovens exhibited higher tensile strengths than the multi-component nonwovens with the same average fibre diameter.

Soliman *et al.* (2010) obtained results conflicting with those described above. This work employed a novel multimodal fibrous scaffold developed by electrospinning of poly(ϵ -caprolactone) such that the fibre distributions were not simply juxtaposed but finely intermixed into a single and truly multimodal layer. The multimodal scaffolds were found to exhibit superior strength and Young's modulus when compared to the monomodal ones, despite exhibiting higher porosity. This was explained by the fact that the monomodal scaffolds showed a tendency to fail by breaking into a bundle of parallel fibres, whereas the multimodal ones failed by delamination.

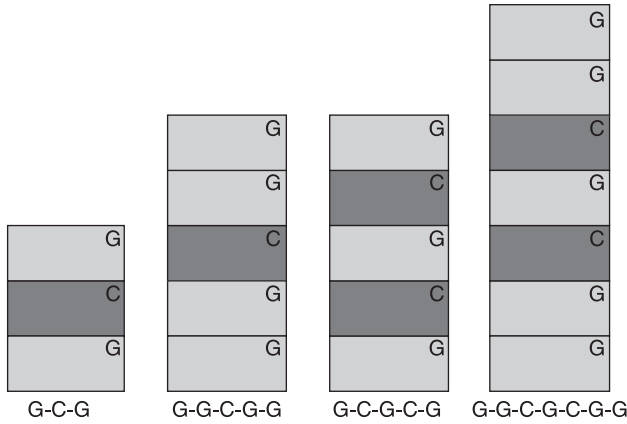
Studies have also been conducted to examine the bursting strength of composite nonwovens. Sun *et al.* (2002) tested the bursting strength of the multi-layered composite nonwovens described above. They did not observe any effect of bonding temperature on bursting strength of the composite nonwovens.

Chattopadhyay *et al.* (2012) examined the bursting strengths of nonwovens with a multimodal fibre diameter distribution and compared these with the bursting strengths of nonwovens showing a monomodal fibre diameter distribution. It was observed that the mono-component nonwovens exhibited higher bursting strength than the multi-component nonwovens with the same average fibre diameter. A significant correlation was found between the bursting strength and the tensile strength of the nonwovens.

Li *et al.* (2012) prepared a series of composite nonwovens by using recycled high-modulus kevlar fibres, nylon-6 fibres and bicomponent polyester fibres, and employed opening, mixing, carding, lapping, needle-punching and hot-pressing manufacturing processes. The Box-Behnken design of experiment was chosen for preparation of the composite nonwovens and the prepared materials were tested for their bursting strength and puncture resistance. The results of the experiments were analysed using the response surface methodology. The relative amount of bicomponent fibre was found to play a crucial role in determining the bursting strength of the composite nonwovens. Also, the needle-punching density and hot-pressing temperature affected the bursting strength significantly. Increasing needle-punching density and hot-pressing temperature resulted in bursting strength which initially increased and then decreased. Further, the bursting strength was found to be linearly dependent on the static puncture resistance of the composite nonwovens.

4.3 Fluid permeability of composite nonwovens

The fluid permeability behaviour of composite nonwovens has been investigated by a number of researchers working in the area of nonwovens. Mohammadi *et al.* (2002) developed a series of multilayered composite nonwovens using glass and ceramic



4.1 Scheme of arrangement of glass (G) and ceramic (C) fibreweb in fabrics.

fibreweb and employing needle-punching nonwoven technology. The diameters of the glass and ceramic fibres were chosen to be $7.3\mu\text{m}$ and $6\mu\text{m}$ respectively. The thicknesses of the glass and ceramic fibreweb were approximately 4.6mm and 6.4mm respectively. The glass and ceramic fibreweb were stacked as shown in Fig. 4.1. They were then bonded by employing needle-punching technology. These composite nonwoven fabrics were tested for their through-plane air permeabilities by using a Frazier air permeability tester. It was found that the composite nonwovens with a higher amount of glass fibres exhibited lower air permeabilities than those with a higher amount of ceramic fibres. Although the glass fibre webs were less dense than the ceramic fibre webs, an increase in glass fibre webs caused an increase in the thickness of the composite nonwovens that might have resulted in a reduced possibility for pore connectivity and hence a reduced air permeability.

Attempts were also made to analytically predict the air permeability of heterogeneous fibrous porous media. Claue and Philips (1997) proposed the following volume-weighted resistivity model for air permeability:

$$k = \frac{\mu_1}{\mu} \frac{1}{k(\mu_1)} + \frac{\mu_2}{\mu} \frac{1}{k(\mu_2)}, \quad [4.1]$$

where k and μ denote the air permeability and fibre volume fraction of the heterogeneous media, $k(\mu_1)$ denotes the air permeability of the homogeneous web consisting of coarser fibres with a fibre volume fraction of μ_1 , and $k(\mu_2)$ denotes the air permeability of the homogeneous web consisting of finer fibres with a fibre volume fraction of μ_2 .

Ethier (1991) proposed an alternative length-weighted resistivity model for the air permeability of heterogeneous fibrous porous media:

$$\frac{(\mu_1/r_1^2) + (\mu_2/r_2^2)}{k} = \frac{(\mu_1/r_1^2)}{k(\mu_1)} + \frac{(\mu_2/r_2^2)}{k(\mu_2)}, \quad [4.2]$$

where r_1 and r_2 indicate fibre radii.

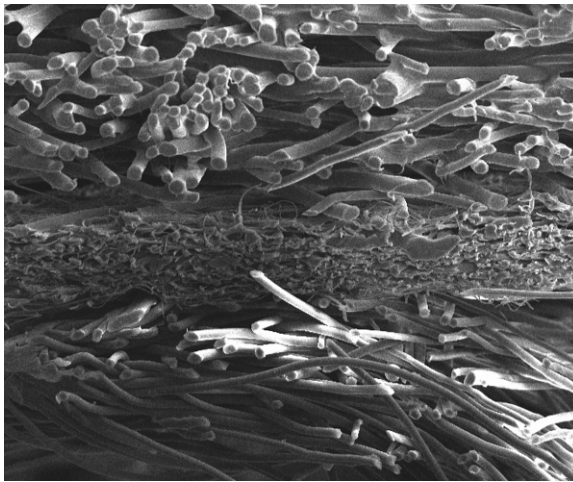
Chammas *et al.* (1994) suggested the following expression for air permeability of heterogeneous fibre porous media:

$$k = \frac{\mu_1}{\mu} k(\mu_1) + \frac{\mu_2}{\mu} k(\mu_2). \quad [4.3]$$

Here, the permeability of the heterogeneous media was expressed as an arithmetic mean of the permeabilities of the homogeneous media weighted by the fibre volume fraction of the individual media.

Mattern and Deen (2008) compared these expressions for air permeability and found that the volume-weighted resistivity expression was the most reliable.

The air permeability of spunbond-meltblown-spunbond (SMS) composite nonwoven fabric has also been examined. Such a material was prepared by placing a meltblown nonwoven fabric between two identical spunbond nonwoven fabrics. The meltblown nonwoven fabric was prepared from polypropylene and had an average fibre diameter of 3 μm , average basis weight of 39.32 g/m^2 , and average thickness of 0.35 mm. The spunbond nonwoven fabric was also prepared from polypropylene, but had an average fibre diameter of 18 μm , average basis weight of 38.46 g/m^2 , and average thickness of 0.37 mm. An image of the SMS composite nonwoven fabric is shown in Fig. 4.2.



4.2 Image of SMS composite nonwoven fabric.

The composite nonwoven fabric was tested for its through-plane air permeability by using a Frazier air permeability tester and the results of the experiments were compared for the individual meltblown and spunbond nonwoven fabrics. The air permeability of the SMS composite nonwoven fabric was measured to be $7.97 \text{ cm}^3/\text{cm}^2 \cdot \text{s}$ whereas that of the meltblown and spunbond fabrics were determined to be $8.91 \text{ cm}^3/\text{cm}^2 \cdot \text{s}$ and $63.23 \text{ cm}^3/\text{cm}^2 \cdot \text{s}$. The presence of the meltblown layer was thus found to reduce the air permeability of the SMS composite fabric.

Adams and Rebenfeld (1991a) investigated the in-plane fluid permeability characteristics of a heterogeneous multilayer fabric assembly by employing an in-plane flow technique and comparing the results to those of homogeneous multilayer fabric assemblies which were prepared by placing an isotropic nonwoven fabric onto an isotropic screening fabric. The isotropic screening fabric was found to have an in-plane permeability of 667 darcy whilst the isotropic nonwoven fabric had an in-plane permeability of 220 darcy.

It was observed that a homogeneous fabric assembly consisting of two layers of the nonwoven fabric yielded virtually the same in-plane permeability as a homogeneous fabric assembly consisting of one layer of the nonwoven fabric. A similar observation was reported in the case of an isotropic screening fabric. However, when the nonwoven fabric was placed over the screening fabric the resulting heterogeneous fabric assembly showed an in-plane permeability of 327 darcy. It was thus concluded that the fluid permeability of the heterogeneous multilayer fibre network differed from those of its constituent layers. Further, it was found that the effective in-plane permeabilities of heterogeneous assemblies were governed by the high permeability layers.

Permeability of the multilayer fibre network was modelled as a weighted average of the permeabilities of the individual layers by Adams and Rebenfeld (1991b) according to;

$$k = \frac{k_1 T_1 + k_2 T_2}{T_1 + T_2}, \quad [4.4]$$

where k_1 and k_2 indicate the permeability of the first and second layers, and T_1 and T_2 refer to the thicknesses of the first and second layers. This model was claimed to have good predictive capability.

Hollowell *et al.* (2013) investigated the air permeability characteristics of hybrid mixed media nonwovens composed of macro- and micro-fibres. They developed a series of hybrid mixed media nonwovens by hydroentangling a homo-component spunbond fabric sandwiched between two layers of 16-segmented pie bi-component spunbond fabric. The air permeability of this structure was compared with that of conventional 100% 16-segmented pie nonwoven fabric. The mixed media nonwovens were found to offer higher air permeabilities than the conventional nonwovens. A tentative explanation for this behaviour was that the homocomponent layer sandwiched between the two

bicomponent layers prevented dense packing of the fibres, thus allowing for higher air permeability. Experimental results demonstrated that the mixed media contained bigger pores when compared to the conventional media.

Tafreshi *et al.* (2009) studied the air permeability of bi-component nonwovens with a bimodal fibre diameter distribution. The air permeability of bimodal media was calculated by solving the Stokes flow equations in a series of 3-D virtual geometries mimicking the microstructure of fibrous materials. It was found that the cube root of the weighted mean cube of the fibre diameters had an acceptable correlation with the air permeability of bi-component nonwoven structures.

4.4 Thermal properties of composite nonwovens

Arambakam *et al.* (2012) studied the steady-state radiative heat transfer through bimodal fibrous media with translucent fibres using a Monte Carlo Ray Tracing (MCRT) simulation technique. It was observed that an increase in either fibre-diameter dissimilarity or the mass fraction of coarser fibres resulted in a slight increase in thermal conductivity through the media and thus also a reduced temperature gradient across the thickness of the media.

Mohammadi *et al.* (2003) studied the thermal properties of multilayered synthetic glass/ceramic composite nonwovens. In this case, the glass and ceramic fibrewebs were stacked according to Fig. 4.1. The thermal conductivity of the composite nonwovens were determined by using Holometrix guard hot plate equipment. It was found that as the percentage of glass fibre in the nonwovens increased, the effective thermal conductivity also increased. From a performance/cost perspective, the glass-ceramic-glass structure was deemed the better choice as an insulating fabric. Further, the following expression was proposed to express the thermal conductivity of the composite nonwovens:

$$\frac{T}{K} = \frac{T_1}{K_1} + \frac{T_2}{K_2} + \dots + \frac{T_n}{K_n}, \quad [4.5]$$

where T and K denote the thickness and thermal conductivity, respectively, of a composite nonwoven consisting of n layers. T_i and K_i ($i = 1, 2, \dots, n$) represent the thickness and thermal conductivity of the i -th layer where the latter was calculated according to

$$K_i = 1 - \left[\frac{1 - (K_{a,i}/K_{f,i})}{1 + \frac{2(K_{a,i}/K_{f,i})(v_{f,i}/v_{a,i})}{1 + (K_{a,i}/K_{f,i})}} \right], \quad [4.6]$$

where $K_{a,i}$ and $K_{f,i}$ denote, respectively, the thermal conductivity of air and fibre occupying the i -th layer, and $v_{a,i}$ and $v_{f,i}$ indicate the volume fraction of air and fibre occupying the i -th layer.

Banks-Lee *et al.* (2004) compared the thermal conductivity of composite nonwovens with the air permeability of the same and obtained a very high degree of correlation. Mao and Russell (2007) observed that a lightweight wool web incorporated into a warp knitted spacer fabric by means of hydroentanglement resulted in an improvement of the thermal insulation properties of the composite nonwovens. This was ascribed to a reduction in convection through the fabric and an increase in reflection of the heat radiating from the surface of the fabric due to the presence of the wool fibre layer. Barker and Heniford (2011) suggested that the use of a thin fibre layer in a multilayered composite structure would be a very effective method of increasing thermal insulation without changing the thickness and basis weight of the structure.

4.5 Liquid sorption characteristics of composite nonwovens

Composite nonwovens were also studied for their liquid sorption behaviour. Rengasamy *et al.* (2011) investigated the liquid sorption behaviour of spunbond-meltblown-spunbond (SMS) composite nonwovens of 45 g/m² basis weight and 0.35 mm thickness. In the same study, they also examined the liquid sorption behaviour of one spunbond nonwoven of 40 g/m² basis weight and 0.32 mm thickness and two meltblown nonwovens of 70 g/m² and 50 g/m² basis weight and 0.60 mm and 0.55 mm thickness, respectively. An in-house fabricated Gravimetric Absorption Testing System (GATS) was used for determination of the liquid sorption characteristics of the media. The liquid sorption capacity was found to be highest with the spunbond nonwoven fabric of 40 g/m² basis weight, followed by, in order, the meltblown fabric of 50 g/m² basis weight, meltblown fabric of 70 g/m² basis weight, and SMS composite nonwoven of 45 g/m² basis weight. A similar ranking was found for the liquid sorption rate. The composite nonwoven showed poor absorbency attributed to its inability to draw water to its top spunbond layer from the middle meltblown layer. When the surface capillaries of the composite nonwovens were supported with plates, spread of liquid took place at a faster rate. The liquid spreading length was found to be predicted reasonably well by the model developed by Kim and Pourdeyhimi (2003) based on the expression given for the directional permeability by Mao and Russel (2000).

Das *et al.* (2008) reported a method of preparation of an absorbent core for ultrathin sanitary napkins using blends of superabsorbent fibres and viscose fibres. The superabsorbent/viscose fibre blended carded webs were sandwiched between two layers of nonwoven fabrics, one made of parallel-laid viscose fibres and the other prepared from random laid viscose fibres. The prepared napkin samples showed an excellent rate of absorption of saline solution. Liquid transport was tested using a UMIST wettability tester, and it was observed that as the proportion of superabsorbent fibres in the absorbent core increased, the resulting composite fabrics exhibited quicker absorption.

Das *et al.* (2012a) studied the liquid sorption behaviour of composite nonwoven fabrics prepared by layer-wise mixing of superabsorbent fibres and regular polypropylene fibres by using a GATS. The tests showed better sorption capacity and better sorption rate when the liquid was first introduced to the polypropylene fibre side of the composite fabric rather than the superabsorbent fibre side. This was attributed to the superabsorbent fibres swelling and blocking the inter-fibre pores. However liquid that first encountered the inter-fibre pores of polypropylene could easily later diffuse into the superabsorbent fibres.

Liu *et al.* (2008) examined the wetting behaviour of an electrospun poly(L-lactic acid)/poly(vinyl alcohol) composite nonwoven. It exhibited better wettability than pure PLLA electrospun fibreweb and the wettability increased with increasing PVA content. A strong affinity between the hydrophilic group of PVA and the water molecules was proposed as a tentative explanation for this effect. Further, higher surface roughness led to a reduction of contact angles, and a smaller fibre diameter and smaller pore size resulted in a higher capillary pressure and thus higher water adsorption.

Chen *et al.* (2011) reported on the liquid sorption behaviour of a green composite nonwoven fabric prepared by using mixtures of lyocell, polylactic acid, and cotton fibres and employing a needle-punching nonwoven line. The line was comprised of an opening and mixing machine, carding machine, laying machine, and needle-punching machine. The water absorbency test was carried out as per the CNS 5611 standard. It was observed that the composite fabric absorbed more water when it contained more tencel fibres which phenomenon was ascribed to the molecular chain of the tencel fibres having many hydroxyl groups that enable water molecules to bond. They further observed that a higher needling density resulted in more water absorption both in the machine and cross-machine directions.

Das *et al.* (2012a) attempted to develop composite nonwoven structures by combining 'normal' plus 'super' absorbent materials to achieve enhanced liquid sorption behaviour. Four sets of composite nonwoven materials were developed by random mixing of superabsorbent fibres with 4DG, trilobal, or regular polyester fibres in different mass proportions and by employing a laboratory-based needle-punching line. The materials developed were tested for their liquid absorption behaviour using distilled water as a test liquid in a GATS. It was observed that the composite nonwovens prepared with a higher amount of superabsorbent fibres showed a higher liquid sorption capacity and liquid sorption rate.

4.6 Particle filtration behaviour of composite nonwovens

Composite nonwovens are widely used for the separation of air-borne particles from a polluted air stream. Fotovati *et al.* (2010) studied the capture efficiency and pressure drop of bi-component nonwovens showing a bimodal fibre diameter distribution. They presented a criterion for defining an equivalent

unimodal diameter distribution for their filter media and took advantage of the existing classical expressions for predicting the pressure drop and collection efficiency of bimodal fibrous media. They concluded that the cube root averaged diameter concept of Tafreshi *et al.* (2009) could be used to design a bimodal filter media quite successfully.

Jaganathan *et al.* (2008) studied the pressure drop across bi-component filter media composed of fibres showing bimodal diameter distributions. They observed that the area-weighted average of the fibre diameters in a bimodal filter, as proposed by Brown and Thorpe (2001), resulted in a relatively good estimation of an equivalent unimodal fibre diameter. Such averaging, however, left the pressure drop prediction sensitive to the ratio of fibre diameters and the distribution of fibre diameters. The authors proposed a correction factor accounting for both effects.

As reported by Hutten (2007), composite structures can be used for the following purposes:

- One or more layers can provide the required mechanical support for the other layer(s) responsible for filtration.
- one layer can serve as a prefilter layer for the layer responsible for filtration.
- Different layers can be organized in a manner to manipulate the gradient in density of the medium so that each layer provides a higher level of filtration efficiency to remove smaller and smaller particles.
- different separation technologies can be combined into one filter medium so that, for example, in the case of cabin air filters, an activated carbon layer is combined with one or more nonwoven layers, where the nonwoven layers filter out particles by means of mechanical capture mechanisms and the activated carbon layer separates molecular contaminants by means of chemical capture mechanisms.
- The outer layers can serve as a containment to inhibit medium migration, dusting, and particle fallout from the inner layers.

Thakur *et al.* (2013) prepared a spunbond-meltblown-spunbond (SMS) composite nonwoven filter medium where the meltblown layer was electrostatically charged. This material was tested for filtration efficiency and found to capture air-borne micro particles quite effectively. Yuksekkaya *et al.* (2010) developed a hybrid woven-nonwoven composite material also for air filtration application. They observed higher filtration efficiency as well as a higher pressure drop due to woven fabric reinforcement, and for the same reason, the bursting strength of the composite structure was found to increase, indicating potentially higher life of the filter.

To understand the role of individual layers in composite nonwoven filters, a systematic study was presented by Das *et al.* (2012b). They took an approach based on a computer simulation technique to generate virtual composite fibrous structures and to simulate the aerosol filtration behaviour of such filter media. A series of virtual composite filter structures were generated using GeoDict codes.

Table 4.1 Description of filters

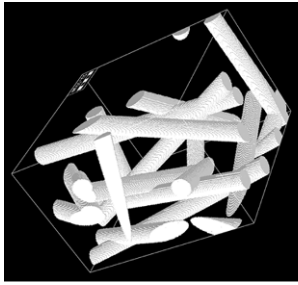
Filter code	Description
S1	Filter made up of fibres of 24 micron diameter, 19g/m ² basis weight and 12% solid volume fraction
S2	Filter made up of fibres of 2 micron diameter, 24g/m ² basis weight and 15% solid volume fraction
S3	Filter made up of fibres of 24 micron diameter, 26g/m ² basis weight and 12% solid volume fraction
S4	Filter with layering arrangement S1–S2–S3
S5	Filter with layering arrangement S1–S2
S6	Filter with layering arrangement S2–S3
S7	Filter with layering arrangement S3–S1

The detail of the structures is given in Table 4.1. The first three structures (S1, S2, and S3) were prepared as mono-layered structures. S1 and S3 were composed of microfibrils, and S2 consisted of submicro-fibrils. These three structures were used to create a multi-layered structure (S4) and a set of three bi-layered structures (S5, S6 and S7) were generated by combining two of the three mono-layered structures. The images of these structures (S1–S7) are displayed in Fig. 4.3. The set of filter structures were presented with particle laden air and the number of particles in the stated domain was fixed at 1 00 000. Face velocity was maintained at 10 cm/s, and the resulting particle capture efficiency was calculated from the ratio of the number of particles captured by the media to the number of particles upstream of the media.

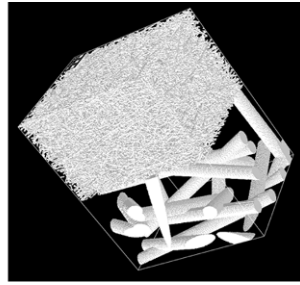
Table 4.2 displays the results for the pressure drop of the virtual fibrous filter media (S1–S7). Out of the three mono-layered fibrous filter media (S1–S3), S1 exhibited the lowest pressure drop, followed by S3 and S2. The pressure drop observed for S3 was relatively low, but for S2 was found to be high. This can be

Table 4.2 Simulated and calculated values of pressure drop and capture efficiency

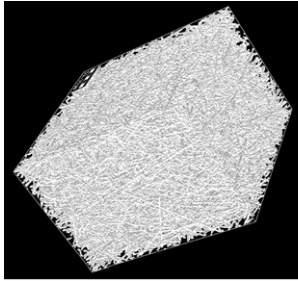
Filter code	Pressure drop (Pa)		Filtration efficiency (%)	
	Simulation	Calculation	Simulation	Calculation
S1	2.27	2.27	3.77	3.77
S2	290.73	290.73	99.81	99.81
S3	2.33	2.33	3.02	3.02
S4	294.13	295.33	99.83	99.82
S5	288.77	292.99	99.68	99.82
S6	268.27	293.06	99.75	99.81
S7	4.31	4.60	5.34	6.68



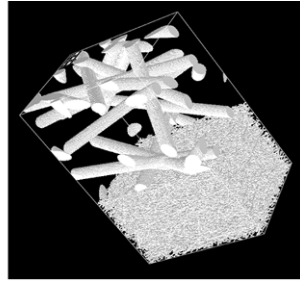
S1



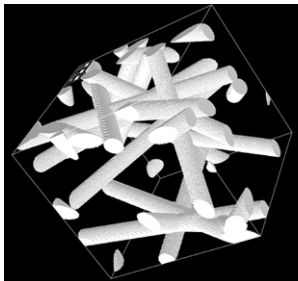
S5



S2



S6



S3



S7



S4

4.3 Image of virtual structures. For explanation of structures S1 to S7, see text.

explained by the negative effect of the higher surface area occupied by the fibres in the filter media. Though S1 and S3 were made up of the same fibres, the basis weight of S1 was less than that of S3 and as a result, the number of fibres occupying per unit area of S1 was less than for S3. S2 was comprised of finer fibres than S1 and S3 and the basis weight of S2 was higher than that of S1, but a little less than that of S3. As a result, the number of fibres occupying per unit area of S2 was higher than for both S1 and S3. The surface area occupied by the fibres in S2 was thus also higher than for S1 and S3, resulting in a higher pressure drop for S2. For the same reason, the presence of S2 in the two bi-layered media (S5 and S7) and in the multi-layered media (S4) resulted in a similarly high pressure drop. The remaining bi-layered medium (S7), because of the absence of S2, exhibited a relatively low pressure drop.

An attempt was made to predict the pressure drop of the bi-layered and multi-layered filter media from the pressure drop of the mono-layered filter media by using the following expression:

$$\Delta p_{\Sigma} = \sum_{i=1}^{i=n} \Delta p_i, \quad [4.7]$$

where Δp_i denotes the pressure drop of the i -th layer and Δp_{Σ} indicates the pressure drop of a fibrous filter medium consisting of n number of layers.

The results of this exercise are shown in Table 4.2 where it can be seen that the proposed expression is in fairly good agreement with the simulation results.

The particle capture efficiency of the virtual fibrous filter media (S1–S7) at the most penetrating particle size of 0.3 micrometer diameter is given in Table 4.2. It can be seen that among the three mono-layered filter media (S1–S3), S2 exhibited the highest capture efficiency, followed by S1 and S3. As the surface area occupied by the fibres per unit area of S2 was the highest, it was expected that the capture efficiency of S2 would be the highest. Similarly, as the surface area occupied by the fibres per unit area of S3 was higher than that of S1, the capture efficiency of S3 was expected to be higher than the capture efficiency of S1, which however was not found to be the case. The reason for this behaviour is not yet known.

Because of the presence of S2, the bi-layered media (S5 and S6) and the multi-layered medium (S4) yielded a high capture efficiency. The remaining bi-layered medium (S7), because of the absence of S2, exhibited a relatively low capture efficiency.

An attempt was made to correlate the particle capture efficiency of the bi-layered and multi-layered filter media with the capture efficiency of the mono-layered filter media according to

$$E_{\Sigma} = \sum_{i=1}^{i=n} E_i, \quad [4.8]$$

where E_i denotes the capture efficiency of the i -th layer and E_z indicates the capture efficiency of a fibrous filter media consisting of n number of layers. The results are shown in Table 4.2. Again, a good agreement with the simulation results was observed.

4.7 Conclusion

The physical properties of composite nonwoven materials including tensile strength, breaking elongation, bursting strength, fluid permeability, thermal conductivity, liquid sorption and particle filtration are discussed. The roles of fibre material and the internal structure on the aforesaid properties of composite nonwovens are described.

4.8 Sources of further information and advice

Composite nonwovens are engineered materials. They provide a solution through creation of multi-functional and economical products through streamlining of manufacturing processes and by the replacement of two or more products by a single one. Good sources of information to monitor on-going developments include the *Textile Research Journal*, *Journal of the Textile Institute*, and the *Journal of Engineered Fibres and Fabrics*. Furthermore, the nonwoven trade journals such as *Nonwovens Industry* and the publications of trade associations such as the INDA and EDANA are useful sources of knowledge.

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Composite nonwovens in absorbent hygiene products

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Abstract: This chapter reports on the use of composite nonwoven materials in absorbent hygiene products. It begins with an introduction to absorbent hygiene products and examines the considerations for the use of composite nonwovens in these products. It then proceeds to describe three important absorbent hygiene products, namely baby diapers, feminine sanitary pads, and adult incontinence pads, and informs about the recent developments that have been taking place on these products. To conclude, the chapter highlights the challenges and promises for absorbent hygiene products.

Key words: composite nonwoven, hygiene product, baby diaper, sanitary pad, adult incontinence pad.

5.1 Introduction

Absorbent hygiene products such as baby care products, feminine hygiene products and adult incontinence products are an essential part of everyday life. Baby care products include baby diapers, training pants, dry and wet baby wipes. Feminine hygiene products encompass sanitary pads, tampons, panty shields, interlabial devices, wipes and cosmetic removal pads. Adult incontinence products cover adult incontinence pads, adult pant diapers, underpads, personal/medicated wipes, and nursing pads. Amongst these products, baby diapers, sanitary pads and adult incontinence pads are the three mostly used disposable absorbent hygiene products.

In the past few decades, the overwhelming majority of innovations in absorbent hygiene products came through composites of nonwovens prepared by using a combination of different materials and different technologies. A large number of possibilities of combining different materials and different technologies was tried. Of them, some are continuously being used in commercial products. The greatest emphasis in the development of composite nonwovens was placed on the use of spunmelt systems (Chatterjee and Gupta, 2002). Examples include spunbond/meltblown (SM), spunbond/meltblown/spunbond (SMS) and spunbond/meltblown/meltblown/spunbond (SMMS). Besides, composite nonwovens were prepared by using air-laid/spunlace combination by incorporating fluff pulp by air-lay technology into a web during spunlacing or by incorporating air-laid pulp with spunlace on a spunlace line. In addition, there were developments of

polypropylene-polyethylene bicomponent spunbond nonwovens with polypropylene core providing the strength and mechanical stability and polyethylene sheath contributing to the softness and greater ease of thermal bonding. Further, many interesting materials such as cotton surfaced spunbond composite nonwoven and cotton centred composite with spunbond and meltblown nonwoven forming the outer surfaces of absorbent hygiene products were also developed. Furthermore, composite nonwovens prepared by combining fluff pulp and superabsorbent polymer granules have been widely used in a variety of disposable absorbent hygiene products.

5.2 Key material requirements

The primary and the most important function of absorbent hygiene products, exemplified by baby diapers, sanitary pads, and adult incontinence pads, is to absorb bodily liquids such as urine and menstrual liquid (Allan, 2005). But attainment of this characteristic is not sufficient because, from a hygienic point of view, after absorbing the liquid the surface of the product must be dry and also the absorbed liquid must be retained inside the product so that it should not leak to the outer surface.

In order to achieve this, the urine or menstrual liquid is required to pass through the surface layer and gets absorbed in the core and retained beneath the core. How is this possible? There are many approaches reported in the literature to tackle this tricky problem. A common solution states that the products are required to be comprised of a gradient of absorbency ranging from near zero at the surfaces to maximum in the core. This gradation is achieved by using a multi-layered composite of nonwoven materials wherein the constituents and their arrangement in each layer need to be appropriately chosen.

Typically, the most popular constituents in today's disposable absorbent hygiene products include hydrophilic cellulosic fibres (wood-derived fluff pulp or viscose rayon), superabsorbent polymer granules or superabsorbent fibres and hydrophobic polyester or polypropylene fibres. The latter constitutes the surface of the product which is in contact with the skin. Despite their hydrophobicity, these fibres can retain some amount of liquid, especially in the interstices of the porous surface layer. This layer is made as thin as possible to minimize the amount of liquid retained and to maximize the feel of dryness.

Further, the composition of the layer immediately below the thin surface layer is selected in such a way that it is capable of withdrawing the interstitial liquid therefrom. Of course, it is not sufficient to merely move this liquid into a layer contiguous to the surface layer, it must be moved deeper into the product. This can be done by modifying the geometry of the pores. As known, the smaller the pore the greater is the capillary pressure driving the liquid. So, a layer with smaller pores would draw liquid from a chemically identical layer with larger pores nearer to the skin. But, this would obviously reduce the absorptive capacity of the

product. This negative effect can be minimized by incorporating superabsorbent polymer or superabsorbent fibre. However, upon absorbing liquid, these polymers or fibres swell tremendously and form a liquid impermeable wall of gel, thus inhibiting the movement of liquid. This is why these polymers or fibres must be distributed randomly within the fibre mass. While the smaller superabsorbent particles result in faster absorption of liquid because of increased surface area, they have a tendency to fall out of the web. Nevertheless, this can be avoided by using superabsorbent fibres.

Another way to influence the movement of liquids in these products requires using blends of hydrophilic and hydrophobic fibres. The latter helps to prevent collapsing and matting of a wetted cellulosic fibre mass. One can thus see that the composite nonwoven materials are offering a unique solution to achieve the desired movement of liquids, such as urine and menstrual liquid, through the complex structure of disposable absorbent hygiene products.

5.3 Baby diapers

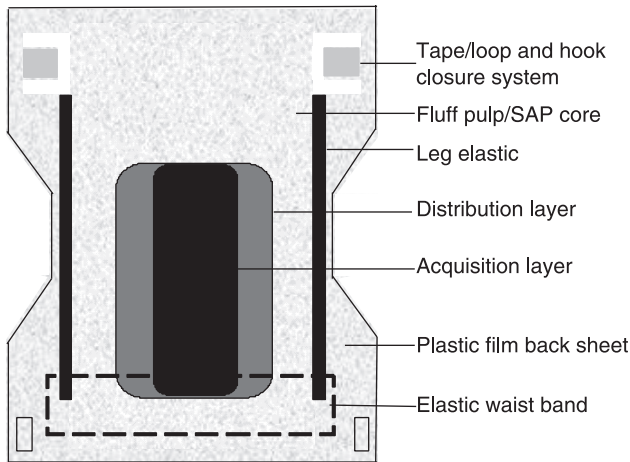
5.3.1 Functions

The baby diaper is considered as one of the important disposable absorbent hygiene products today. The functions of a baby diaper are to (1) absorb the baby's urine, (2) isolate wetness from the baby's skin, (3) retain urine inside their absorbent core, (4) contain faeces, and (5) isolate urine and faeces from the babies environment. These functions should be accompanied by providing maximum comfort for the baby, a good fit around babies legs and bottom, good practical usefulness, and less diaper rash for the baby. In order to achieve these functions, the requirements of a baby diaper are to

- 1 keep the surface layer as dry as possible in order to facilitate good skin care conditions;
- 2 transfer liquids from the surface through to an effective storage layer;
- 3 absorb and store transmitted liquids in such a way that they will not be released back through the structure to the surface;
- 4 provide an efficient containment system to contain the absorbent layers in order to protect the user's environment;
- 5 be capable of appropriate and environmentally compatible disposal after use.

5.3.2 Components

In the last few decades the baby diaper has evolved from a relatively simple structure comprising a large volume of fluff pulp covered on one side by a nonwoven material and on the other side by a thin impervious film, to a multi-layered complex structure where each layer has a specifically allocated task. Though there are many variations and combinations around this structure followed



5.1 Schematic diagram of the baby diaper structure; SAP, superabsorbent polymer.

by different companies, typically a disposable baby diaper consists of coverstock (top sheet), acquisition and distribution layer, absorbent core, back sheet, tissue, leg cuff, elastic, later tape, frontal tape, etc. Figure 5.1 presents a schematic diagram of the baby diaper structure, of which the coverstock, acquisition and distribution layer, absorbent core, and back sheet contain nonwovens. The function and composition of each of these four layers are discussed below.

Coverstock

The top surface of a baby diaper which is in contact with the baby's skin is known as coverstock. This layer allows the liquid to flow into the core of the diaper. Earlier, hydrophilic viscose rayon was used to manufacture the coverstock by employing nonwoven technology. At that time it was thought that the coverstock had to be absorbent for optimum performance. Later on, it was understood that a dry surface of the coverstock was essential to maintain a good skin health. Then, hydrophobic synthetic fibres such as polyester and polypropylene were started to be used for making the coverstock. Gradually it was understood that the hydrophobicity in a diaper facing was necessary but not sufficient for optimum performance. The coverstock must also quickly pass the liquid through to the core of the diaper (rapid strike-through) and at the same time it must restrict the passage of the liquid back through in the reverse direction (wet-back) so as to maintain a dry surface to the skin. This tricky problem was solved by applying a small amount of an effective rewetting agent on the surface of the coverstock. Today, the coverstock is generally made up of polypropylene spunbond nonwoven, however, polypropylene carded and thermally bonded or polypropylene/

polyethylene bicomponent spunbond nonwoven or lofty through-air bonded nonwovens or spunbond–meltblown composite SMS, SMMS, SSMMS structures are also used. A good overview on the use of these materials in coverstock is given by Chatterjee and Gupta (2002). An effective durable rewetting agent is uniformly applied onto this material to make it hydrophilic. Sometimes, in order to create novelties for product differentiation, several topical lotions are added to the nonwoven coverstock, such as aloe vera, almond oil, vitamin E, vitamin D, etc. The use of antibacterial lotions, such as tertiary ammonia or silver salt compounds onto the coverstock is, however, not recommended by many paediatricians.

Acquisition and distribution layer

This is an inner layer placed between the top sheet and the absorbent core. Though this is mostly used as a patch near the target zone where urine is most likely to be deposited, it sometimes is used in full length. This layer is needed especially when the absorbent core is very thin. It provides rapid acquisition, quick transport and thorough distribution of the liquid. Further, this layer is very important to give a sense of dryness to the skin by providing additional separation between the coverstock and the absorbent core. Also, it reduces potential leakage. This layer is generally used whenever the mix of superabsorbent polymer in the absorbent core exceeds about 15% by weight or when the liquid penetration time requires a boost in order to avoid diaper leakage due to liquid accumulation inside the diaper.

The acquisition and distribution layer generally takes the form of a multi-layered composite nonwoven material. The top layer is made up of coarser fibres and has relatively large pores and high porosity, especially effective for acquisition of the liquid. The middle layer is made up of fine fibres and has relatively small pores and low porosity and is especially effective for transferring the liquid into the core of the diaper. The bottom layer is made up of finer fibres and has smaller pores and less porosity. As there is a gradient of porosity or density and pore size along the thickness of the material, there is a gradient of capillary pressure which would help to move a greater volume of liquid effectively to the absorbent core of the diaper. The acquisition and distribution layer is generally made of through-air bonded nonwovens, but an aperture film made of perforated plastic has also been used successfully.

Absorbent core

The absorbent core is the heart of any disposable absorbent products and the baby diaper is no exception to this. It gives integrity and absorbing capacity to the diaper and placed in-between the acquisition and distribution layer and the back sheet. Today, the absorbent core of a baby diaper is mostly comprised of an optimum combination of fluff pulp and superabsorbent polymer (SAP). The earlier diapers utilized fluff pulp only; although this showed quite high absorption

capacity when the diaper was in free swell, it showed less absorption capacity under pressure. What followed was the utilization of superabsorbent polymer in the absorbent core of a baby diaper. The superabsorbent polymer is typically used in fine granular form. It helps to increase liquid absorption capacity tremendously, but at the same time increases liquid retention capacity, thus allowing the product to be thinner with improved performance.

The dominant superabsorbents available in the market today are based on cross-linked sodium polyacrylate gels. In the molecular structure of sodium polyacrylate, there are sodium carboxylate groups hanging off the main chain. When it comes in contact with water, the sodium detaches itself, leaving only carboxyl ions. Being negatively charged, these ions repel one another so that the polymer unwinds and absorbs water, which is attracted by the sodium atoms. The polymer also has cross-links, which effectively leads to a three-dimensional structure. It has high molecular weight of more than a million; thus, instead of getting dissolved, it solidifies into a gel. The hydrogen in water (H-O-H) is trapped by acrylate due to the atomic bonds associated with the polarity forces between the atoms. Electrolytes in the liquid, such as salt minerals (urine contains 0.9% of minerals), reduce polarity, thereby affecting superabsorbent properties, especially with regard to the superabsorbent capacity for liquid retention. Linear molecular configurations have less total capacity than non-linear molecules but, on the other hand, retention of liquid in a linear molecule is higher than that in a non-linear molecule, due to improved polarity. The detail physical chemistry of superabsorbent polymers can be found elsewhere (Chatterjee and Gupta, 2002).

Back sheet

The back sheet is used to prevent the absorbed liquid from leaking out of the diaper. The back sheet is a breathable but liquid impervious film and it is generally made up of polyethylene. Sometimes, the back sheet is given a cloth-like look by adding a thin polypropylene non-woven sheet to the film, using either the hot melt process or the heat and pressure method with direct extrusion to the nonwoven.

5.3.3 Recent developments

Disposable absorbent hygiene products are in general a subject of immense interest to a large number of product development scientists in many multinational companies. The baby diaper, being one of the important disposable absorbent hygiene products, is not an exception to this. In the recent past, a series of patent disclosures was made on the baby diaper and its components. Interestingly, a few of them were based on composite nonwoven materials.

Seneviratne (2009) disclosed a patent on the development of biodegradable personal products such as the baby diaper comprising an outer cover, an absorbent core formed of starch grains or flakes and hydrogel dispersed in viscose fluff, a

hydrophobic layer, a biodegradable film and a hydrophilic layer such that the last three layers were formed by using polylactic acid. In another patent disclosure, Luo (2009) reported a novel absorbent structure for the use in disposable hygiene products comprised of at least two nonwoven meltblown lyocell fibrews with superabsorbent polymer placed in-between the two fibrews.

Wood *et al.* (2009) disclosed a disposable absorbent article made up of an absorbent material and a degradable thermoplastic polymer composition comprising an aliphatic polyester. An antimicrobial composition is formed into webs by melt extrusion, such as nonwovens and films that are incorporated into disposable absorbent products. Amos *et al.* (2012) disclosed a disposable absorbent article comprising an absorbent material and an antimicrobial composition. The antimicrobial composition included a carrier comprising fatty alcohol, a poly(alkyleneoxy) polymer, and an antimicrobial agent. This composition might be coated onto component substrates such as nonwoven and films that were incorporated in disposable absorbent articles. Udengaard *et al.* (2010) developed an absorbent hygiene article with barrier component, which comprised at least a spunbond web or a meltblown web, or a combination of both obtainable from a mixture of thermoplastic polymers and a selected organic melt-additive component.

Martin (2003) disclosed an elastic nonwoven sheet for the use in the manufacture of diapers, which was prepared by substantially uniformly impregnating a necked nonwoven substrate with an elastomeric polymer by treatment with an elastomeric solution. Coronado *et al.* (2004) reported an invention of a nonwoven laminate printed with graphics that exhibited a soft cloth-like feel and was lightweight, impermeable and suitable for application as a back sheet in disposable absorbent hygiene articles. Isele and Chhabra (2005) developed a nanofibre web by employing a melt film fibrillation process for use in a baby diaper as a barrier-on-core, outercover, and/or leg cuff. Nguyen (2006) developed a bonded nonwoven material comprising extensible fibres for use in articles such as baby diapers. Barge *et al.* (2004) disclosed a liquid acquisition layer with improved caliper recovery and re-wet properties for the use in disposable absorbent products. Koczab (2002) disclosed a patent on composite nonwoven material for the use in absorbent hygiene articles, which was prepared by needle-bonding or thermo-bonding two carded fibre layers such that one was comprised of higher denier fibre than the other.

Fleissner (2001) developed a composite nonwoven material for the use in absorbent hygiene articles by hydroentangling a spunbond nonwoven fabric and a layer of pulp fibres. Dharmadhikary *et al.* (2004) developed nonwoven products for hygiene application by laminating one or more nonwoven substrates and one or both sides of a cast film produced by employing multiple extruders.

Sun *et al.* (2002) reported on development of innovative cotton-surfaced and cotton core nonwoven laminates for use in absorbent hygiene products. The cotton surfaced nonwovens were developed by applying cotton fibres on one or both

sides of a base structure, generally polypropylene spunbond web, and then laminating all the layers by employing the thermal calendar bonding technique. The cotton core nonwovens were prepared by laminating a cotton core layer with meltblown and/or spunbond webs by employing the thermal calendar bonding technique. These materials showed excellent soft hand, breathability, absorbency and tensile properties.

Wu *et al.* (2007) developed cost-effective microporous films by using polyolefinic material and inorganic fillers for disposable hygiene articles. They also developed microporous composites by combining microporous films with specialty fabrics such as nonwovens and thus obtained the advantages of the liquid barrier properties of the film and the strength and aesthetics of the fabric. The composites were claimed to be used in disposable hygiene products.

5.4 Feminine sanitary pads

5.4.1 Functions

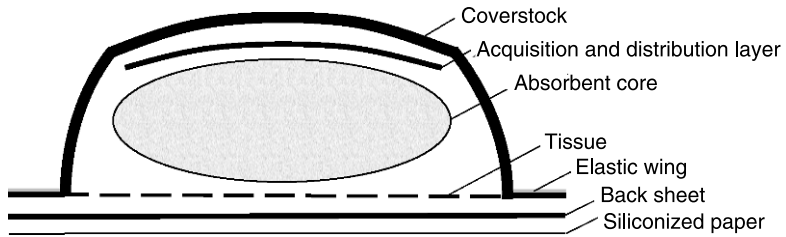
A feminine sanitary pad is another important disposable absorbent hygiene product. Its functions are to (1) absorb menstrual liquid discharge, (2) isolate wetness from the skin, (3) retain menstrual liquid discharge, and (4) isolate menstrual liquid from the female's environment. These functions should be accompanied by providing a feel of maximum comfort, having an aesthetic appearance, preventing odor, and staying in place.

5.4.2 Components

The feminine sanitary pad is constantly being innovated. Although the ultrathin products have begun to garner a higher market share, there is still a need for a thick product as it is believed to be a sign to most people of a good product with superior protection. Like baby diapers, this product is also a multi-layered complex structure where each layer has a specifically allocated task. Figure 5.2 shows that a disposable sanitary pad that typically consists of coverstock, acquisition and distribution layer, absorbent core, back sheet, tissue, elastic wing, and siliconized paper. Of them, coverstock, acquisition and distribution layer, absorbent core, and back sheet are made up of nonwovens. The function and composition of each of these four materials are discussed below.

Coverstock

In general, the coverstock of a sanitary pad is lighter than that of a baby diaper. Nevertheless, in common with baby diapers, the nonwoven coverstock in sanitary pads was earlier thought to be as absorbent as possible. As a result, we observed



5.2 Schematic diagram of the sanitary pad structure.

that viscose rayon was extensively used to prepare the coverstock. It was then thought that the coverstock should be hydrophobic to offer better skin care; hence synthetic fibres such as polypropylene and polyester were found in the coverstock of sanitary pads. Later, it was understood that the hydrophobicity in sanitary pads was necessary but not sufficient for optimum performance. The coverstock must also quickly pass the liquid through to the core of the pad (rapid strike-through) and at the same time it must restrict the passage of the liquid back through in the reverse direction (wet-back) so as to maintain a dry surface to the skin. This tricky problem was solved by applying a small amount of an effective rewetting agent on the surface of the coverstock. Today, the coverstock is generally made up of polypropylene spunbond nonwoven, treated by a small amount of rewetting agent. Besides this material, perforated films were found limited usage as a coverstock in sanitary napkins.

Acquisition and distribution layer

The acquisition and distribution layer of a sanitary pad is expected to perform the same functions as the acquisition and distribution layer of a baby diaper does. As the absorbent core cannot absorb the localized discharge instantaneously, this layer imbibes the liquid away from the point of discharge, distributes it laterally, and holds it for the core to absorb it. This layer is generally made up of thermally bonded or through-air bonded composite nonwoven material. As known, most of the structures can do an adequate job of acquisition and transporting a relatively small amount of liquid, such as that needed to be managed during menstruation. However, when large amounts of liquid need to be acquired and distributed, none of the structures seems to function well enough to justify the incremental cost (Chatterjee and Gupta, 2002).

Absorbent core

The absorbent core of a sanitary pad was earlier made up of wood pulp. But there has been continued interest to replace this by air-laid pulp in combination with superabsorbent polymers at the desired position in the structure. There is a

significant use of superabsorbent polymer in many brands of sanitary pads. In many cases, the solid polymer in powder form is lightly affixed to a tissue. This composite layer is then inserted between the back sheet and the absorbent pulp pad or in a lower layer of the pad. The position of the superabsorbent polymer is very important in a sense that it must absorb and hold liquid, but must not retard the flow-in of the subsequent additional liquid by blocking the pores of the structure due to swelling.

Back sheet

The back sheet is an impermeable thin film or barrier fabric that prevents leakage. It is a breathable but liquid impervious film and generally made up of polyethylene.

5.4.3 Recent developments

In recent years, the feminine hygiene market has been characterized by lighter, thinner and more absorbent products, leading to greater wearer comfort. The arrival of the short fibre air-laid nonwoven absorbent core has revolutionized feminine hygiene products during the last decade. This means that nowadays more nonwoven material is being used per product unit. Like baby diapers, the superabsorbent polymer has been extensively used in making lighter, thinner and more absorbent sanitary pads. Das *et al.* (2008) reported developing a series of high absorbent light-weight sanitary pads where the absorbent core was made up of super absorbent fibres and viscose rayon fibres. They tested the absorption behaviour by using saline water as a test liquid. It was observed that the saturation absorption of the core followed a linear relationship with the percentage of superabsorbent fibres in the core and the basis weight of the core.

In a patent, Trillas *et al.* (2007) reported on development of a plasma-treated nonwoven fabric for the use in feminine hygiene products. It was claimed that it is possible to control the addition of hydrophilic and hydrophobic groups in the fabric by controlling the plasma generation and application. Chi (2007) made a patent disclosure on a hygiene product with far infrared anions. This product was made of an outer leak-proof layer, a middle absorbent layer made of water absorbent material, and an internal contact layer made of water penetrating material. The fibres of the materials were attached with a constituent capable of releasing far infrared anions to achieve a sanitary anti-bacterial effect and a nursing care condition. Bentz (2007) disclosed a hygiene article for use in sanitary pads, which was developed from a textile fabric having a multiplicity of fibres onto which microencapsules, including materials in which a phase transition from solid to liquid and vice-versa took place in a temperature range from 15°C to 40°C, were applied.

Digiacomantonio *et al.* (2007) reported a novel absorbent article, which was made of three layers: a body-facing surface, an absorbent structure, and a garment-

facing structure. The structure was comprised of a central liquid acquisition system, a first visually discernible lateral zone situated on one side of the central zone, and a second visually discernible lateral zone situated on the opposite side of the central zone. Kim *et al.* (2001) reported an absorbent article with fluid intake intensifier which was made of a low density air-laid nonwoven. Harriz (2003) developed a super absorbent composite for the use in personal hygiene products which was composed of a nonwoven core with super absorbent polymer uniformly distributed throughout the thickness of the core and bonded to the core with an adhesive.

5.5 Adult incontinence pads

5.5.1 Functions

The adult incontinence pad is another important disposable absorbent hygiene product. Its functions are to (1) absorb and retain wearer's urine, (2) isolate wetness from wearer's skin, (3) contain faeces, and (4) isolate urine and faeces from the wearer's environment. These functions should be accompanied by providing a feel of maximum comfort, having an aesthetic appearance, preventing odour, and staying in place.

5.5.2 Components

The current adult incontinence pads are composites consisting of a variety of different materials, some in the form of pre-formed webs, to create a series of functional layers to achieve the aforesaid functions. As stated by White (2003), the products designated for management of heavy adult incontinence were based on the design and manufacturing technology of baby diapers, while feminine hygiene product developments were used in the case of light incontinence products. In both cases, it is important to remember that the adult incontinence products were required to deal with larger volumes of liquid and yet handle them in an effective way. Nevertheless, the building blocks of adult incontinence pads are made up of coverstock, acquisition and distribution layer, absorbent core, and back sheet. The function and composition of each of these four components are discussed below.

Coverstock

This is the top sheet layer of adult incontinence pads which can be a pre-formed nonwoven carded fibre web or a continuous filament web or a plastic film with carefully designed holes. The spunlaid thermal bonded polypropylene nonwovens have become the material of choice for use in coverstock application. Also, the spunlaid composites are favourably used in making the coverstock of baby diapers.

Acquisition and distribution layer

The acquisition and distribution layer of an adult incontinence pad is a nonwoven material which is made up of synthetic fibres or a modified cellulosic fibre layer. In fact, there are two different approaches taken to create an effective acquisition and distribution layer in order to provide a temporary holding of the liquid transmitted through the topsheet, keeping the skin contact surface of that layer dry and then effectively distributing the liquid into the absorbent core. One type of structure is based on the use of modified cellulosic fibres to create a reduced swelling and open pore structure that provides temporary storage capacity. This type of web is often coupled with an open structure highloft nonwoven to provide fluid distribution. The other approach is to use a low density, through-air bonded nonwoven that can provide both functional requirements. Note that, whichever approach is taken, the coverstock and acquisition and distribution layer must work in concert to ensure dryness of the surface of the coverstock.

Absorbent core

This is a liquid storage layer that is made up of cellulose fluff pulp and superabsorbent polymer. The use of superabsorbent polymer results in a drier skin that minimizes rash and irritation and provides greater comfort and personal hygiene. This also results in lowering the amount of fluff pulp required to produce a satisfactory storage core to be significantly reduced, which in turn offers a significantly thinner product. Sometimes powders are added in the absorbent core for odour control.

Back sheet

This is a backing containment layer that is normally a plastic film, either breathable or not. Sometimes a nonwoven layer is added to the external surface of the film in order to improve aesthetics and impart a cloth-like feel to the external surface of the product.

5.5.3 Recent developments

A well-designed engineered nonwoven structure for the use in disposable adult incontinence products for incontinence management has been a rapidly growing area of interest among the nonwoven scientists and researchers worldwide. As stated by White (2003), there has been a major effort seen in the past few years to develop absorbent air-laid products by using M&J Fibretech and DanWebforming systems and combining wood pulp, synthetic fibre, binder fibres and granular superabsorbent polymer into a multilayer composite material. Also, attempts were seen to insert pre-formed web material into the structure of adult incontinence products. Further, multiforming heads were used to develop a structure comprising

of different fibres in different layers that could be ultimately combined with pre-formed webs produced by other technologies. This led the way to the production of multi-process and multi-layered composite products where specific performance characteristics might be built into each layer. Rahbaran *et al.* (2011) made a patent disclosure of a highly absorbent reusable pad for use in incontinence and hygiene products, wherein a nonwoven fabric containing a blend of man-made cellulose fibres and synthetic fibres with multi-lobal cross-section was used.

5.6 Conclusion and future trends

The key issues associated with absorbent hygiene products are related to dermatitis and disposability. The interaction between skin and absorbent hygiene products is reported in detail by Runeman (2008). It is learnt that the skin problems due to the use of these products are mostly associated with the climate or chafing discomfort that would lead to irritant contact dermatitis and eventually superficial skin infections. It is suggested that individuals with frail, sensitive skin or with skin diseases should preferably use high-quality products, equipped with superabsorbent polymers and water-vapour-permeable backsheets, to minimize the risk of skin complications. There is always strong demand for absorbent hygiene products to show biodegradability. The air-laid nonwovens offer possibilities for biodegradable air-laid, which is a big plus over many nonwovens (Mango, 2005). There are some products in the market which are said to be biodegradable and of biological origin, compared to many leading branded products with a very high oil-based content. Also, the fibre-producing industry is heavily active in research on new fibre types that are derived from renewable sources, such as polylactic acid was derived from corn or other vegetable starches. Besides dermatitis and disposability issues, environmental considerations, including flushability concern, is also growing. The modern hygiene products are expected to show great flushability to disintegrate as quickly as possible. Despite these issues and concerns, the marketers of absorbent hygiene products continue to focus on product innovation to woo customers, thus creating a highly competitive global market. As predicted by Freedonia Group in a market research report (2011), the personal hygiene market will continue to account for the single largest share of nonwoven demand in 2015. The use of these goods will expand the fastest in developing areas, fuelled by growth in population and a high standard of living. The demand for further thinner, lighter and more absorbent products, leading to greater wearer comfort is increasing. In this respect, one can expect further development and application of pre-formed multi-layer and multi-component composite structures in baby diapers, sanitary pads, and adult incontinence pads. Further, in order to maximize the efficiency and effectiveness of the composites, a synergy between the individual layers assigned to specific tasks for working coherently together is required. In doing so, they are expected to deliver a performance that is far superior to that of the individual layers in isolation.

5.7 Sources of further information and advice

Absorbent hygiene products are composites of nonwoven and allied materials. A very good source of information on the technical developments of these products can be patents as a large number of excellent innovations are found to be reported in this form. Yet the rising demand for further thinner, lighter, more absorbent and more comfortable hygiene products may pave the way for newer combinations of nonwovens in order to create a variety of disposable absorbent products. One may therefore like to watch for newer patents reporting on further interesting innovations on these products. Besides, there are several trade journals which are continually publishing latest information on absorbent hygiene products. They include *Nonwoven Industry*, *Nonwovens World*, *Nonwoven Markets*, *Nonwovens Reports International*, etc. These journals can therefore be of interest to obtain the latest information on market scenario and developments of absorbent hygiene products. Further, the publications of professional bodies such as INDA and EDANA and research scientists worldwide can also be the source of further information on absorbent hygiene products.

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Abstract: Dry and wet wipes are widely used in personal care, household and industrial applications, and the majority of wipes are made from nonwovens. The selection of fibre(s), technology of web formation and bonding of fibres to make nonwovens, and surface texturing of them, are important in achieving the desired properties of wiping products. This chapter contains a brief introduction to the types of wipes, the technology used in web formation and bonding of fibres, and surface texturing of wipes. Various processes, products and their salient features pertaining to hydroentangled and thermobonded composite nonwoven wipes produced from carded, airlaid pulp, wetlaid pulp, spunbonded, spunbond-meltblown-spunbond (SMS), Coform and elastic layers are discussed. The chapter also outlines recent developments and future trends in the development of wipes from bio-degradable and recycled fibres, and flushable wipes.

Key words: airlaid, carded, cleanroom, hydroentangled, ion trigger, spunbond, surface texturing, thermobonded, wetlaid.

6.1 Introduction

To wipe is defined as ‘to rub with’ or ‘something soft for cleaning’ or ‘to clean’ (Merriam-Webster). Wipes can be a paper, tissue or nonwoven and are subjected to light rubbing or friction in order to remove dirt or liquid from the surface. Consumers want wipes to absorb, retain or release dust or liquid on demand. One of the main benefits that wipes provide is convenience. A wipe is quicker and easier to use than the alternative of dispensing a liquid and using another cloth or paper towel to clean or remove the liquid (Sahu 2012).

Wipes can be categorized as disposable and semi-durable wipes. Disposable wipes are disposed of after single use; hence, there is no need to worry about cross-contamination. Wipes can be broadly classified into dry wipes and wet wipes (containing lotion) according to the types of applications. Wipes are produced from wovens, nonwovens, composite nonwovens and flock of fibres, etc. Based on the end user applications, wipes can be classified into consumer wipes (personal care including baby wipes, household/home cleaning) and industrial wipes (general purpose and speciality). According to EDANA, industrial wipes are: ‘disposable nonwoven products used for a variety of applications in industry ranging from heavy duty cleaning to fine polishing’, for which the wipes are single use products or limited use products that become waste material after use (edana.org).

Wipes started at the bottom or more precisely, the baby’s bottom. Still, baby wipes constitute a major segment of wipes; but the share is declining with the

influx of many wipes being introduced in the market for specific applications in the personal care, household and industrial segments. A large number of wipes made from nonwovens cater to personal care such as toddler toilet care, cosmetic (deodorant, facial), adult moist toilet tissue, adult incontinent/bath wipes, feminine hygiene wipes and healthcare wipes, etc.

Household wipes include regular wet and dry floor wipes, cleaning/disinfectant wipes, kitchen wipes, mop pads, dishwashing, apparel care, furniture cleaning, glass wipes, food service and automotive care wipes, etc. More importantly, the electrostatic wipes constitute 38% of value of global sales of home care wipes (Bell 2011). Nonwovens are electrically treated to enhance particle attraction to improve the efficiency of picking up dust and dirt (Keck *et al.* 2006). Industrial wipes are used in the automotive industry, machine/instrument cleaning/degreasing/surface preparation, the electrostatic, optical, printing and electronics industries, and clean room applications, etc.

Currently, the share of personal care, household and industrial wipe products in the wipes market are about 62%, 23% and 15% respectively. Baby wipes accounted for 63% of personal care wipes sales in 2010 (Bell 2011). The market for personal care, household and industrial wipes were growing at 16%, 8% and 13% respectively in the year 2010. As per the EDANA's report in 2010, the total wipes deliveries in 2010 amounted to 283,058 tonnes as compared to 250,356 tonnes in 2009. Between 2007 and 2017 the consumer wipes market is forecast to increase from over \$7.6 billion to \$12.6 billion, with an annual growth rate of 5.2%. In the same period, the industrial wipes market is expected to increase from about \$1.8 billion to \$3.2 billion. The leading companies with brands that employ wipes include Unilever, Procter & Gamble, Kimberly-Clark, Johnson and Johnson, S C Johnson, Colgate-Palmolive, Kao Corporation, Henkel, Reckitt & Benckiser and Clorox.

6.2 Materials in wipes

The most important requirement for a wipe is rapid absorbency and the ability to pick up dirt. Wipes designed to pick up aqueous liquid are made from hydrophilic materials such as rayon, wood pulp and cotton. Wipes to pick up oil-based liquids are made from hydrophobic fibres such as polypropylene and polyester, etc. Some wipes are designed to pick up both these liquids. The materials used in wipes vary depending on the applications and are petroleum-based fibres (polyester and polypropylene), cellulose-based fibres (wood pulp, fluff pulp, specialty paper pulp, viscose rayon, Lyocel, acetate, Tencel and cotton), splittable bicomponent fibres, blends of cellulosic and synthetic fibres and polylactic acid, latex binders. The technical wipes used in the aerospace, automotive, optical and electronics industries and other special wipes are especially made from splittable bicomponent fibres.

The majority of wipes are made from blends of polyester and viscose fibres/wood pulp. The cellulose fibres/wood pulps provide high absorbency

and are biodegradable. The synthetic fibres provide strength, abrasion resistance, and solvent resistance; and can be treated with antimicrobial and static dissipation finishes for certain applications. The microfibres in wipes provide soft handle, flexibility and smooth surface; and the bicomponent fibres give added functionality.

Wipes for certain applications require incorporation of finishing or ingredients such as biocides (antimicrobial, mildewicide, antiseptic, disinfectant sanitizer, germicide, algaecide, preservative) abrasive particles, perfumes, alcohol, and activated carbon, etc. The anti-microbial nonwoven wipe has a nonwoven substrate comprised of a non-ionic binder and a cationic disinfectant. When water is introduced into the wipe, the disinfectant is readily released from the wipe. Alternately, a nonwoven with a non-ionic binder can be used along with a separate commercially available disinfecting or sanitizing solution (Ellis *et al.* 2011). For high absorbency, super absorbent fibres are used. For heavy duty cleaning applications, wipes are incorporated with abrasive particles such as aluminium oxide, metal carbides, borides, and nitrides, fused alumina zirconium, sol gel abrasive particles and minerals. A scrubbing wipe is made by printing a texture layer on to one or both surfaces of a nonwoven layer. The texture layer is a non-crosslinked and abrasive resin-based material. The texture layer does not cover the entire surface of the substrate and protrude about 50 microns from the substrate surface to have a distinct scrubbyness (Johnson and Lindquist 2010).

6.3 Wet wipes

Wet wipes are pre-moistened with solution, using either single or multi compounds. Baby wipes are used to cleanse the sensitive skin of infants. They contain saturated solutions such as gentle cleansing ingredients and alcohols. Cleansing pads for preventing infection may be soaked with water, alcohol and other active ingredients for a specific intended use. Anti-acne pads usually contain salicylic acid, vitamins, menthol and other compounds.

A customer survey conducted by Dow has revealed that the wet wipes currently available in the market are yet to meet the following criteria (Anonymous 2008, pp. 16–22):

- wipes that stay wet longer;
- more consistent lotion loading;
- better dirt removal;
- more bulk and softer touch;
- environmental friendly wipes such as flushable and biodegradable;
- multifunctionality such as clean and protect, clean and moisturise and clean and cool;
- substrates free of non-desirable residuals;
- lotions that do not extract non-desirable residuals;

- better entrapment and killing of microbes;
- wipes that leave a surface shiny;
- wipes that won't scratch delicate surfaces.

In wet wipes, the substrates play an important role in deciding the following characteristics and properties: sorption rate and capacity, rheology, hand, strength, extensibility, thickness, brightness, texture, abrasiveness and disposability (Robinson, 2005). Sometimes formaldehyde is used to improve the bactericidal properties of wet wipes; however there is evidence of the carcinogenic potential of formaldehydes. In Europe, a maximum authorized limit of 0.2% free formaldehyde is well established for the lotions of personal care wet wipes under a cosmetics directive (Anonymous 2011a).

6.4 Web forming technologies for wipes

Fibres are laid in the form of a web or sheet using carding, airlaid, wetlaid, spunbond and meltblown technologies. Hydroentangling, thermal bonding (calendering rollers and hot air oven), needlepunching and stitch bonding are used to bond the fibres in webs. For thermal bonding, the web must contain some proportion of low melting fibres. The technologies of web forming and bonding affect the functional properties and cost of wipes. In the wipes market, hydroentangled (referred to in the trade as 'spunlaced') products made from both carded and airlaid webs constitute 49%, airlaid-thermal and airlaid-chemical bonded (referred to in the trade as 'airlaid') is about 26% and the rest (needlepunched, wetlaid-chemical/binder fibre bonded, and spunlaid-calendered and composite nonwovens that combines webs made using different technologies) are about 25%.

6.4.1 Carded nonwoven

Viscose rayon, Tencel, cotton, polypropylene and polyester fibres with long cut lengths are used in carding. Prior to carding, fibres are opened and blended. The fibres in carded webs are more oriented in machine direction. In order to reduce the ratio of strength in machine and cross direction, webs are cross laid. The webs are bonded by needlepunching or thermal bonding or hydroentangling or stitch bonding. Hydroentangled carded nonwovens have high softness, drape, bulkiness and resilience. Heavy duty industrial and household wipes are made from viscose rayon or Lyocell or synthetic fibres or blends through carding and needling. Needle punched wipes can store large volumes of liquid/lotion compared to hydroentangled wipes. Pre-moistened wipes containing anti-bacterial soap used in post-operative care are needled structures. Needled structures are also used for polishing cloth.

Multi-layer carded webs are stitch bonded using Malivilies technology. Absorbing and polishing cloths are made from Malivilies fabrics. Theses fabrics

are composed entirely of fibres and no filaments. Viscose, reclaimed fibres, polypropylene and polyester fibres are used.

6.4.2 Airlaid nonwoven

In the airlaid process, woodpulp available in rolled sheet form is converted into fibres in hammer mills. The woodpulp fibres are transported by conveyor to the forming head drum of an airlaid unit. When the airlaid webs are to be thermal bonded, melt fibres are also supplied through bale opener and weight metering systems. When there are two types of non-woodpulp fibres required to be mixed with woodpulp (example: two types of melting fibres, short length polyester, polypropylene or bicomponent fibres), then two opening lines feed these fibres to the forming head drum. The perforated drum in the forming head rotates and suction is applied inside the drum. The fibres adhered to the surface of the drum are transported with vertical air flow produced by a vacuum inside the suction box to the web formation belt, where they are deposited. The products weight range is 10–600 g/m² (Watzl 2006).

Airlaid webs are bonded by thermal bonding or chemical (latex) bonding or hydroentangling. Latex bonding is the most common bonding process. In latex bonding process, the top surface of the web is sprayed with chemicals and dried, and then this sequence is repeated for the bottom surface of the web. In the thermobonding process, the airlaid web containing the melt fibres are heated by flow of hot air in a belt oven until they start to melt and bond with the loose pulp fibres. This process is clean and energy-saving as compared to the latex bonding. However, the surfaces of thermobonded airlaid web still contain loose pulp fibres that form dusts during production and use of the web. Further, the thermal bonded airlaid product does not have enough strength. To avoid this, the surfaces are impregnated with lightweight latex foam using a foam padder. Alternatively, only the surfaces are padded with foam, leaving the inner layer as bulky and absorbent. Both the thermal and chemical bonded products are not preferred for baby and cosmetic wipes, and these are used mainly in household and surface care applications.

Airlaid nonwovens are isotropic, lofty, have high porosity (95–99%), high absorbency and wicking rate due to the presence of woodpulp fibres, softer handle, good resiliency and adequate tensile strength. Hence, some wipe manufacturers prefer airlaid-thermal bonded over carded-spunlaced materials due to a softer, spongier feel and lower production cost (Bitz 2002).

Hydroentangled-airlaid web offers textile-like handle (softness and flexibility) and strength to wipes and in most cases absorbent characteristics (rapid absorption and retention of liquid). Airlaid-spunlaced nonwovens are softer, spongier and cheaper than the carded-spunlaced nonwovens, hence are more suitable for wiping products (Bitz 2002). With increasing water jet pressure during hydroentangling, the fibre consolidation improves, thus enhancing the strength; however, the shear

modulus remains more or less the same, thus retaining the softness. Further, the hydroentangling of web containing splittable bicomponent fibres (polyethylene on the surface and polypropylene in the core of the fibre) gives added benefit of very soft feel as the fibres split into microfibrils.

Fusible fibres used for thermal bonding are costlier and the fused regions present on the surface of wipes give a harder feel to the skin. Because of these reasons, in the last few years, the hydroentangling is increasingly substituting the airlaid-thermal bonded nonwovens, especially in the personal care wipes market. In the impregnated wipe market (wet wipes), both the airlaid-hydroentangled and airlaid-thermal bonded are present. Multiple layers of webs (carded, airlaid, spunlaid) having different characteristics such as softness, absorbency and strength are combined using hydroentangling. Because of the advantages of hydroentangling, many integrated production lines comprising carding, airlaid and hydroentangling units are manufactured.

6.4.3 Wetlaid nonwoven

The wetlaid technology has the capability to process a wide range of fibres such as very short fibres and brittle fibres, incorporating binders and particulates in the structure. Wetlaid are bonded using hydroentangling or binder fibres. Premium Nice-Pak^(R), a thin wipe, is made from a mix of woodpulp fibres using wetlaid and hydroentangling, whereas economy wipes are wetlaid-thermobonded (Wilson 2003). In future, the demand for flushable-dispersible wipes will grow; the wetlaid will play a significant role in this segment as the dispersibility of used toilet wipes requires incorporation of very short fibres.

6.4.4 Spunlaid nonwoven

The production speed of spunbond is very high, about 600 m/min. The spunbond process requires a heavy investment cost, but the cheaper polymer chips and direct conversion from them into fibres reduce the manufacturing cost considerably. Fewer fibres are required or thinner web can be made for a given strength of product, thus saving on production costs. Recycled polymers which are much cheaper can be processed using the spunbond method. The spunbonded products are the strongest and have better dimensional stability, but the spunbond process is least flexible in the sense that it can only be used for thermoplastic fibres. Products containing cellulose fibres cannot be made. The spunbond wiping products are stiffer.

Spunlaid nonwovens have very high strength in machine and cross directions compared to other nonwovens. The spunlaid nonwovens are usually calendered. Calendering compresses the web and generates melted fibre intersections which increases stiffness of webs. For personal care applications, they are not suitable. The recent trend is to combine spunbond with hydroentangling. The spunlacing of

spunbonded fabrics does not fuse fibres and stiffen the fabric because it bonds the individual filaments. Hydroentangling the calendered spunbond nonwovens also gives a softer feel compared to traditional spunbond-calendered. In this case, the temperature during calendaring can be reduced as further bonding is done using hydroentangling. The benefit is energy saving.

Rieter offers the 'Perfobond 3000' spunlaid system for web forming and the web bonding can be done with either a calender or hydroentanglement by 'Jetlace 3000' (Wilson 2003). The Rieter's integrated system, 'Perfojet' combines the spunlaid and hydroentanglement systems. Other integrated spunlaid-hydroentanglement systems used to produce fabrics include Freudenberg's Evolon^(R) from splittable bicomponent filaments and the Polymer Group Inc.'s SpinlineTM for single component filaments.

Oil sorbent pads made by using meltblown technology constitute an important category of spunlaid nonwovens. Single layer webs are sonic bonded to improve strength and durability. To remove oil spill on water bodies and also to clean oil and grease in kitchens, on floors, walkways and machines, polyolefin fibres (polypropylene and polyethylene) are used. Meltblown polypropylene webs are also thermal calendered to produce oil sorbent wipes. Several commercial wipes are manufactured using this nonwoven material.

The oil sorption and retention capacities of the wipes are important for oil spill cleanup. The surface energy of polypropylene is slightly higher than the surface tension of many oils and much below the surface tension of water. Hence, polypropylene is highly oleophilic and hydrophobic making it suitable for oil spill removal. The oil retention capacity (g of oil/g of fibres) of the oil absorbing pads must be very high to reduce material consumption. The meltblown structures have very fine pores with narrow distribution, this improves the sorption rate and sorption capacity of oil-sorbents.

Hydroentangled spunlaid bicomponent fibre nonwovens are suitable for cleanroom wiping application. The combination of polymers and their arrangement in fibre cross section must be considered in developing such wipes. Evolon^(R) fabrics are spunlaid produced from splittable bicomponent filaments (16 segmented pie, polyester and nylon66 in 65%/35% proportion) of about 2 d.tex, which are hydroentangled at up to 400 bar to split the filaments into multiple microfilaments about 0.09–0.13 dtex. These fabrics have very high filament surface area, softness, strength and abrasion resistance. These have potential applications in cleanroom wipes besides the current applications in sportswear and active wear (Anand *et al.* 2007).

6.5 Web bonding processes for wipes

6.5.1 Needlepunching

The production speed of needlepunching is very low. Lightweight wipes cannot be produced using needlepunching. The high draft required during needling alters

the strength ratios in the principal directions of wipe. Needling generates broken fibres in the web that results in strength reduction and also gives the appearance of a rough surface and needle spot marks which are not preferred for personal care wipes.

6.5.2 Chemical bonding

Water-born latex is mostly used as a chemical binder which is applied about 5–30% by weight. Saturation, foam, spray, print and powder are methods of application to the nonwovens. Chemical binders in wipes have low skin tolerances and gives slight odours. The process is not environmentally friendly, hence they are not preferred for personal care wipes. Abrasive pads are made by bonding abrasive particulates to the nonwovens using latex.

6.5.3 Thermobonding

The high price of melt fibres adds to the cost of wipes. A blend of synthetic melting fibres with natural fibres results in low strength to the wiping product. All natural or cellulosic fibre wipes cannot be produced using thermobonding.

6.5.4 Hydroentangling

The production speed of a hydroentangling line is 200 to 400 m/min., about one-half of a spunbond line. In the case of apertured products, the production speed is limited to about 200 m/min. Hydroentanglement lines require higher investment costs than the carded-needling lines, but the hydroentangling process does not require a chemical binder or costly melting fibres to bind the fibres. All natural fibre or cellulose fibre products can be made. The draft given to the web during hydroentangling is very low so that the final product does not undergo shrinkage, i.e., is dimensionally stable; and the strength ratio (MD/CD) is also low. Hydroentangled wipe products are smooth, soft and have textile-like handle and drape. They are stronger than the needlepunched, thermobonded and chemical bonded fabrics, and hence the wipes can be made thinner resulting in a saving in production costs. Spunlaced nonwovens are the leading substrates for personal care and household cleaning wipes. For facial cleaning wipes, all-staple spunlaced nonwovens are preferred.

6.6 Surface texturing of wipes

Wipes are apertured during hydroentangling on a cylinder with knuckles around which fibres are directed and entangled. The support structures of web, especially the open area during hydroentangling, also affect the texture of fabrics. To create aperture on the surface of fabrics during hydroentanglement, a high water jet pressure is employed. Apertured fabrics have the appearance of woven fabrics

(Evans and Shambelan 1970). Cleaning effectiveness is the most important factor among wipe users in selecting a wipe in the market. Incorporation of suitable patterns on wipes will improve their cleaning performance. A patent awarded to Polymer Group Inc., deals with imparting a three-dimensional image/pattern to nonwovens, resulting in a lofty material with a number of fibrous ends and loops extending beyond the surface of the recesses or pockets that improve the fabric's: ability to collect low-viscosity contaminants present on skin (Chang and Edward 2004); thickness to hold chemicals and substrates; durability and scrubbing power (Wilson 2004). Floor wipes such as P & G's Swiffer^(R) are made with deep ridges and Clorox mops (Readymop) are quilted for better cleaning.

The Polymer Group Inc. (PGI) introduced ApexTM technology that creates complex embossed patterns on hydroentangled fabrics in the range 50–400 g/m², such as Miratech^(R) fabrics and derivatives, Mirastretch^(R) for good elastic recovery and Miraguard^(R) for barrier properties. Using appropriate patterns, the fabrics assume the appearance of woven and knitted textiles. Hydroentangling the fabrics on a laser imaged three-dimensionally patterned support surface transfers patterns onto the fabrics (Anand *et al.* 2007). To adjust the softness, shrinkage and drape of fabrics or to introduce elasticity to the fabrics or to improve the durability of pattern definition in the fabric, polymeric binders are added after hydroentanglement. To improve the durability of pattern definition in the fabric, blends containing fusible fibres or woven scrims are also used (Black and Deleon 2004). Oran-B Brush-Ups^(R) single-use swabs introduced by the Gillette Company are stretchable and textured; and used to clean the gums and teeth without toothpaste or water (Frederick 2004).

6.7 Composite nonwoven wipes

Nonwovens produced from each fibre are unique in terms of their functional and durability characteristics. Wipes can be manufactured with improved functionality at lower cost using composite nonwovens having a mixture of fibres and particulates or fibres that differ in their chemistry or denier or shape in their structures. This may be obtained by layering the webs or homogeneous mixing of fibres/particulates. In the case of layered structures, two or more nonwoven layers each having different fibres or mix of fibres made using different technologies are combined with or without wovens.

Composite nonwoven wipes have the capability to offer more overall functionality as compared to a plain nonwoven which has motivated the wipes' manufacturers to spend most of their research and development efforts, including machinery upgrades and new plant investments, in composites. Through composites, the wipe manufacturers have the option of combining nearly any type of nonwoven together to produce products with distinguished features. The development of composite nonwoven wipes has provided the market with wipes having higher abrasion resistance, high wet and tear strength and

increased barrier protection. Dual-surfaced composite nonwoven wipes having softer (needlepunched or spunlaced layer) and abrasive sides (meltblown layer) have improved bulk, are easier to handle and clean better than a plain product. Using composite nonwoven technology many advantages could be obtained ranging from improving the strength and durability of lightweight products (by having a spunbond or a meltblown layer in the composition), obtaining softness, absorption and strength (using a combination of fibrillated bicomponent fibres, spunbonding the pulp and synthetic fibres) and ability to form shapes (using an elastic film as one of the layers).

The composite nonwoven route offers a never ending product range due its unlimited possibilities of combinations, lending the producers to expand into new market applications. Often in single layer wipes, when the basis weight is increased, the thickness, strength and bending stiffness increase and vice versa. It is difficult to isolate and manipulate the individual attributes as they are interdependent. In composite nonwovens, keeping a basis weight constant, the strength, softness, opacity, texture and stiffness can be varied by having layers differing in properties. The approach adapted by the machinery manufacturers in designing and fabricating the machines/lines to produce wipes with improved efficiency of dirt removal, strength and softness, reduced cost and imparted with multifunctional characteristics through composite nonwovens, resulted in a reduction of manufacturing steps and development of products that substitutes two or more products. All these optimised the products in terms of cost and functionality with improved value addition.

6.8 Multi-fibre composite nonwoven wipes

Viscose rayon blended with polyester or polypropylene or woodpulp are the common materials used in manufacturing of dry wipe products such as baby wipes, dusters, food service wipes and cleanroom wipes and also wet-floor wipes. The mixtures are airlaid, hydroentangled and the surfaces are apertured. The aperturing destabilizes and weaken the structure, especially the thinner fabrics. If the hydroentangling is done at low pressures (below 80 bar), then the structure is given either chemical or thermal bonding to stabilize and improve the strength of wipes. The binders usually increase the stiffness of wipes, so careful selection of binder type is important Viscose-pulp wipes used for household applications require application of 7–27% of binder on fabric to increases their durability in the wet state. The binder content can be reduced in the case of polyester–viscose blends. Point thermal bonding can be employed if polypropylene fibres are blended.

Hydroentanglement at low pressure followed by point thermal bonding at reduced temperature and pressure than normally employed for thermal bonding alone would minimize the overall energy consumption and the resulting products are softer than the one that are only thermal bonded (Anand *et al.* 2007).

Baby wipes are produced with 70:30 viscose rayon–polyester and 50:50 viscose rayon–woodpulp with a basis weight 55 g/m^2 . Food service wipes have 80:20 viscose rayon–polyester with basis weight $69\text{--}80 \text{ g/m}^2$. The dusters have 75–91% polyester and 9–25% polypropylene with basis weight $30\text{--}65 \text{ g/m}^2$. To improve dust pick up, embossed 3D patterns or mock piles surfaces are produced. Typical compositions of hydroentangled floor wipe are: 70:30 or 65:35 viscose rayon–polyester and the basis weight is about $90\text{--}100 \text{ g/m}^2$. The mixture of viscose rayon and polypropylene can be pre-needled, followed by hot air thermal bonding which melts the polypropylene and binds the fibres in the fabric. The proportion of polypropylene is around 15% for effective thermal bonding of fabric.

Cleanroom wipes are hydroentangled made from 100% polyester or blend with Lyocell or viscose rayon fibres. Commercial wipes consist of airlaid polyester–viscose in 30:70 and 50:50 and other weight ratios. The important requirements of cleanroom wipes are extremely low linting, absorbent capacity and rate. It has been demonstrated that substantial reduction of lint generation can be achieved by employing higher than normal water jet pressure and slightly elevated jet-water temperature during hydroentanglement, which physically removes and particularly dissolves the removed particles. Water should not be re-circulated during hydroentangling. First, hydroentanglement is done on a flat screen with six injectors operating with increasing pressures from the first to last (7 bar to 140 bar) followed by final hydroentanglement on a drum module with six injectors with increasing pressures from 31 bar to 140 bar which give best results in terms of reduced linting measured by particle sorbency quotient (Oathout 1994).

Sontara^(R) fabrics produced by using DuPont's patented technology are hydroentangled at very high jet pressure and are continuously washed during manufacturing to provide the wiping products extremely low-linting and exceptional cleaning ability. They are exceptionally strong even when wet and have high abrasion and tear resistance. Cleanroom wipes and surface preparation wipes used in aviation, automotive refinishing, the food service, life sciences and the printing industry as well as a variety of maintenance and manufacturing applications are made by using this technology (McIntyre 2009).

Bamboo fibres have high moisture-absorbing capacity and good anti-bacterial properties. Semi-durable wet wipes can develop unpleasant odours after use and the customer leaves the wipes to dry out as much as possible between uses or rinses them in a chemical such as bleach so that they remain hygienic during their lifetime. It has been shown in one patent that the anti-bacterial properties of bamboo fibres help in containing the foul smell emanating from the used wet wipes. Thermobonded carded and cross lapped nonwovens having a mixture of 75:15:10 bamboo, polyester and thermobonding fibres; 37.5:37.5:15:10 bamboo, viscose rayon, polyester and thermobonding fibres; and latex bonded needlepunched nonwovens having 75:25 bamboo and polyester, were tested. The

nonwovens containing bamboo needed less time to dry in an oven and better resistance to bacterial contamination as compared to latex bonded wet wipes made from 75:25 viscose and polyester fibres (Rivera *et al.* 2009).

6.9 Multilayer composite latex bonded nonwoven wipes

About 85% of pulp fibre-based airlaid products are latex bonded and the rest are bonded by thermal and other bonding methods.

An airlaid pulp (one or two layers) placed between two surface layers made from rayon is latex bonded in a distinctive pattern. The binder solution (or emulsion) is sprayed onto the surface of the pulp layer and then sandwiched between the two rayon layers which are airlaid or carded. The combined structure is cured (thermally bonded) by hot air. The surface of the composite structure is apertured/patterned to improve the cleaning of dirt particles.

The major problem of latex bonding is the ability of the binder to penetrate into thick structures. The suction applied to the composite structure during sandwiching compacts it, preventing the binder reaching the interior of the pulp. To improve the flow of binder, a binder with low glass transition temperature is preferred. Many latex-based commercial wipes are available, mainly for industrial applications. Traditional latex binders give slight odour. Because of the limitation of latex binders, wipes manufacturers are switching over to the airlaid-hydroentangling process. With the availability of new types of binders, there is a possibility of the former process being revived in the future.

6.10 Hydroentangled (spunlaced) multilayer composite nonwoven wipes

Wipes with required softness and drape along with absorbency, non-linting and non-collapsing (in the case of wet wipes) during use are made with composite nonwovens, wherein the pulp is airlaid on to carded web or spunlaid web. The composite is hydroentangled and requires no thermal or chemical bonding. The hydroentangled multilayer composite wipes available in the market are:

- carded-pulp-carded (CPC)
- carded-pulp (CP)
- carded-pulp-spunbond (CPS)
- carded-spunbond-carded (CSC)
- carded-spunbond (CS)
- carded-net-carded (CNC)
- carded-SMS (CSMS)
- carded-SMS-carded (CSMSC)
- carded-carded

- spunbond-airlaid pulp (SP)
- spunbond with wetlaid using pulp, glass and other short fibres (SW)
- spunbond-pulp-spunbond (SPS).

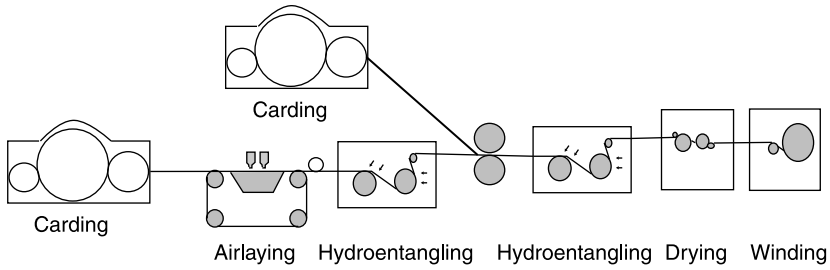
The pulp-based composite wipes are economically attractive because of the low cost of pulp. To improve strength and durability of wipes, the composites have either spunbond or woven scrim in the core. Hence, the hydroentangled CSC and CNC composites are used for industrial wiping products. The hydroentangled scrim-reinforced carded composite fabrics are also used in domestic wipes such as Procter & Gamble's Swiffer^(R). The use of elastic net, elastomeric foam/filaments/perforated film in the core of CNC improves elasticity of fabrics which are suitable for stretchable wipes. The spunlaid-pulp composite nonwovens (SP and SPS) are stronger, durable and cheaper than carded-pulp composites and are targeted for industrial wipes. In three-layer nonwovens (CPC, CPS, SPS), some wipe manufacturers use cotton lint as the core layer in place of pulp.

Hydroentangled two-layer (SP) and multi-layer (SPS) wipes are made with spunlaid and pulp layers. Spunlaid (spunbond, meltblown and SMS) webs can be hydroentangled to introduce fibre entanglement and then combined with a layer of 100% pulp or pulp blends with synthetic/viscose rayon to produce wipes. To introduce adequate fibre entanglements in spunlaid structures and to avoid further bonding such as thermal calendering or chemical bonding, very high water pressures of 300–400 bars are required. The spunlaid-hydroentanglement lines have very high production speeds of up to 600m/min in widths up to 5.4m. Further, products made using a single layer of 10g/m² and multi-layers with 400g/m² can be made on a multi-drum module hydroentanglement installation with five injectors followed by hydroentanglement on a flat belt module with one or more injectors.

Spunlaid hydroentangled fabrics are free from thermo-fused regions introduced by calender bonding. This is advantageous in wipes as they would have comparatively high bulk and flexibility, good tactile properties and high tear strength.

6.10.1 Carded-airlaid pulp-carded (CPC) wipes

The carded-airlaid pulp-carded (CPC) composites are used to make disposable wipes for both dry and wet applications. The CPC hydroentangled composites are made on a dedicated line consisting of two cards, one airlaid unit and a spunlacing unit. This three-layered composite has a core layer that contains either 100% pulp or pulp in blends with other short fibres (3–15 mm). The core layer may be either sifted airlaid or wetlaid. In a sifted airlaid, the pulp fibres are sifted through a coarse screen and deposited in the form of a sheet using suction below a forming wire. Additives such as odour control and super absorbent powders can be added during this stage. In the core layer, other short fibres (such as polypropylene,

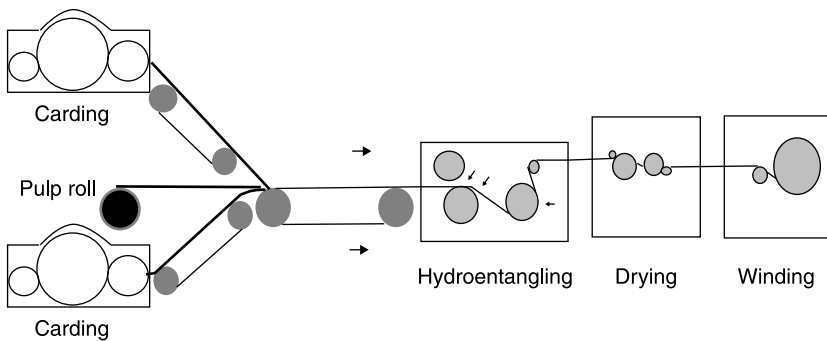


6.1 Process sequence for making hydroentangled CPC composite wipes.

polyester, viscose rayon, other cellulosic fibres or in combinations) are also used in addition to pulp. The carded webs consist of polyester, polypropylene or viscose rayon or blends. To make a CPC composite, a core pulp layer is first hydroentangled on to a carded web. Then, another carded web is laid on top of the pulp layer, and the composite is subjected to hydroentanglement (Fig. 6.1).

Another way of making the CPC composites is to lay a pre-formed tissue on top of a carded web and another carded web is laid on top of the CP layers prior to wetting and final hydroentanglement (Fig. 6.2). The use of tissue roll lowers the initial investment cost of the processing line, but fluff pulp is cheaper, which can more than compensate for the higher investment cost (Wilson 2003).

A typical hydroentangled CPC wipe of $56\text{--}65\text{ g/m}^2$ may have a pulp layer of $40\text{--}45\text{ g/m}^2$ in the core and each card web on the surface is about $8\text{--}10\text{ g/m}^2$ (Anand *et al.* 2007). The CPC composites are highly suitable for wet wipe applications, since the core pulp layer holds lotion and the surface carded layers prevent dusting of pulp from wipes during use. The CPC composites provide



6.2 Process sequence for making hydroentangled CPC composite wipes using pre-formed tissue.

good absorbency and are also highly suitable for dry wipes such as baby wipes, bodycare, food service and industrial cleaning applications. In CPC structures (three-layer composite), pulp masks the irregularities of carded web and improves the appearance compared with carded web-alone structures. Further, there is no risk of dusting during conversion of layers into products and no deposit of pulp particles when wiping, as there is with two-layer CP wipes. In the three-layer composite, pulp weight can be much higher in comparison to the two-layer composite; this lowers the manufacturing cost of wipes. To produce heavier structures used for make-up removal pads ($200\text{--}250\text{ g/m}^2$), multiple cotton cards are employed. The hydroentangled CPC composites are cheaper and softer as compared to hydroentangled all-fibre carded wipes due to the cost advantage of soft pulp over staple fibres. However, the strengths of CPC and all-fibre products can be approximately the same.

6.10.2 Carded and pulp wipes

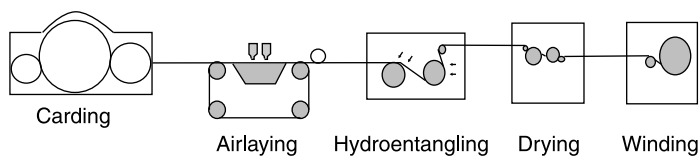
The following are carded and pulp-based composite wipes:

- carded-airlaid pulp
- carded-paper or preformed tissue
- carded-wetlaid pulp
- carded-airlaid synthetic fibres-paper or preformed tissue.

Carded-airlaid pulp wipes

The composite structure is produced by using an integrated line having a card, an airlaid forming head and a hydroentanglement unit (Fig. 6.3). The production line meant for producing CPC composite can also be used by by-passing one of the two cards. One or more double doffer cards are used to produce webs in the range $20\text{--}80\text{ g/m}^2$ (Anand *et al.* 2007). The carded web used in a CP composite is heavy compared to that used in a CPC composite and is prone to dusting during conversion and wiping.

In the case of synthetic carded fibre webs (polypropylene or polyester), the carded web is pre-bonded by hot air thermal bonding. In an other process, the airlaid pulp layer is given pre-bonding by hydroentangling. Then it is



6.3 Process sequence for making hydroentangled CP composite wipes.

hydroentangled on to a carded layer to make composite. The purpose of pre-bonding of individual layers is to ensure good bonding and minimize the loss of pulp. Even with these precautions, the loss of woodpulp is about 4–5%. However, the use of much cheaper pulp instead of costly rayon brings cost advantage. The weight ratio of synthetic and pulp depends on the basis weight of carded and pulp layers. The hydroentangled carded-airlaid pulp wipes are used for industrial wipes that give required softness, strength, abrasion resistance and good absorbency.

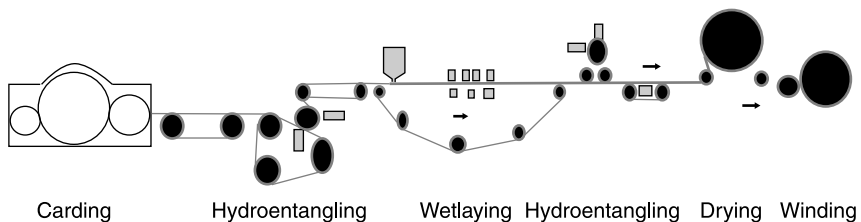
In principle a spunbond or meltblown line can also be combined with the airlaid-hydroentangling process. This process to produce polypropylene pulp is capital intensive and less flexible than a carding line. Therefore, in practice, an airlaying machine of particular type must be dedicated to a few similar products (Dobel 2002; Feroe 2002).

Carded-paper or preformed tissue

The carded web is pre-wetted and hydroentangled on a twin-cylinder module fitted with alternating injectors. The carded web and tissue are combined on a flat bed hydroentanglement module using two injectors to make the composite nonwoven.

Carded-wetlaid pulp

A patent awarded to Ahlstrom (Jeambar 2009) describes the process of making carded-wetlaid pulp hydroentangled composite nonwoven wipes suitable for bath towels. An aqueous dispersion of pulp fibres (about 0.8 to 8 mm) is put on top of a pre-hydroentangled carded web comprising 20% viscose rayon fibres and 80% polyester fibres, and excess water is filtered through the lower web using a perforated apron and air suction. The composite is hydroentangled and then embossed prior to drying (Fig. 6.4). This process is more economical compared to the other two processes that use airlaid pulp or paper. Further, the composite having wetlaid pulp is more uniform and less delaminating than the other two CP composites described above.



6.4 Schematic representation of the process sequence for making hydroentangled carded-wetlaid composite wipes.

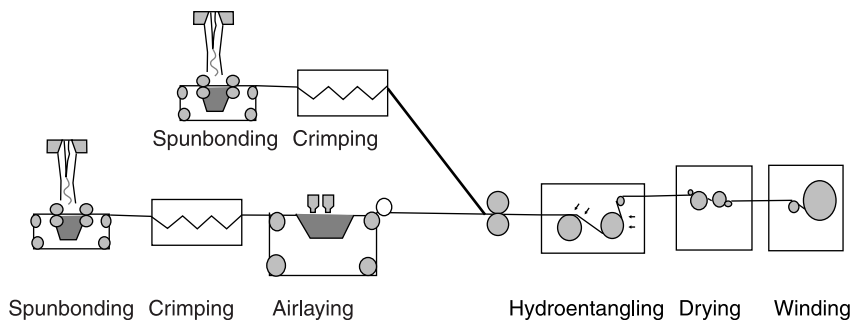
Carded-airlaid synthetic fibres-paper or preformed tissue

Synthetic fibre webs are made by using carding and airlaid technologies. In a patent issued to Polymer Group Inc., it is reported that polyester fibres of 1.2 denier fineness and 38 mm length are used to form both carded and airlaid webs. These webs are separately hydroentangled on drums. These pre-entangled webs are combined over a belt and a paper is placed on them. Then a final hydroentanglement is given with reduced energy to both surfaces of the composite (Moody III 2002). In one approach, the carded and airlaid webs are not given any pre-entanglement (Oathout 1995). They are combined in the dry state with a pulp layer and finally subjected to hydroentanglement on one side only. It is claimed that pre-entanglement of webs prior to combining them with a pulp layer reduces the loss of pulp fibres into the filtrate water employed during hydroentanglement. The pre-entangled synthetic fibre webs act to filter pulp fibres, so as to minimize loss of pulp fibre in filtrate water. Additionally, the pre-entanglement of synthetic fibre webs permits the use of reduced energy input for hydroentangling the synthetic and pulp fibre webs, which is also believed to contribute to reducing the loss of pulp fibres (Moody III 2002). These composite nonwovens are stated to have good absorbency, softness and low particle counts suitable for clean rooms, food service and other applications.

6.10.3 Spunbond-airlaid pulp-spunbond (SPS) and spunbond-airlaid pulp (SP) wipes

Wet wipes are produced from spunbond-airlaid pulp-spunbond (SPS) composites. The SPS wipes are targeted for the price-sensitive baby wipe market. Both the pulp and polymer chips are much cheaper as compared to viscose rayon and synthetic staple fibres, respectively. The pulp acts as an absorbent core and the outer spunbond layers provide abrasion resistance and structural reinforcement when the pulp is wet. In the core layer, cotton linters are also used in place of pulp. The spunbond layers resist linting, dusting and pilling in use. The process flow chart of producing the SPS nonwoven composite is given in Fig. 6.5. The filaments of spunbond layers can be crimped during production to improve porosity and softness of wipes (Anand *et al.* 2007). The SPS composite nonwoven provides a tougher surface and higher strength as compared to carded staple fibre wipes, but polyester spunbond is a faster process due to its more hydrophilic surface. However, polypropylene is cheaper and gives better coverage than polyester due to its low density; so less polypropylene material is required. Overall, the polypropylene outscores polyester in spunbonds.

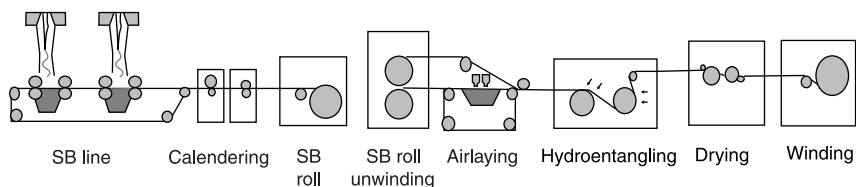
Reicofil introduced the concepts of 'in-line' and 'off-line' to combine spunbonded polypropylene with absorbent webs to make wiping composites (Anonymous 2008, pp. 16–22). In both systems, an airlaid unit adds a fluff-pulp core between two lightweight spunbonds and the composite is hydroentangled.



6.5 Typical process flow chart for producing SPS composite wipes (in-line system).

In the off-line system, pre-made spunbonds are fed from unwind stands into an existing line (Fig. 6.6). The in-line process is limited to about 350 m/min by the slower pulp airlay combination; whereas the off-line system can go up to 550 m/min. In the off-line system, 3.2 m wide spunbond (SB) rolls are slit into 1.6 m, to provide top and bottom layers to a 1.6 m wide airlay line with hydroentanglement. A dedicated in-line process requires at least 3.2 m wide to produce 25 000 tonnes per annum of one wiping product, then the economy favours the in-line process. When the market size for a product is small, then the 'off-line' approach would be beneficial, where wipe producers concentrate only on assembling the final product, leaving the job of making spunbond to upstream suppliers.

Fleissner offers integrated production lines to produce hydroentangled two-layer and three-layer composites (SP and SPS). The production speed of SP and SPS lines is about 400 m/min. The SPS composites have better strength as compared to CPC composites, because the spunbond web is stronger than the carded staple fibre web. This offers opportunity in reducing the basis weight of the spunbond layer and increasing that of the pulp layer (up to 75% of the composite weight) in the composite. The result is a cheaper product with improved absorbency. The SPS composites do not have pilling of fibres on the



6.6 Typical process flow chart for producing SPS composite wipes (off-line system).

surface of the product unlike CPC and all staple fibre carded products. Further, the SPS composites are more absorbent and cheaper because of the pulp, improved appearance and uniformity of the product due to spunbond layers, but have similar softness as compared to all-fibre products.

Procter & Gamble has patented a process of making SPS composite nonwoven wet wipes with improved fluid retention characteristics (Brennan and Balasubramanian 2007). When pre-moistened wipes are stacked in an impervious container, some liquid from the top layers move to the bottom ones, resulting in gradients of liquid retention. The liquid retention (g/g) would be less and less from the bottommost wipes to the wipes stacked on the top layers. The bottom layers in a stack would be subjected to more pressure, leading to compaction of pores, so the liquid from the top layers would tend to move towards the wipes at the bottom. To objectively evaluate this, the 'Saturation gradient index' (SGI) is quantified for the stacks of pre-moistened wipes. The SGI is the ratio of the average lotion load of the bottom ten wipes in a stack to that of the top ten wipes in that stack. An ideal ratio is one, which is difficult to get; nevertheless, a lower ratio is acceptable.

Various materials in the top and bottom spunbond layers were tried, such as polypropylene of 3 and 4 denier fineness and 50/50 polypropylene/polyethylene (side by side in fibre cross section) bicomponent fibres of 2 and 3 deniers. The weight proportion of core pulp component in composite was about 30%. The composite structure was hydroentangled and patterned on the surfaces. All the wipes exhibited bi-modal distribution of pore sizes; the maximum peaks were observed at 240 μm diameter pores for the 2 and 3 deniers bicomponent fibres, whereas for the polypropylene fibres of 3 and 4 deniers it was about 400 μm diameter. The wipes containing the finer bicomponent polypropylene/polyethylene fibres exhibited a lower SGI of about 1.3.

In another method of production of SP composite nonwovens, prior to hydroentanglement of the composite, the spunbond layer is pin/point thermal bonded between a roller with square pins and a plain anvil roller, such that about 16% of the surface area of the layer has a bonded surface. If the spunbond layer is loosely bonded, the filaments are generally too mobile to form a coherent matrix to secure the pulp fibres during hydroentangling. On the other hand, if the total bonded area of the substrate is too great, the penetration of pulp fibres into the substrate will be poor and also cause a splotchy composite fabric because the jets of water will splash and wash off pulp fibres (Everhart *et al.* 1994).

6.10.4 Carded-SMS (CSMS) and carded-SMS-carded (CSMSC) wipes

Conventional sanitary wipes such as baby wipes, hand wipes, household cleaning wipes and industrial wipes are made from a single layer of homogeneous material

or a mixture of synthetic and cellulose fibres. In single-layer wipes, it is difficult to optimize the physical characteristics of a wipe, such as thickness, texture, strength, structural integrity, softness, flexibility, opacity and resiliency depending on the application. A patent (Child *et al.*, 2010) describes production of two- and three-layer nonwoven wipes for sanitary application. In two-layer structures, the top layer is carded and consists of viscose and polyester (30:70), the bottom layer is SMS. In a three-layer structure, the SMS layer is sandwiched between the two outer carded web layers. The SMS may be pre-bonded. When pre-bonding is not required, multiple beams of SB and MB can be installed directly into the wipe production line instead of a roll unwind to introduce a previously formed fabric. The total composition (all the layers) is hydroentangled. In addition, they can be hydropatterned by using a square design.

It is also possible to produce webs using airlaid or wetlaid from staple fibres consisting of a mixture of synthetic (polypropylene or polyester fibres) and cellulosic (viscose rayon, cotton, pulp, bamboo, hemp or blends) or PLA fibres (polylactide). The layers can be bonded by using thermal or chemical or hydroentangling.

Compared to single-layer wipes, the multilayer wipes exhibited improved opacity and tensile strength and reduced elongation in cross direction for a given basis weight. Meltblown structures have superior opacity due to better coverage of fibres in fabric. A composite wipe relatively light in weight offers the visual security of high opacity and provides lower ratios of tensile strength (MD/CD) and elongation (CD/MD). The tensile strength in cross direction is relatively closer in value to that in machine direction compared to other wipes. The composite wipes provided more uniform multi-directional strength. The orientation of fibres in all layers of SMS and draft on the card webs must be controlled to get the desired effect.

6.10.5 Carded-spunbond (CS) wipes

The carded-spunbond composite nonwoven combines the benefits of carded (bulkiness, drape, softness and resilience) and spunbond (strength) to wiping products. The splitting of bicomponent fibres during the spunbonding and meltblowing processes is possible. Differentially shrinking bicomponent filaments having eccentric core-sheath or an asymmetric arrangement of components can be split into helically crimped filaments by quenching after extrusion and deposited on to carded web or sandwiched between two carded webs to produce soft and bulky fabrics. The size of fibre after splitting is about 200nm to 1000nm, whereas regular fibres obtained during the meltblowing process is in the range of 500nm to 10000nm. This shows the benefit of using bicomponent fibres in generating a very large surface area to obtain a textile like softness to wipes. Hydroentangling can be performed at low pressure as fibres are already very fine so require less energy.

6.10.6 Carded-carded (CC) wipes

Synthetic fibres and viscose rayon fibres are processed separately using cards. The carded synthetic web is lightly hydroentangled to improve the fibre entanglement before combining with the cellulose fibre web. The combined structure is hydroentangled.

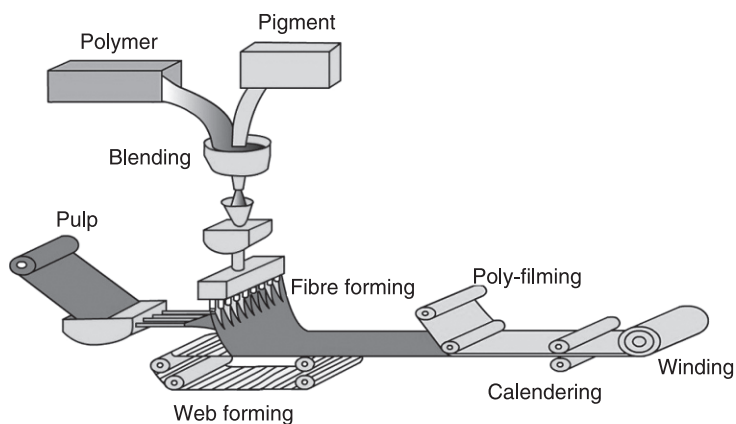
6.11 Thermobonded multilayer composite nonwoven wipes

6.11.1 Coform (pulp-meltblown)-spunbond/meltblown wipes

The Coform^(R) is a patented process of Kimberly-Clark, where the fiberized pulp from woodpulp sheet is injected from one side on to tacky meltblown fibres as they travel from the die to the collector. When the synthetic fibres cool, wood pulp fibres adhere to synthetic fibres. In the next stage, a preformed spunbond or meltblown or film is thermally laminated to at least one side on to the Coform layer to form an absorbent composite (Fig. 6.7). By changing the composition of the layers, a variety of products can be made.

6.11.2 Coform (pulp-meltblown)-elastic wipes

Stretchable nonwovens are highly useful for developing oral care wipes. A wipe ‘Oral-B-Brush-Ups’ can slip on a finger. Wipes with textured surfaces can be made using stretchable nonwoven. Two patents (Lange *et al.* 2002 and Baer and Close 2010) are concerned with a process of producing elastic wet wipes having

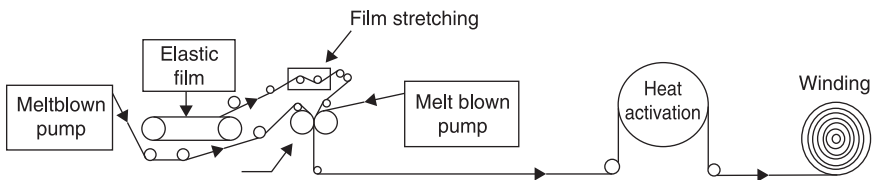


6.7 Schematic representation of the Coform process to produce composite wipes.

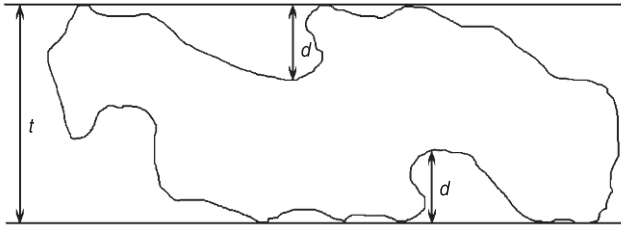
a softer and more cloth-like feel by using composite nonwoven. A gatherable layer is formed by a mixture of microfibres and woodpulp fibres using a Coform process (as previously described) that integrates a primary and secondary air stream containing meltblown microfibres and woodpulp fibres, respectively, and directing the integrated air stream onto a forming surface, to get a coherent integrated fibrous structure, without adhesive bonding. The preferred weight ratio of melting and absorbent fibres in the Coform layer is about 35:65. Two gatherable layers (top and bottom layers) are placed above and below, respectively, an elastic layer stretched to 100% and the composition is thermally bonded by calendering at fixed points (Fig. 6.8). To induce shrinkage on the film, heat activation is carried out before winding.

The elastic layer is formed by meltblown technique and the elastic fibres may be profiled into different shapes and diameter. To improve the process ability during formation of the elastic layer, polyethylene can be blended with elastomeric polymer. A compatible tackifying resin can also be added to the extrudable elastomeric compositions to improve adhesiveness. To improve the retraction and dimensional stability of the composite, it is heat set at the glass transition temperature of the elastomeric layer. It is possible to have pre-formed elastic and gathering layers in roll forms and then combining them into a composite nonwoven. The softness of the wipes are measured by the cup crush method, the energy (g-cm) required by a spherical plunger to deflect the wipe kept over a cup by 4.5 cm. A lower cup crush value indicates a softer material. It is claimed that the composite wipes having an elastic layer have less cup crush values, indicating that they are softer.

Another patent (Kopacz *et al.*, 2005), similar to the one described above, is concerned with production of wet wipes with a 'cloth-like feel' by using an elastic layer laminated between two gathered layers. When the stretched elastic layer retracts, the outer layers assume corrugated shapes, resulting in texture to both surfaces of the wipe in the form of peaks and valleys which are mostly out of phase (Fig. 6.9). The patent claims that the ratio of wipe thickness (t) to the sum of the valley depths (d) on the top and bottom surface could be between 1 and 4, indicating high and low textured surfaces respectively. The stretch level of an elastic layer prior to bonding and post-heat setting of the composite decides the



6.8 Schematic representation of the process to produce elastic composite wipes.



6.9 Peaks and valleys on surfaces of elastic composite nonwoven wipes (t : wipe thickness, d : valley depth).

level of texturing of the wipe surfaces. Wipes with textured surfaces can be more efficient in cleaning the surfaces. A patent awarded to 3M innovative (Bergsten *et al.* 2003) deals with a two-layer composite wipe, where one layer having peaks and valleys is adhesive bonded along the valleys to the other layer.

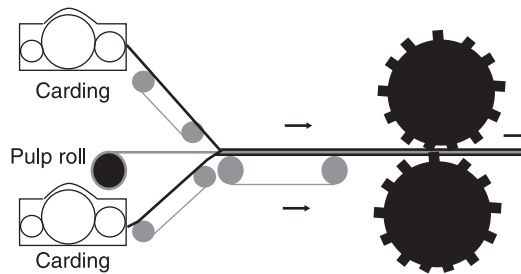
6.11.3 Bicomponent-airlaid pulp (BicoP) wipes

It has been demonstrated that high wet strength, high wet elongation in cross direction and reduced stiffness required for baby wipes can be produced by using an homogenous mixture of bicomponent fibres (polyester in core and polyethylene on sheath) or multilayers having pulp and bicomponent fibres (Hurley *et al.* 2006). The bicomponent fibres are 2 dpf with 6 mm cut length and are partially drawn having 100% extension. In three-layer structures, the top and bottom layers consist of airlaid webs having a high proportion of pulp and a low proportion of bicomponent fibres. The middle layer consists of either 100% bicomponent fibres or a homogeneous mixture of pulp and bicomponent fibres. In a two-layer structure, the top layer has 100% bicomponent fibres and the bottom layer is made of an homogeneous mixture of bicomponent fibres and pulp. Three-layered composites are manufactured by using an airlaid system having three forming heads. The individual layers are combined and compacted by rollers and then cured by using hot air.

For producing on homogeneous mixture of pulp and bicomponent fibres, a cellulose pulp sheet is fed into hammermills for conversion into individualized fibres, which are then air entrained in an airflow of controlled humidity and temperature. The bicomponent fibres are then introduced into the controlled airflow on its way to the forming head, where they are mixed with pulp fibres in the air stream before the mixture is deposited by the forming head. It is reported that by increasing the percentage of bicomponent fibres, the strength and elongation of nonwoven increases; but the layered structure has more strength than the nonwovens having an homogeneous mixture of pulp and bicomponent fibres.

6.11.4 Thermal bonded carded multilayers and carded-spunbond wipes

Composite structures such as carded-carded-carded (CCC), carded-carded (CC), CPC and carded-spunbond (CS) are thermal bonded by using calendering to produce cleaning pads (Singh *et al.*, 1999). The top and bottom layers are carded having a mixture of rayon and polypropylene fibres. For hard cleaning surfaces, the denier of polypropylene fibres can be as high as 6.7 or the proportion of polypropylene can go up to 80% in one of the surface layers, or a two-layer structure can be used with one of the layers spunbond. For regular cleaning, the linear density of polypropylene may be as low as 2.2 dpf. The middle layer is carded, consisting of rayon of 1.5 dpf and polypropylene of 2.2 dpf, with a weight ratio of 70/30. The final composition is thermobonded using calender rollers. A schematic representation of the process for producing thermal bonded CPC composite wipes is shown in Fig. 6.10.



6.10 Process for producing thermal bonded CPC composite wipes.

6.12 Needle punched composite nonwoven wipes

A patent (Ramkumar 2009) demonstrates that chemical protective composite wipes that remove nerve gas and harmful chemicals from a soldier's skin can be manufactured by H1 technology needling that uses oblique angled needle penetration. This is achieved by means of an asymmetrically curved needling zone, accompanied by a straight needle movement. The advantages of this technology are a longer needle path providing better fibre entanglement and reduced needling density that enhances the construction of composites. The top and bottom layers consist of pre-needled polyester or cotton carded webs and the middle layer is an activated carbon mat. It is shown that many combinations are possible, such as the number of top, bottom and adsorbent carbon layers, needling sequence, needling density and types of fibres and blends on the surface layers. The mesopores in the activated carbon fibres adsorb harmful liquids, odours and

chemicals during wiping of contaminated surfaces such as human skin and cloth, etc., while the surface layer helps in trapping the particles and providing a soft feel. The wipe had a PMP (Soman) uptake of about 0.15 g/g as compared to the 0.06g/g uptake of the M291 decontamination kit currently issued to troops in the US military (Anonymous 2008).

6.13 Other multilayer nonwoven wipes

Wipes for abrasive market contain meltblown material combined with either a needlepunched or spunlaced layer, to offer high bulk and abrasiveness. Jacob Holm's Bi-active is one such product. SMS and SM polypropylene oil sorbent pads have increased strength, durability and reusability than single-layer meltblown pads. However, the oil sorption and retention capacities must be low as compared to meltblown pads as the spunbond layers have larger pores due to the presence of coarse fibres in the structure.

6.14 Conclusion and future trends

The developments that have taken place in composite nonwovens will be pursued more vigorously by wipe manufacturers by using permutations and combinations of different fibres, pulps, blends, webs, layering, additives and technologies to stay ahead of each other. This will result in many wipe products being marketed, ranging from value added to affordable wipes in the consumer and industrial sectors. In future, the price competition will intensify in household cleaning wipes, so the nonwovens need to be economical. Many wipes in personal care and for household use will be introduced in the market with added functionalities, so much so that the consumer will be confused by the choice. Wipe manufacturers must be cautious in developing new products and should lay greater emphasis in differentiating their products. When nonwoven manufacturers develop new wipe substrates, advanced nonwovens will be available to enhance wipe differentiation and stimulate demand in the creative product category. The independent wipe manufacturers must acquire broad capabilities for formulation of compositions, selection of substrates, product put-up options, rapid production turnaround, packaging, cost control, quality assurance and timely delivery of products.

Nevertheless, the environmental pressure will oblige the wipe manufacturers to focus simultaneously on the aspects of developing wipes using recycled fibres and biodegradable fibres that are flushable-dispersible-biodegradable. The demand for truly dispersible nonwovens for flushable wipes will increase. It has been demonstrated that bicomponent fibres that are splittable during hydroentanglement offer a very fine and smooth fibre surface, but their cost is prohibitive for use on a large scale in technical wipes and high end personal care wipes. When these fibres are affordable, many value added wipe products will be available in future.

6.14.1 Wipes from recycled fibres

Reduce, Reuse, Recycle; these words have become synonymous with the Green Movement (Anonymous 2011b). Wipe manufacturers are working hard to make sure that their customers have lots of choice when it comes to environmentally friendly products. Some of Ahlstrom's spunlace products are made from recycled polyester. The recent trend is to produce wipes from recycled fibres, so that the impact of landfill arising out of disposable wipes can be minimized. In future, the trend of producing recycled polyester fibres from used bottles and containers, and producing wipes from these fibres, will pick up. It has been shown that five 16-oz polyester bottles will produce 72 wipes each of 50 g made with 70% recycled polyester (EcoSure fibres) and 30% others. The recycling of polyester reduces energy consumption by 84% and greenhouse emissions by 71% (Katz 2011).

Recycled rayon fibres from used woven or knitted fabrics are also used for making industrial wipes to a limited extent. The nonwovens from recycled fibres are made in dry form and are latex bonded to provide low linting. Wipes made from cotton recycled from jeans, shirts, towels, sheets and other clothing will also increase. The problem with recycled cotton is the high variability in length which poses a little challenge in carding (Anonymous 2011b).

6.14.2 Wipes from biodegradable materials

Every year, about 250 000 tonnes of wipes are disposed in landfills after use. One can imagine the environmental impact they pose to present and future generations, even if they contain a low proportion of synthetic fibres. Environmental concerns are raised from many quarters and the talk of reducing carbon footprints in many forums is gaining momentum. Pressure from the environmental lobby and citizens from Europe and America will force many governments to pass regulations on production, use and disposable aspects of wipes that are made from non-biodegradable fibres such as polyester and polypropylene.

In anticipation of this, the leading wipe manufacturers are focusing their research on developing biodegradable wipes and wipes having a smaller proportion of synthetic fibres. But the availability of a large quantity of natural (cotton) and industrial-made biodegradable materials (viscose rayon, Tencel) and the cost associated with them are the issues to be addressed. The effort made in this direction yielded wipes that are prepared with more woodpulp content and a smaller content of viscose and non-biodegradable petroleum fibres. However, the economy favours petroleum fibres, as they are cheaper, stronger and at present abundantly available.

Suominen's 'Biolace' and Sandler's 'Bio wipes' are composed of 100% viscose fibres, which are fully biodegradable and are certified according to the PEFC (Programme for the Endorsement of Forest Certification) standard

which advocates sustainable handling of wood and products made from it (McIntyre 2011). A recent innovation to produce cellulosic nonwovens by using meltblown technology is very encouraging. Meltblown lyocell nonwovens which have potential applications in wipes are produced in a pilot scale plant by the Fraunhofer Institute by combining its Lyocell process with Weyerhaeuser's meltblown and Reicofil's nozzle. The dope extruded through a die is subjected to hot blown air and subsequently coagulated by spraying water or a mixture of water with NMMO. This results in a self-bonded nonwoven without distinct adhesion of single fibres. Practical tests have shown that films are formed when the dope is not sprayed with water. The production of durable wipes requires a maximum tensile strength of 1600 N/m for basis weight less than 100 g/m². This could be achieved by a meltblown-lyocell microfibre self-bonded nonwoven with a basis weight of 65 g/m². The liquid absorptive capacity and wicking rate of this cellulose-meltblown nonwoven are similar to the spunlaced nonwovens made from viscose rayon or lyocell fibres (Ebeling *et al.*, 2006). Depending on the throughput, webs of 8–50 g/m² having fibres about 4 to 8 micron diameter are produced. These webs are strong, lint free and resembling traditional spunbond rather than meltblown products (Anonymous 2008).

There will be renewed interest on cotton wipes in the future. The use of cotton in nonwovens is less than 2% of all fibres currently used. In the USA, commercial products like cosmetic pads and facial wipes contain 100% cotton. Differentially entangled carded cotton nonwoven using hydroentangling is reported (Barge *et al.*, 2004). A similar concept is used in Japan to produce hydroentangled cotton cosmetic pads (wet wipes). The drylaid fibres are hydroentangled by using extremely low injector pressure (40 bar). This results in very low entanglement of core fibres, whereas the surface fibres have an adequate degree of entanglement. This maximizes the porosity for better absorbency and minimizes the linting in use (Anand *et al.*, 2007). The other approaches followed to bond the fibres in web are: surface impregnation with binder; thermal bonding with bicomponent fibres; and embossing by using calender rollers.

Most of the cotton used in the nonwovens up until now has been bleached, which is expensive and complex to process, especially in carding. This affects the production rate of a hydroentanglement line. So there is considerable effort to develop a wipe using nonbleached (virgin) cotton. SRRC, New Orleans has demonstrated that virgin cotton could be processed directly on existing carding equipment. Several lightly pre-needled webs of virgin cotton were produced on commercial needlepunching equipment to investigate further bonding using hydroentanglement. During this hydroentanglement, a large proportion of wax is removed at low energy, which increases the hydrophilicity of fibres, an essential requirement for wet wipes. This is advantageous as the costly process of scouring and bleaching of cotton and the difficulty in processing it might be eliminated (Anonymous 2011c). The strength of hydroentangled cotton fabrics tends to increase as the fibre becomes finer but the fabrics have a harsher handle. Fine

cotton fibres are prone to form neps in hydroentangling, hence coarser cotton fibres are preferred; an added advantage as coarser cotton fibres are cheaper than the finer ones.

The solvent spun cellulosic fibre, Tencel (formerly lyocell) from Lenzing have higher wet strength and wet modulus than viscose rayon. Their absorbency is slightly lower than viscose rayon but still good for wiping products. These properties provide resistance for wet wipes to prevent them collapsing during use. Lyocell fibres are dispersed easily in water. Because of their relatively high modulus than viscose rayon fibres, longer lengths can be used for wet laying. Their round cross section produce large amounts of inter-fibre contact resulting in a high degree of cohesion of the wet web. This facilitates excellent web transfer. Their low water imbibition allows easier drying of the web during processing (White 2007). Further, their ability to fibrillate under applied force such as used in hydroentangling make them finer with a large surface area. This offers a smooth fibre surface to the wipes, making them very soft, but still strong (Anonymous 2011b) and also with excellent pattern definition. Because of the superior properties of Tencel fibres, they will be used as wetlaid-hydroentangled nonwoven wipes, especially in the wet wipes category in future.

More recently, a nonwoven manufacturer has partnered with a fibre developer to create technology that allows for the incorporation of PLA (polylactide) fibres into a hydroentangled web that will naturally biodegrade in landfills in two weeks (Robinson 2005). At Fiberweb, efforts are focused to develop PLA fibre nonwovens that can be thermal embossed with attractive patterns suitable for baby wipes. Currently, PLA fibres are expensive and supply is limited.

6.14.3 Dispersible nonwovens for flushable wipes

The wipes which are ideal candidates for flushability are ones that can be disposed of immediately, rather than stored in the home waste receptacles. Customers prefer baby wipes, bathroom cleaning wipes, feminine hygiene wipes, haemorrhoidal wipes and medicinal pads to be flushable. A truly dispersible wipe is one which can disperse like toilet paper in a short time after being put in the toilet and flushed out and should not clog up the plumping system to the city sewage treatment plant causing breakdown or increased maintenance of the entire sewage system. It is important that flushable products are not buoyant and readily sink to the bottom of the holding tank so that they can be removed with the sludge (Drinkwater *et al.*, 2011). The wipes produced from short cellulose fibres using wetlaid-hydroentangling do not have adequate strength in use as wet wipes but are dispersible and biodegradable.

Currently, for making flushable wipes, airlaid pulp is bonded by ion sensitive cationic polymer binders or by light hydroentanglement. Trigger technologies use a component that causes the nonwoven web to change its strength properties after it is immersed in water by becoming weak enough to be

flushable. Kimberly-Clark introduced such triggerable binders. The ion level based triggers are better compatible with sanitation applications and skin contact (Mango 2004, 2008). Three-layer composites with wetlaid pulp in the core supported by fibre webs comprising synthetic and natural fibres are hydroentangled at selected areas, leaving others unbonded to promote disintegration of the structure in the sewer system (Ngai 2003). Hydraspun^(R)784 is one such wipe. The wet strength of this product prior to flushing is sufficient for current wipe applications, but may limit the development of other markets in the future. It is reported that it prevents strain on municipalities' sewage treatment systems and it passes ISO 14851 biodegradability tests (Levy 2011).

Wetlaid fabric composed of short synthetic and natural fibres can be produced for dispersible wipes. All these wipes are designed to breakdown under agitation in water. Water dispersible fibres from sulfopolyester and multicomponent fibres comprising water dispersible sulfopolyester and non-dispersible polymer arranged side by side in the cross section of fibre are reported (Haile *et al.*, 2012). These have potential applications in flushable wipes.

Mechanically weakened two-layered structures joined together by water responsive binders are targeted as dispersible-flushable wet wipes (Noda *et al.*, 2010). The layers could be carded or airlaid webs consisting of cellulose fibres or blends with pulp. Each layer is passed between a pair of gear/tooth-shaped cylinders or the pair could be a combination of a recessed top cylinder and a smooth bottom cylinder. This weakens the layers at selective locations. The layers are staggered during overlapping such that a weakened portion on the top layer does not coincide with that of the bottom layer, so that the wipes have adequate strength in use. The fibres and the structures are said to be stable up to three years in pre-moistened wipes. During flushing, the agitation of water is sufficient to disperse the fibres in the toilet. This type of wipe made from biodegradable fibres with the right selection of fibre length, controlled weakening and binding of layers could be a potential candidate as a truly dispersible-flushable wipe.

Many wipes currently marketed as 'flushable' contain a small proportion of non-biodegradable fibres to give adequate strength to the wipes in use. These are only flushable and not dispersible in the true sense that they do not degrade, hence they clog the plumping and sewer systems in the form of fibre clumps. In future, many city governments will pass stringent regulations on disposable aspects of flushable wipes. A truly dispersible wipe could be made only by using biodegradable materials (pulp, short natural or regenerated fibres) and appropriate web forming and bonding technique (including binders or controlled entanglement of fibres). Further, they should have adequate wet strength and cleaning ability. Development of raw material must be compatible with a variety of water treatment technologies utilized. The chemicals used in waste water systems do not allow to re-gather the dispersed fibres from the flushed-out wipes. In terms of raw materials, most experts focus on traditional biodegradable fibres with some form of cellulose-like pulp, short rayon or short cotton fibres (Kim and Hergeth 2012).

The airlaid, carded and wetlaid technologies are promising for making truly dispersible wipes. The insolubilized polymeric binders developed for premoistened tissue, that can cause a wet wipe with effective wet strength in a lotion to lose strength in water on dilution (ion concentration trigger), have real potential in flushable wipe applications (Mango 2004). The patent protected status of these binders and the required skills in processing are the deterrent for developing flushable wipes. Developing true dispersible nonwovens for flushable wipes that are functional and affordable will undoubtedly pose tremendous challenges to wipe manufacturers in future.

6.15 References

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Composite nonwovens in filters: theory

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Abstract: This chapter embodies filtration mechanisms and characteristic requirements of nonwovens as filters. Different filtration media rely on different physical interaction mechanisms for separation and collection of particles. Apart from the most common particle entrapment by physical principles while separating solids from liquid/gases, different mechanisms exist in liquids–liquids separations and gas–liquid separations. Textile filter media have proved to be superior in many applications of gas and liquid filtration. Among textile media, use of nonwovens is most prominent as the filter media. Structure and media characteristics largely depend on filtration-specific requirements, machine oriented requirements and application oriented requirements.

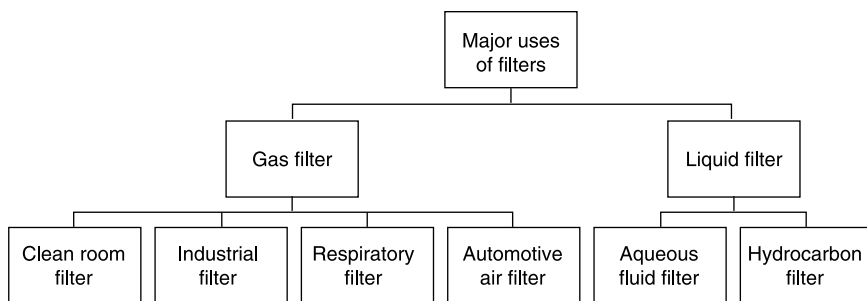
Key words: adsorption/absorption, coalescing, mechanisms of filtration, media characteristics, particle capture/entrapment.

7.1 Introduction

A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution, or suspension, and is impermeable to the remaining components. Broadly, the filtration process embodies solids–gases separations, solids–liquids separations, solids–solids separations, liquids–liquids separations, gas–liquid separations, and gas–gas separations and these are an essential part of countless industrial processes, contributing to the following:

- purity of product;
- imbining functional performance (e.g., cleanroom for tissue culture);
- saving in energy;
- improvement in product and process efficiency;
- protection of machine/instruments and their components;
- recovery of precious materials;
- environmental pollution control.

The fluid stream to be filtered may be liquid or gas. Figure 7.1 shows the major uses of filters. Wide variations in filter material composition and structures are available in the market, depending on the field of application. Although the random fibre structure is the backbone of the web, it may contain other components that are part of the forming process, including (but not limited to) particulate



7.1 The major uses of filters.

fillers (clays, calcium, adsorptive powders, etc.), sizing agents, wet strength agents, antimicrobial additives, plasticizers, dyes and pigments, softening agents, and wetting agents. The fabric may be exposed to other chemical and mechanical treatments to enhance its properties. Examples are coatings and finishes, flame retardants, antimicrobial agents, water repellents, dyes and softening agents. It may also be exposed to downstream mechanical conversions such as creping, corrugating, embossing, slitting and rewinding, pleating, bag making, sheeting, dye cutting, and stamping, as necessary for the end use filter and/or separator application (Hutten, 2007).

In the case of gas filters, the most common applications are engine (automotive panel air filter, heavy duty air filter and cabin air filter), indoor air (heat, ventilation, air conditioning (HVAC), particulate removal, odour/gas removal) and industrial air filtration (gas turbine and dust collection filter applications), and respiratory filter (Anonymous, 2013). For gas filters, the fluid is most often air. There are other applications where gases other than air are filtered, for example, process filters for gaseous fuels such as natural gas and propane, and specialized filters for the manufacture of special gases such as oxygen, nitrogen, helium, hydrogen, etc. However the need for non-air filters is quite small compared to the demand for air filtration. On the other hand, the market for liquid filtration can be substantially divided into filtration of aqueous fluids and filtration of hydrocarbon fluids. Filtration of aqueous fluids involves water treatment plants, water desalinization, water discharge treatment plants, industrial process streams, industrial chemicals (e.g., paints, lattices, electroplating solutions, printing inks), drinking water filtration, beverage filtration (e.g., coffee filter, nonalcoholic beverages, wine filtration, beer filtration), filtration of aqueous foods, medical filtration applications (e.g., blood filters, vent filters), pharmaceutical applications, swimming pool filters, etc. Hydrocarbon fluids include fuels, engine lubricants, hydraulic fluids, cooling fluids for metal working operations, and edible oils.

Very often protection is the goal of a filter. The purpose may be to protect an inside environment from the contamination of an outside environment or to protect the outside environment from contaminants of the inside environment. To

illustrate, high efficiency particulate air (HEPA) filters were first developed for nuclear processing facilities to provide a barrier against any radioactive dust or contaminants leaking to the outside world. At present, use of HEPA filters is most common for cleanroom applications where the goal is to prevent even the minutest amount of contaminant from the outside world to enter the workplace. HEPA filters are typically employed in particle removal and retention within the air cleaning systems of cleanrooms in hospitals and in the biomedical (e.g., tissue culture), pharmaceutical, genetic research, food processing, nuclear and semiconductor industries (Anonymous, 2013). HEPA filters are often used in HVAC systems, to protect the system from buildup of dirt and debris that might impair the performance of these systems. The life span of the unit is thereby increased and the maintenance decreased.

As regards to industrial gas filtration, it is of prime importance in many process industries to control the particulate matter emission and to recover the valuable particles. The emissions of particulate matter are variable with particle concentration ranging from $<1 \text{ g/m}^3$ to more than 250 g/m^3 with the size of particles predominantly very fine ($0.1\text{--}25 \mu\text{m}$). Mechanical types of separator are in general effective for the removal of coarser particulate matter; they can only be used to reduce the burden of the final filter unit. In general, for collecting small particulate matter, electrostatic precipitator (ESP), wet scrubber and fabric filters (usually needle-felt) are the only options. Among all the filters, the most efficient and versatile is the fabric collector, especially when processing very fine particles, which are slow to settle, cause greater health hazards and by virtue of their greater light scatter, more visible to the naked eye. In one of the structural embodiments, the fabric filtration technique is embedded with a pulse-jet cleaning system. In the past decade, the use of industrial bag filters operated under the principle of pulse-jet filtration (Mukhopadhyay, 2009, 2010) has had rapid growth as they prove to be most efficient and versatile (Mukhopadhyay and Pandit, 2013). Pulse-jet fabric filters are widely used in many industries, such as solid-fuel-fired power generation, bulk solid processing and plasma-aided manufacturing, etc. The pulse jet filtration process has been considered as one of the most sustainable technologies worldwide. It may be added that mainly nonwoven fabrics are used in the pulse-jet filtration process. However, woven filter materials are also used, in particular, in the cases of the reverse air jet and mechanical types of cleaning systems.

There are also growing concerns for in-house dust level due to industrial activity such as welding, laser and plasma cutting, abrasive blasting, metalworking, mixing, and grinding dry materials which release minute dust particles in the air where they float freely or settle on surfaces. Indoor air is often two-to-five times more polluted than outdoor air and can be up to 1000 times as dirty. Industrial environments require dust control systems that are designed to protect plant personnel from exposure to these hazardous airborne dust particulates. There are a variety of cleanable dust collectors ranging from cartridge dust collectors to

baghouse designs. Dust collectors can also be portable types (Brahm, 2012). In the textile media, mainly nonwovens are used for maintaining a clean industrial environment. The textile filter media is also effective for separating moisture and oil mists from contaminated air streams as required in compressed air operations, lubricated machining, cutting processes, etc, through the coalescence process. The same mechanism is also valid for separation of liquid moisture particles/organic particles from organic/water streams.

Broadly, liquid filtration applications are concerned with the filtration of either aqueous or hydrocarbon fluids. When the proportion of solids in a liquid is less, the term clarification is used. It is a common operation which is widely employed in production of sterile products, bulk drugs, and liquid oral formulation. The suspension to be filtered is known as slurry. The accumulated solid that deposits on the filter is referred to as filter cake and the clear liquid passing through the filter is known as filtrate. The large-scale liquid filtration is accomplished mostly by cake filtration. Many forms of filter equipment use a filter fabric to support the cake and filter efficiency increases as the filter cake forms. The cake becomes the filter media and the porous medium acts as a septum to retain the filter cake. Filter cakes can be effectively washed *in situ* and backwashed from the filter housing. Often, the fabric is woven filter cloth, link fabric, duplex, or semi-duplex fabric; however, there are applications where needlefelt nonwoven is the popular choice. In recent years, there has been an emergence of spunlace (hydroentangled) fabrics for industrial liquid filter applications. Nonwoven and paper filter media are popular in filter presses. In liquid filtration, there are also important applications for nonwoven-supported membrane filters.

In many filter applications, nonwovens are used as replaceable filter elements. Two of the most common types are liquid bag filters and cartridge filters. Liquid bag filters are often made of woven fabric filter media; however, there are some applications where a nonwoven or a nonwoven composite material is used. The biggest use of nonwovens in liquid filtration is as cartridge filters where high purity is demanded or where ultra high efficiency is expected (e.g., health care and related industries). Cartridge filters are also used in consumer filter applications such as home water filters and swimming pool filters (Hutten, 2007).

Another important segment is engine filtration wherein the uses of nonwovens and composites are quite extensive. Engine filtration is the term applied to the filtration requirements of engine powered vehicles and equipment. This includes automobiles, farm equipment, trucks, off the road construction equipment, aircraft, railroad trains, boats, and a multitude of specialty engine operated equipment ranging from mine drilling equipment to lawn mowers. Turbines can also be considered as a form of engine. There are many filters within an engine powered vehicle. The major uses can be reduced to the following:

- lube oil filtration
- air intake filtration

- fuel filtration
- cabin air filtration.

In addition, there are filters for transmission fluids, power steering fluids, brake systems, exhaust systems, crankcase emissions, etc. Computerization of the engine has required additional filters to protect electronic components. Under engine filtration, gas turbine filtration is a major category in itself. In automobiles, there are 8 to 15 different filter elements. The filter elements are used for filtration of oils, fuels and air. A wide range of specifications are needed depending on exactly where in the automobile or engine the filters are used, and what directives are in place in the country of use. It is important to note that some of the filter media are not changed throughout the whole life of the car. There are also a large number of filter elements which require routine maintenance. Their working temperatures vary between 40 °C and 1000 °C. Composite media find broad application in engine filtration applications, including the filtration of lube oil, diesel fuels, and aviation fuels.

The demand for filter media is continuously rising. Over the years, there has been a significant rise in the consumption of air filters in the fields of industrial dust filtration (baghouse filters and cartridge filters), consumer/residential HVAC filters, HEPA/ULPA, disposable face masks and in-cabin automotive air filters. One of the fastest growing markets is the consumer/residential HVAC market. Due to the increased awareness of global environmental conditions, the market demand for industrial filter applications is also increasing. The regulation placed a limitation on the amount of PM_{2.5} concentration present, a considerable challenge to many industrial regions. Liquid filtration is also a fast growing market for nonwovens. In the sectors of wet filtration, a steady growth of nonwoven uses is visible in the fields of process filtration, water filtration and applications in automotive and life sciences, with the highest in water filtration (waste and desalination) and life sciences (laboratory, diagnostics, medical). It also includes food and beverage filtration electric processes; blood filtration; tea bag, coffee and juice filters; cooking oil filters and oil/fuel filters for automotives. In the fields of process filtration, the sectors of chemistry and pharmacy are of special importance. Nonwovens have been successfully used in the industry as membrane support for micro-filtration, ultra-filtration and reverse osmosis filtration.

From the foregoing matter, it is quite apparent that there are very wide gamut of uses and many niche areas where the filter media are used. The importance of separation is to grow even further, primarily due to following reasons (Svarovsky, 2000):

- The ever-increasing demands on product purity, particularly in the pharmaceutical, biotechnology and food industries.
- The gradual reduction in the quality of raw materials, this being a particularly serious problem in mineral processing.
- The growing demands for environmental acceptability of waste materials.

The main reason for the demand for textile filter media is due to their performance, design and structural flexibility and manoeuvrability depending on applications, which finally leads to one of the most sustainable technologies. Over the past decade, significant attention has been paid to designing and developing several types of filter for enhancing performance and many new designs, differing in construction and raw material, are continuously evolving. The main issues for such developments are:

- filtration efficiency;
- flow resistance;
- filter life (resistance to blinding/plugging, improved resistance to thermal, chemical, hydrolytic and oxidative degradation);
- size;
- greater storage/dirt holding capacity, wherever applicable;
- optimum cleanability;
- specific performance characteristics (absorption of gases, antibacterial, antimicrobial oil/water repellent, static dissipating, spark resistant, abrasion resistant);
- lowest cost vs. performance/benefit.

In addition, current world, social, economic and environmental conditions have created a new set of requirements to add to the above:

- disposability/recyclability;
- sustainability;
- 'green' impact in production (minimal environmental impact);
- energy savings.

All these requirements have impact on industry and its producers, but their products are still, to a degree, unknown, although major media manufacturers are moving to meet these objectives and to capitalize on them as well. New ideas and market needs may come from the end users or from modifying and improving existing ideas or features. Composite nonwoven is one such development which stimulates accelerated growth of the use of nonwovens in filters.

7.2 Mechanisms of filtration: general

Different filtration media rely on different physical interaction mechanisms for separation and collection of particles. Apart from the most common particle entrapment by physical principles while separating solids from liquids/gases, different mechanisms exist in liquids–liquids separations and gas–liquid separations. In the following cases, textile filter media in isolation or in composite form are associated with different principles of separation:

- adsorbent media (e.g., remove toxic and obnoxious chemicals from fluid);
- absorbent media (e.g., polyolefin materials in controlling oil spills at sea);

- coalescing media (remove immiscible liquid particles from fluid);
- media for gel removal;
- electro-filtration (removal of charged particles);
- antimicrobial media (prevent the migration of biological microorganisms);
- extraction (extraction is a phenomenon that is not built into a filter medium, but rather the medium serves as a structural support for the extraction process, e.g. teabag).

In this and the following sections, a brief overview of particle entrapment and other mechanisms of filtration along with the factors influencing filtration are discussed.

Broadly, particle capturing by filter media is ascribed due to particle interaction with single fibre and fibrous assembly. Beside these, many other aspects influence capture of particles and final effect depends on combination of several mechanisms/factors classified as:

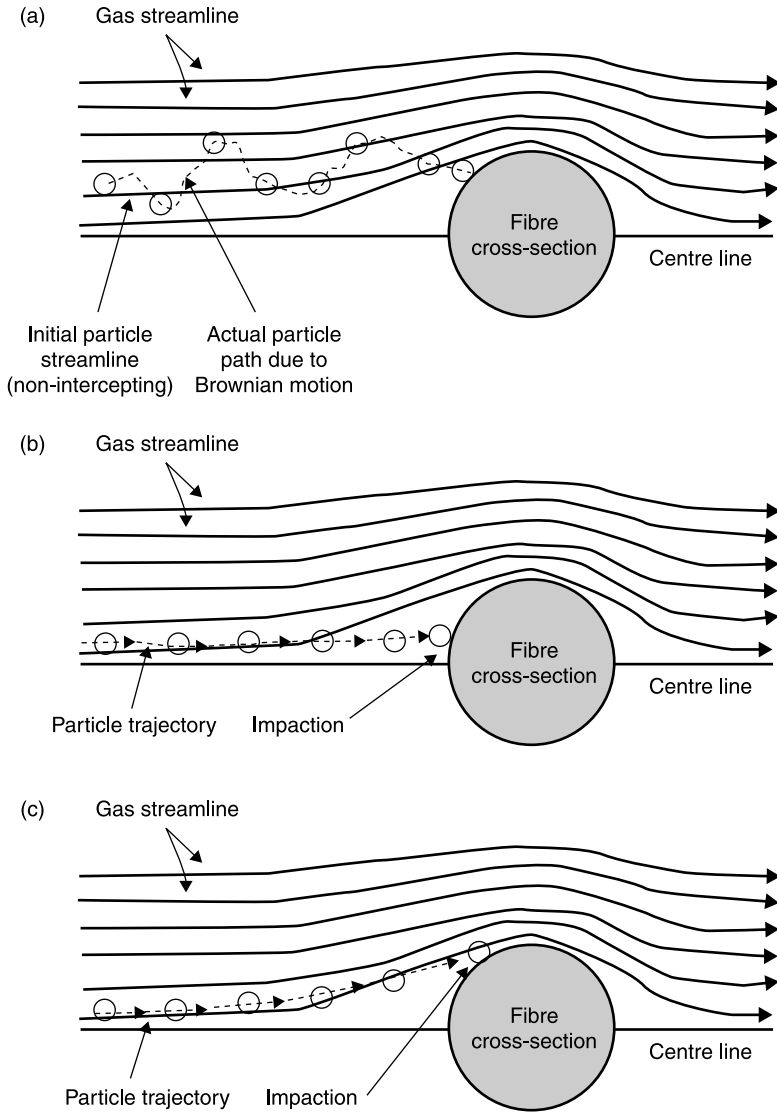
- single fibre theory;
- capture by fibrous assembly;
- capture based on the mode of filtration (e.g., cake vs. non-dust cake filtration, filtration through electrostatic charging);
- capture influenced by design of filter unit;
- capture governed by operating parameters.

In the following section, the focus is mainly on the role of media and the mode of filtration on particle capturing; therefore discussions on captures influenced by design of filter unit and also by operating parameters have been omitted.

7.3 Mechanisms of filtration: particle capture entrapment

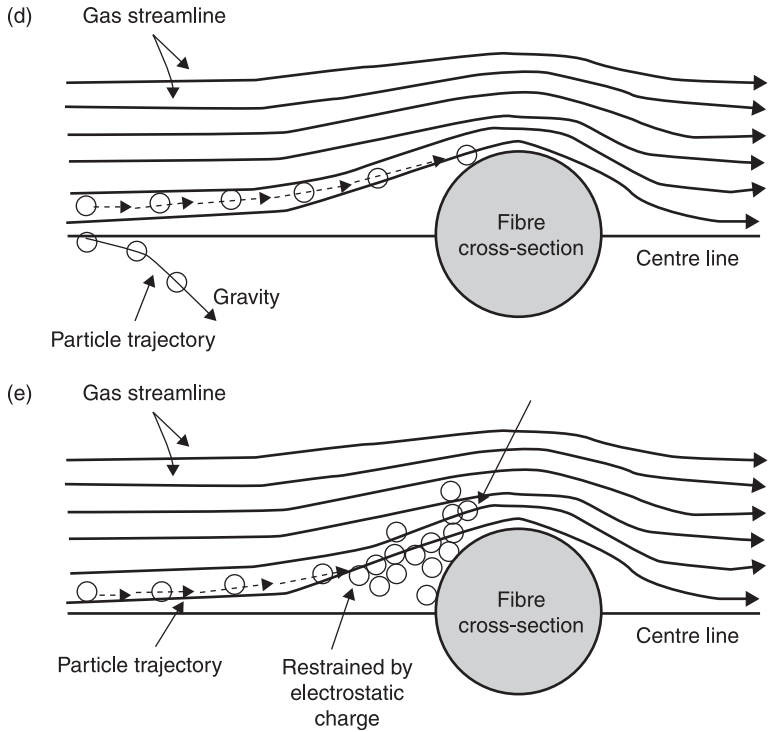
7.3.1 Single fibre theory

Single fibre theory is mainly prevalent in the case of solid–gas filtration. Under particle capturing based on single fibre theory (Mukhopadhyay, 2010; Donaldson Company, Inc., 2013), capture of particles on a stationary cylindrical object (in this case a fibre of the fabric) follows one or combinations of the following mechanisms – diffusion, inertial impaction, direct interception, gravitational settling, and electrostatic attraction (Fig. 7.2). The diffusion phenomenon is significant when flow velocity is low, particles are smaller (collection by diffusion decreases as the particle diameter increases) and temperature is high. To illustrate, the removal efficiency of the HEPA media against a 0.027 micron viral particle is dominated by the diffusion filtration mechanism. Relatively larger size particles can exhibit inertial impaction and interception. In case of inertial impaction, a suspended particle in the fluid may not be able to move along with fluid if its momentum is high (for particles of larger size/higher mass); higher inertia may be sufficient to break away from air streamlines and impact the fibre. The interception



7.2 Single fibre theory. (a) Diffusion, (b) inertial impaction, (c) direct interception. (Reprinted from Mukhopadhyay (2010) with permission of Taylor & Francis, UK.)

(Continued)



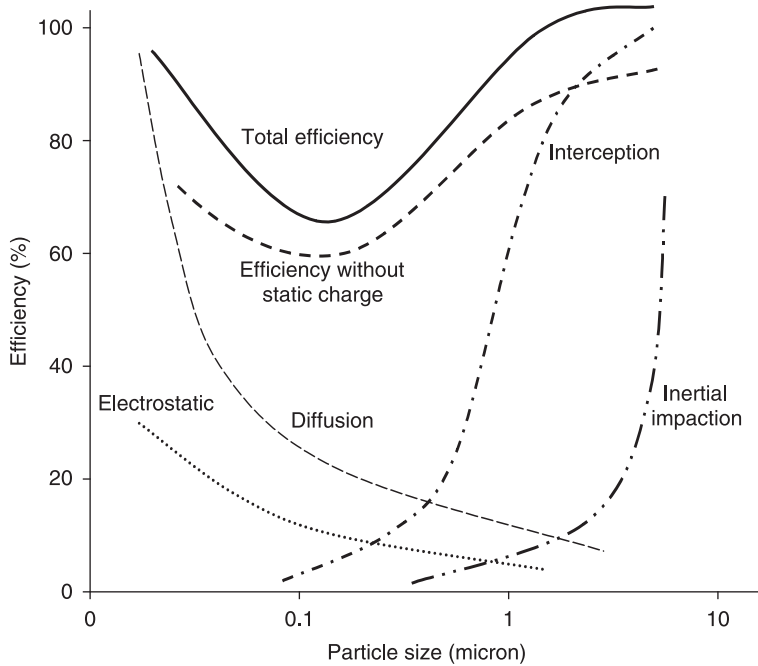
7.2 Continued. (d) Gravitational and (e) electrostatic attraction.

occurs when a particle does not have sufficient inertia to break away from the streamline but, however, comes close enough to the fibre so that natural forces will attach the particle to the fibre.

For heavier dust, the particle settles down at the bottom by the action of gravity. Although in this mechanism there is no interaction between fibre and particle, overall filtration efficiency will be affected by this mechanism. Particle separation by electrostatic attraction is based on an electric or electrostatic charge on the particles and/or fibre that will force the particle to divert from the streamline and attract to the fibre. Which collection mechanism will finally be the most effective depends on particle size and the mass, velocity, density and viscosity of the gas, electrostatic forces and the filter used (Fig. 7.3). Moreover, the different mechanisms are not independent but operate simultaneously.

7.3.2 Depth and surface filtration

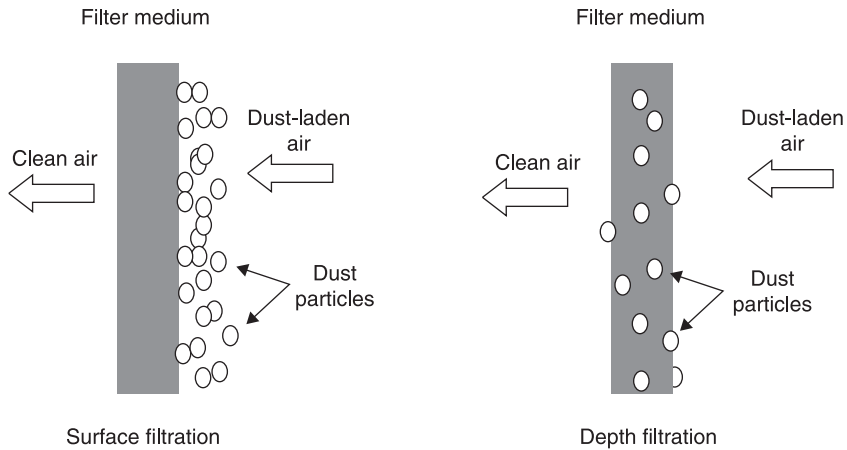
In the overall particle capturing, in addition to single fibre theory, size and shape of pores defined by the fibrous assembly play a vital role in particle filtration. Orientation of fibre can also influence the particle filtration. Broadly, particle



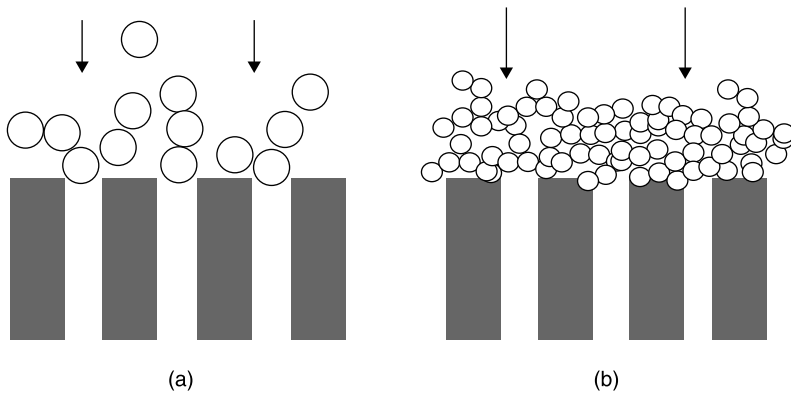
7.3 Single fibre efficiency as a function of the combination of several mechanisms.

capturing of filter media can be distinguished as surface and depth filtration (Fig. 7.4). By definition, surface filtration ideally involves the collection of all particles on the surface or upstream face of the medium, with none passing into its depth; thereby the efficiency of the medium is totally dependent on the pores at the surface being sufficiently small for the required purpose. It may be added that surface type media are not perfectly smooth on their surfaces nor are their pores perfectly uniform in shape and direction. The small particles, which are unable to be retained over the surface of the filter media, penetrate inside the fibrous assembly and are likely to get trapped due to tortuosity and the confined region in the pore structure. This phenomena can be distinguished as depth filtration.

In surface filtration, even the particles which are smaller than pores can be retained over the surface through formation of bridges over the pores. Therefore in surface filtration, two different mechanisms – sieving and bridging filtration (Fig. 7.5) do exist. Most cake formation occurs by a combination of blocking and bridging. In depth filtration, the mechanisms of filtration may result in the trapping of far smaller particles that might be expected from the size of the pores in the medium. In aerosol filtration, both depth straining and depth retaining are common (Fig. 7.6). However, it is practically difficult to realize total depth/surface filtration. For example, some depth filtration is inevitable for industrial surface filters and filtration can be



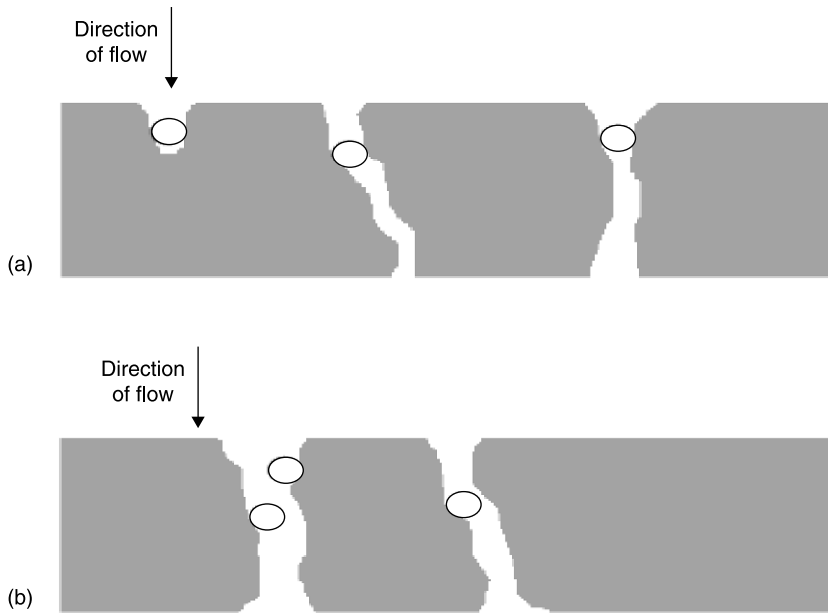
7.4 Surface and depth filtration. (Reprinted from Mukhopadhyay (2010) with permission of Taylor & Francis, UK.)



7.5 Mechanisms of surface filtration: (a) complete blocking filtration, (b) bridging filtration. (Reprinted from Mukhopadhyay (2010) with permission of Taylor & Francis, UK.)

conceived as a three-stage process. First occurs a period of depth filtration where most particles are collected within the fibrous medium. In a second phase, surface filtration becomes prominent, with the formation of a cake at the medium surface. The last period corresponds to the filtration by deposited cake (Mao *et al.*, 2008).

The general condition for surface and depth filtration, and comparison of depth and surface filtration is given in Table 7.1. It is important to note that depth filter media can be operated at lower pressure due to a relatively open structure. Surface-loading filters are used where high dust concentrations apply, i.e. $>5 \text{ mg/m}^3$.

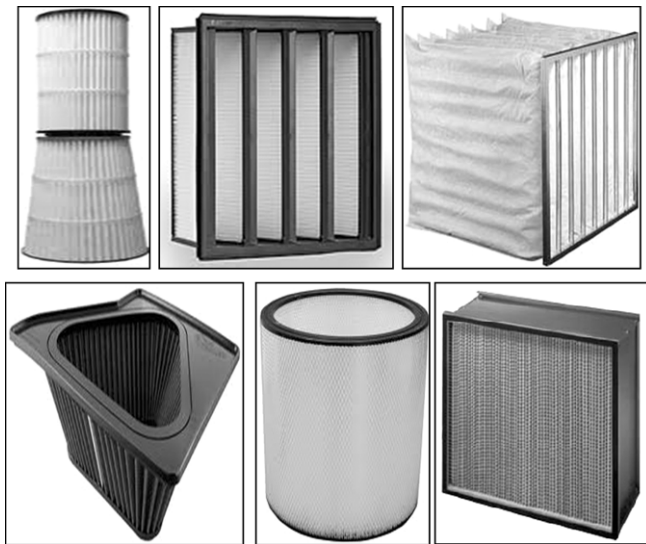


7.6 Depth filtration: (a) depth straining mechanism, (b) depth retaining mechanism. (Reprinted from Mukhopadhyay (2010) with permission of Taylor & Francis, UK.)

Table 7.1 Comparison of depth and surface filtration

Aspects of comparison	Depth filtration	Surface filtration
Field of application	HVAC and process air technology	Process air and de-dusting technology
Mechanism	Separation of particles within filter media; filter has to be replaced when clogged	Separation primarily by media surface; cleaning is necessary
Material characteristics	Voluminous nonwoven, porosity is in general high (90–99%); mass/unit area=50–800 g/m ² , type of fibre depending on application	Compacted nonwoven, porosity is low (45–80%); mass/unit area=80–1000 g/m ² , type of fibre depending on application
Typical parameters	Concentration < 5 mg/m ³ Air velocity = 0.2–4 m/s Pressure differential = 20–600 Pa Temperature = –20°C–60°C	Concentration > 5 mg/m ³ Air velocity = 0.005–0.05 m/s Pressure differential = 1000–3000 Pa Temperature = 20°C–250°C
Filter media	Filter mats, rigid filters, pocket filters, filter cartridge, EPA/HEPA/ULPA filter	Filter bags, filter cartridges, filter plates, filter candle

However, this is a typical guideline which may change according to the situation. In general, surface filters can be backwashed and cleaned more easily, while depth-type filters normally have to be disposed of when clogged. Therefore, depth filters are usually referred to as single-use replaceable filters; whereas surface filters work on the mode of regeneration. However, surface filters are also replaced after their lifetime. Typical examples of surface filters are bags, pleated cartridges and pleated plates. For high dust density, surface filtration is the only option as the filter can be effectively cleaned intermittently for regeneration purposes. Otherwise, under the depth filtration situation, filter media would have clogged very rapidly and cleaning could be very difficult for depth-filtered particles. In case of depth filtration, the medium has a significant amount of thickness providing depth in filtering. The mechanism of filtering then becomes much more complex. The path through the filter is much longer and random, providing greater possibility for both direct interception and dirt retention. Retention efficiency is achieved by means of a series of low efficiency particle capture. In general, large particles will tend to be trapped in the surface layers, with the finer particles trapped by succeeding layers. If necessary, the structure of the filter can be density graded. This has a particular advantage where the particle size of the contaminant is widely distributed; less so if they are of more or less uniform size where a surface filter may be equally effective. Examples of depth and surface filters are given in Figs. 7.7 and 7.8.



7.7 Depth-loading filters (from left to right): top row – turbo machinery, HVAC systems, healthcare facilities; bottom row – automobiles, respiratory protection, cleanroom.

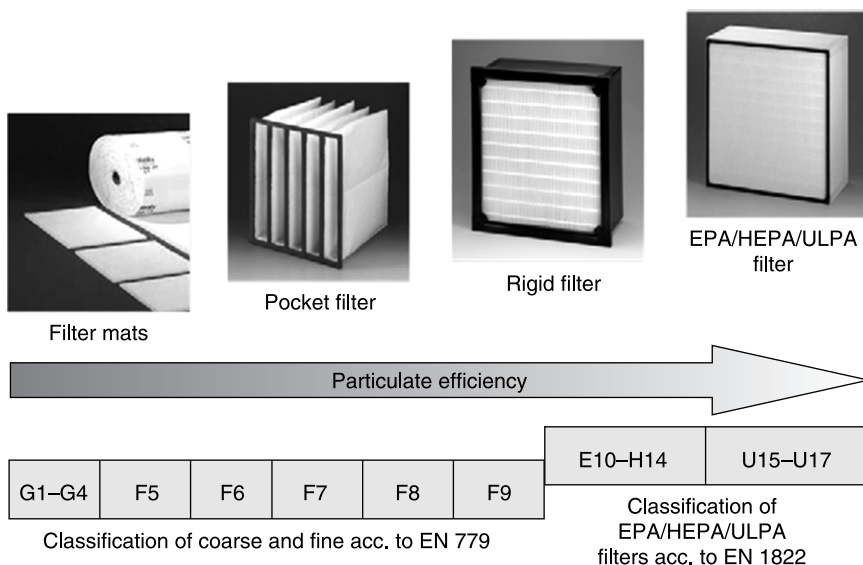


7.8 Surface-loading filters (from left to right): top row – welding applications, heavy duty oil filters, pharmaceutical industry; bottom row – use in compressors, industrial bag filters.

Typical areas of application of depth-loading filters are building ventilation (HVAC), air handling in cleanrooms, process intake air in the chemical, pharmaceutical or food and beverage industries, air purification in paint booths, air intake filtration of gas turbines engine air intake filtration, breath protection masks or filters for office devices (i.e. laser printers, document shredders). Depth filters are normally made of randomly oriented fibres with high porosity and are used at dust concentration $<0.2\text{mg/m}^3$. One of the major characteristics of depth-loading nonwoven filter media is its low density and high porosity, which provide the space for dust holding. Various layers or blends of different nonwovens types can be combined to design, for example, progressively structured filter media for a well-balanced performance according to the specific application of both filtration efficiency and dust holding capacity. In many filter applications, the homogenous storage of solid and liquid aerosols allows for either an enhanced life time or for a reduction of the dimension in comparison with paper-based filter elements. The media are disposed of once limiting pressure drop is reached at the end of media life.

Cleanable surface filters like cartridge filters are used for high dust concentrations (>0.5 to 1 mg/m^3). The cartridge surface is designed to build a dust-cake and prevent small particles from entering into the filter media. The advantage of surface filtration is that at the time a preset differential pressure is reached, the filter cartridge is cleaned by a reverse air jet. In the range between depth and surface filtration (0.2 to 0.5 mg/m^3), the choice of a filter system should be based on local and machine-specific parameters. Depth filter cartridges demonstrate a considerable reduced pressure loss and at the same time much higher separation efficiency when compared with pulse filter cartridges (Sauer-Kunze and Grochowski, 2011). There are different gradation of depth filter media available, as illustrated in Fig. 7.9. In almost all applications of depth-loading filters, there is a trend to higher (mechanical) particle removal efficiencies. The shortage of primary energy resources and the imperative to reduce CO_2 emissions lead to the request for energy efficient filters at the same time (Sievert, 2011).

For gas turbine applications, high efficiency material protects the sensitive blades of the turbine from dust particles. In the aforesaid case, both types of filter media (depth/surface) are prevalent. Based on high dust concentration in industrial cleaning environments or in gas turbines located in desert environments, a high efficiency depth filter is not the best solution – air passages in the filter will be blocked due to dust cutting off the air flow. Surface filtration



7.9 Classification of depth-loading filters according to EN 779 and EN 1822. Reprinted from Sievert (2011), FILTECH 2011 Conference Proceedings.

is desired for collecting the dust on the surface of the filter because it creates a homogeneous, linear rise in pressure drop (Wertz and Schneiders, 2009).

It is important to note that liquid filtration mechanism is different from gas filtration as viscosity of liquid is much higher than that of gas. Primarily, the liquid–solid separation is dominated by the following three mechanisms:

- Screening or straining: particles are retained by the medium only as and when they are confronted with an aperture which is smaller than the particles themselves.
- Depth filtration: in this mechanism the particles are captured through attachment to the fibres within the body of the filter medium.
- Cake filtration: once formed, the cake effectively becomes the filter medium with the fabric thereafter acting simply as a support. Cake filtration is most common in the case of surface filter media. In cases where it is difficult for the particles to form a naturally porous cake, the use of a special precoat or body feed may be employed to assist in this task.

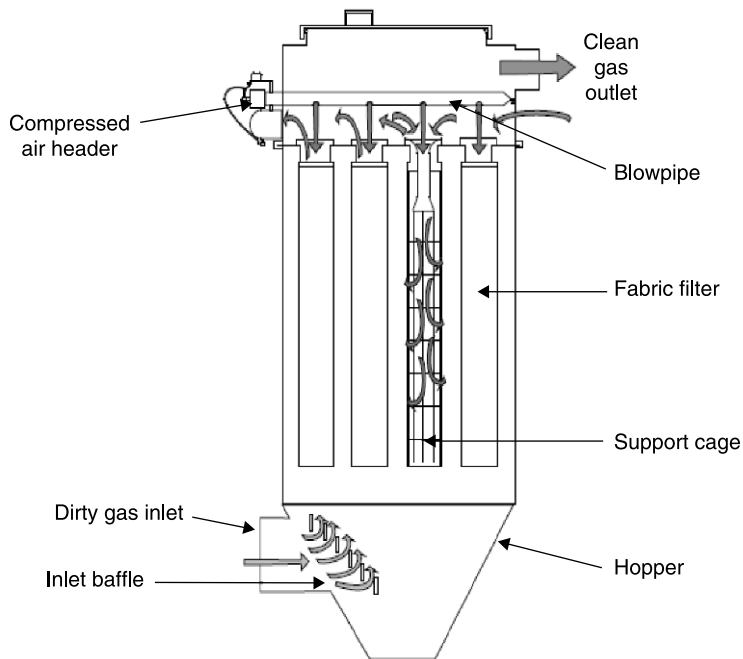
Notwithstanding the fact that the filter fabric is used to effect the maximum separation of particles from liquids, absolute clarity is not always necessary. In certain gravity- or vacuum-assisted screening operations the filter fabric is simply designed to capture particles greater than a specific size and in other filtration systems a measure of solids in filtrate can be tolerated before cake filtration takes over and the necessary clarity is achieved. Recirculation of the slurry may also be possible in some applications until the same condition prevails. From this it will be appreciated that in some cases the solids are the more valuable component in the slurry, whereas in others the process is concerned with clarification of the liquid, the solids thereafter being of little or no value.

7.3.3 Capture based on mode of filtration

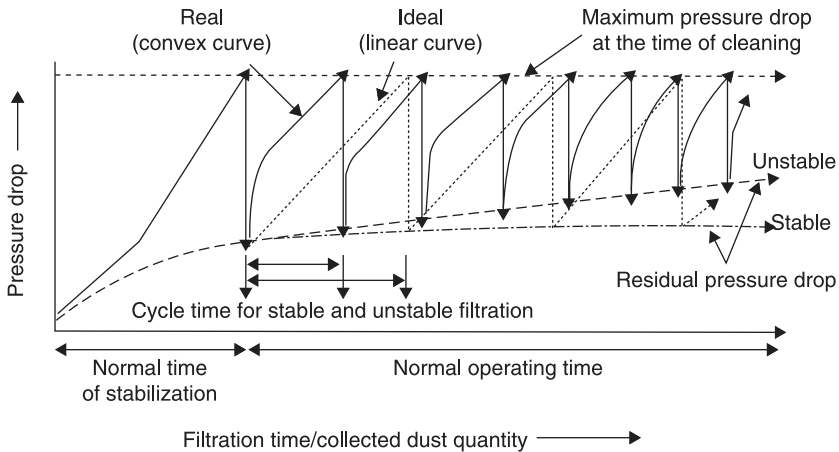
There are many ways to define the mode of filtration: cake vs. non-cake filtration, tangential vs. dead end filtration, filtration through electrostatic charging, etc. In case of cake filtration, the role of fabric becomes secondary once the cake is formed. In the industrial gas filtration process, the cleaning of fabric is performed either in reverse-jet or in pulse-jet air pressure. In the reverse-jet system, cake filtration is very prominent; whereas the pulse-jet filtration system is available in two different forms (cake filtration and non-cake filtration). It may be noted that the pulse-jet filtration process can be conceived as the most sustainable technology worldwide. During filtration, a positive effect is associated with greater filtration efficiency due to cake filtration, and on the other hand, a negative effect is associated with increased pressure drop. Since industrial filters encounter high-dust density (more than 250 g/Nm^3), pressure drop increases steadily with time. Therefore, filter bags must be periodically regenerated either on the basis of a preset time interval or based on specified pressure

differential, usually by pulse-jet cleaning. This operation involves injecting high-pressure back-pulse air (3–7 bar) into the filter bags for a very short time (50–150 ms). Back pulse dislodges dust cake from the filter surface and then the filtration process continues regularly, so called on-line cleaning. A typical set-up for a pulse jet filtration system is shown in Fig. 7.10.

In the process of filtration, the pressure drop pattern is quite different for steady and unsteady processes (Fig. 7.11). Due to clogging of the media, the pressure drop across the system increases gradually and even at steady state quite a small and imperceptible change takes place in the normal operational stage. The residual pressure drop (the pressure drop across the filter just after cleaning) exceeds the pressure drop of the virgin filter element because of a residual dust layer, the occurrence of patchy cleaning, and/or particles which have penetrated the filter medium and have not been removed by the cleaning action. This residual pressure drop and henceforth the total system pressure drop will continue to increase from cycle to cycle. In normal cases, it will reach a relative stable value after a so-called ‘conditioning’ period. It can also be seen from Fig. 7.11 that a partially concave shape of the pressure drop curve results during the first conditioning phase. This indicates particle separation on the inside of the filter (depth filtration) or, in the



7.10 A typical set-up of a pulse jet fabric filtration system. (Reprinted from Choudhary, and Mukhopadhyay (2012) with permission of Elsevier.)



7.11 Fabric filter behaviour in relation to pressure drop vs. time.
(Reprinted with permission from Mukhopadhyay (2010) with
permission of Taylor & Francis, UK.)

case of larger dust surface weights, a compression of the dust cake. However, a convex curve progression shows after just a few cleaning processes (cleaning cycles), which is determined by the structure of the cleaned-off filter surface. With only partial removal of the filter cake (patchy cleaning) or the formation of fissures, this effect may be very prominent and leads to a significant reduction of the filtration cycles (Gang, 2009). A convex curve is also apparent in the case of so-called stable operation. In a steady state, dust penetration remains constant and pressure drop also tends to be constant. For the steady state, the highest pressure drop is reached after a long operating time after which bags must be replaced. The rate of increase in residual pressure drop during the filtration cycle is very important since it determines the lifetime of the filter bag. A medium is said to be blinded when cleaning fails to remove residual solids, which are adhering to it or embedded in it, so that its resistance to flow remains unacceptably high (Purchas and Sutherland, 2002).

In the case of liquid filtration, cake filtration is very common. However, unlike the liquid filtration process in which cakes are built in a two-phase system (solid and liquid phases), dust filter cakes are built sometimes in a three-phase system (solid, liquid, and gaseous phases). Dust cake buildup therefore introduces more influencing parameters. The tendency of dust cake compression depends on non-equilibrium pressure drop across the system and the forces arising from the cake material (interparticulate forces and stiffness of particles) resist compression. In dust filter cake, a slight change in adhesion forces between particles has much larger implication than the liquid filtration process (Brown and Wake, 1999).

In the case of liquid filtration, cake is formed in both pressure filtration and vacuum filtration situations:

- *Pressure filtration:* The solid-liquid suspension to-be-filtered is passed through a medium under pressure which allows the flow of the suspended fluid but retains the suspended particles to form a cake of the upstream side of the medium.
- *Vacuum filtration:* The solid-liquid suspension is filtered through a filter medium under vacuum, allowing the fluid to pass through and retain the solid particles.

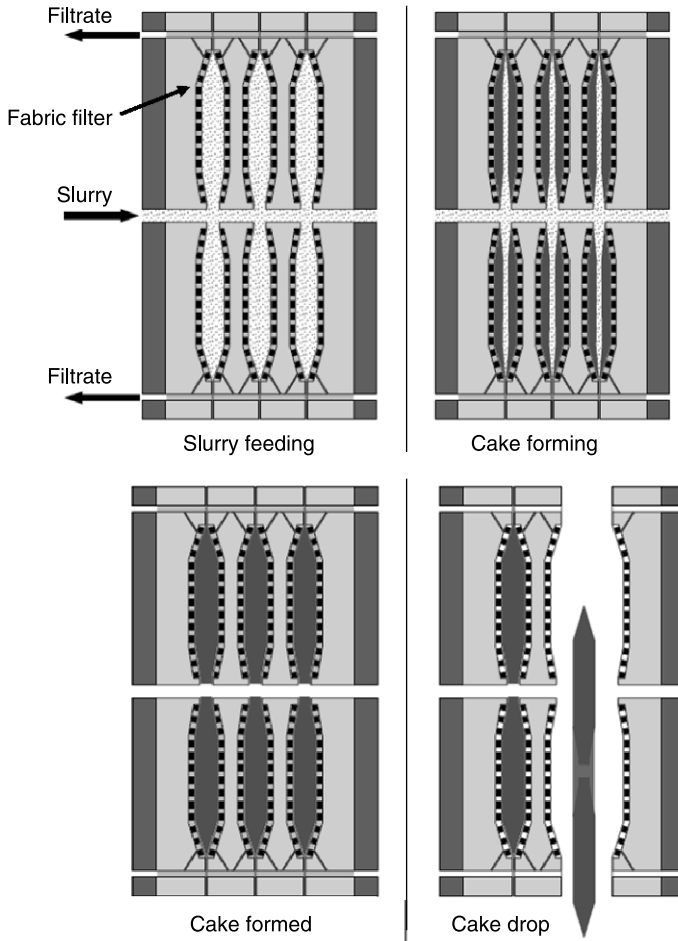
Figure 7.12 is a diagram of a typical plate and frame filter press. A filter fabric is inserted between each plate and frame. The inlet flow is into the frames, through the fabric, and through the foraminous fabric support structure of the plate. The filtrate is discharged from the plate. The cake builds up on the filter fabric until the filter cycle is terminated. When the press is opened, the cake is then discharged to some sort of collection device such as a conveyor or collection bin. Filter fabrics can be woven cloth, nonwoven fabrics such as needlefelt or spunbond, or industrial filter papers. Filter sheets are used when the effect of depth filtration is desired (Hutten, 2007).

It may be added that leakage from the joints is a common problem with the filter press, because the material forming the sealing gasket is a part of the filter medium, and therefore intrinsically porous – a problem that can be solved by using filter media that have been coated with elastomeric materials around the required sealing areas (Sutherland, 2008a).

In general, there are several ways of limiting cake growth in liquid filtration, and these areas are classified into five groups as follows (Svarovsky, 2000):

- Removal of cake by mass forces (gravity or centrifugal), or by eletro-phoretic forces tangential to or away from the filter medium.
- Mechanical removal of cake by brushes, liquid jets or scrapers.
- Dislodging of the cake by intermittent reverse flow.
- Prevention of cake deposition by vibration.
- Cross-flow filtration by moving the slurry tangentially to the filter medium so that the cake is continuously sheared off.

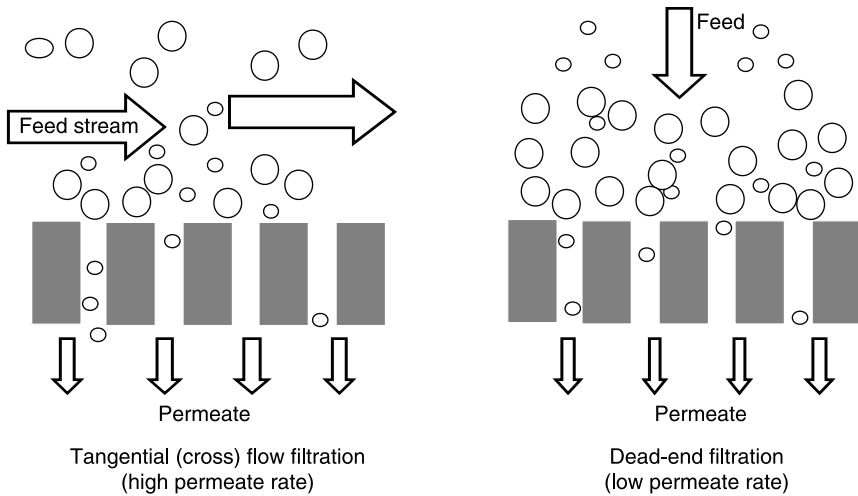
The extent of commercial exploitation of the above listed principles in the available equipment varies, but cross-flow filtration (Fig. 7.13) is certainly the one exploited most of all. The main benefit of cross-flow filtration is that it uses a membrane with an absolute pore size to clarify liquid without the need for media to act as a sieve. Cross-flow filtration can be classed as one of a number of thin layer filter systems. It is one of the three main practical filtration processes (the others being cake filtration and depth filtration, with surface straining being a less-used fourth process). The dynamic cross-flow filters address the problem of reduction of flow through the filter medium (filtrate flux), which is caused either



7.12 Filter press with conventional plates. (Reprinted from Sparks (2012) with permission of Elsevier.)

by fouling of the membrane surface and consequent blockage of the pores in the membrane, or by the increase in concentration of the particles or large molecules as they approach the membrane, but are not being allowed through it. The fouling and increased concentration will both restrict passage of the liquid to and through the membrane. The dynamic systems reduce the impact of fouling or concentration polarization by agitating the zone close to the membrane surface in some way so as to create additional shear in it (Sutherland, 2008a).

Cross-flow filtration can be described in general terms as a multi-pass technique with which difficult to filter liquids can be clarified and cell, proteins, enzymes



7.13 Tangential and dead-end filtration.

and viruses can be concentrated, cleaned or separated. Cross-flow filtration differs from normal pressure filtration in that the liquid to be filtered is not pressed vertically against the filter surface, but is pumped through a thin channel between a pair of filters. Some of the liquid will pass through the filters, but the major part will flow out of the thin channel, back into the retentive container, to be recycled through the system.

7.4 Adsorption

Nonwoven filter media containing adsorbents are used for adsorption of contaminants both from air and water. In both situations, they compete with granular or pellet adsorbents used in bed form. Adsorbent media are used in a number of applications including filters for odour and irritant vapour control in automobile cabins, residences, commercial HVAC (heat, ventilation, air conditioning) systems, and workplace environments. Adsorbent media are also used for control of VOC emissions in industrial locations that otherwise would source these contaminants to the environment. They are very important in the protective clothing, face masks, and respirators used to protect military personnel and civilians that may be exposed to the toxic and poisonous gases used in warfare and terror incidents. Middlebrooks (2004) lists the following mechanisms of adsorption:

- *Physical adsorption:* In the physical attraction, the particle is bound to the surface by weak Van der Waals forces; similar in concept to the condensation of gases. It is a reversible process.

- *Chemical adsorption*: A molecular species is attracted to a surface and reacts with that surface or something on that surface to form a chemical bond which holds it in place. Chemical adsorption is irreversible at constant conditions. Often the surface is impregnated with a chemical that promotes a desired reaction to remove specific contaminants.
- *Catalysis*: A molecular species is attracted to the surface which encourages a chemical reaction. The reaction product moves away leaving the surface unchanged. Typically, the reaction is considered irreversible.

One of the most prominent applications of adsorption principle is in the composite wherein a carbon layer is sandwiched between two nonwoven layers for removal of odour. The life of an adsorptive filter depends on the surface area and number of binding sites available. Once all the binding sites are exhausted, particles will pass right through the filter. Adsorptive filters do not exhibit any significant increase in pressure drop with removal of particles.

7.5 Absorption

Absorption involves the taking of molecules of one substance directly into another substance. The process may either be physical or chemical. Physical absorption involves such factors as solubility and vapour-pressure relationships. Chemical absorption involves chemical reactions between the absorbed substance and the absorbing medium. Absorption is contrasted with adsorption in which the molecules adhere only to the surface of the second substance.

7.6 Coalescing

Coalescence is a process by which a filter medium can remove immiscible liquid particles from a liquid or gas stream. The fluid can either be gas or liquid. This includes dispersed hydrocarbons from water, oil mists from air, moisture and vapour from air, and moisture from aviation fuel. The phenomenon is particulate filtration, in that it requires a matrix of fine fibres to trap the liquid particles and hold them on the fibres. An additional effect is provided for the transport of the entrapped liquid particles so that they can be removed from the media as a separate stream, either by flotation or by a gravity settling mechanism.

Gas phase separations are used to separate moisture and/or oil mists from contaminated air streams. There are two different modes of gas phase separations (Hutten, 2007).

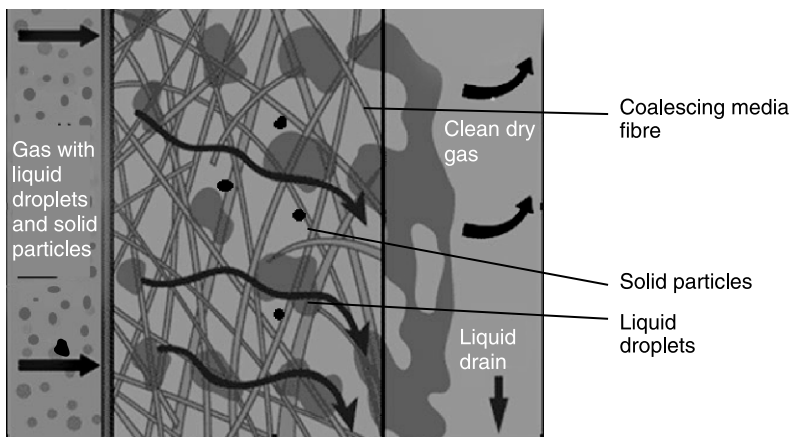
- 1 Separation of moisture from moisture laden air streams (demisters).
- 2 Separation of oil mists from air streams (compressed air operations, crank case ventilation, lubricated machining, and cutting processes, etc).

In the case of liquid phase separations, two different modes of separation can be identified (Hutten, 2007):

- 1 Separation of liquid moisture particles from organic streams (moisture removal from fuel pipeline streams, diesel fuel filtration in engine operated vehicles).
- 2 Separation of liquid organic particles from water streams (environmental clean-up of oily water waste streams, purification of water for drinking water and high purity applications in industry, removal of unwanted oil in water-based coolants used for metal working operations).

A large scale use of coalescing media is for industrial mist eliminators (demisters). The medium is often a bed or thick mat of glass fibre. Gas-liquid separation is used to remove oil and particles from compressed air streams. The coalescing filter element uses glass media with fine fibre diameter distribution. This reduces the amount of oil penetrating the filter material. Air velocity through the medium must also be low enough to ensure proper filtration (Hutten, 2007). Generally, the coalescing theory involves interception of liquid particles either by direct interception, by inertial impaction or by Brownian movement (diffusion). Once collected on the fibres, the droplets have to grow into large drops of sufficient size to be removed from the fibre surface, either by the friction and viscous forces of the fluid flowing through the medium, or by gravity forces, or both (Hutten, 2007). Figure 7.14 shows removal of mist (liquid droplets) through coalescing media. The drops so removed from the fibres either separate by settling to the bottom of the medium or separate in a separating chamber downstream of the media.

There is a concern whether the fibres should be wettable (hydrophilic in case of water mists) or non-wettable (hydrophobic for water mists). If the wettability of



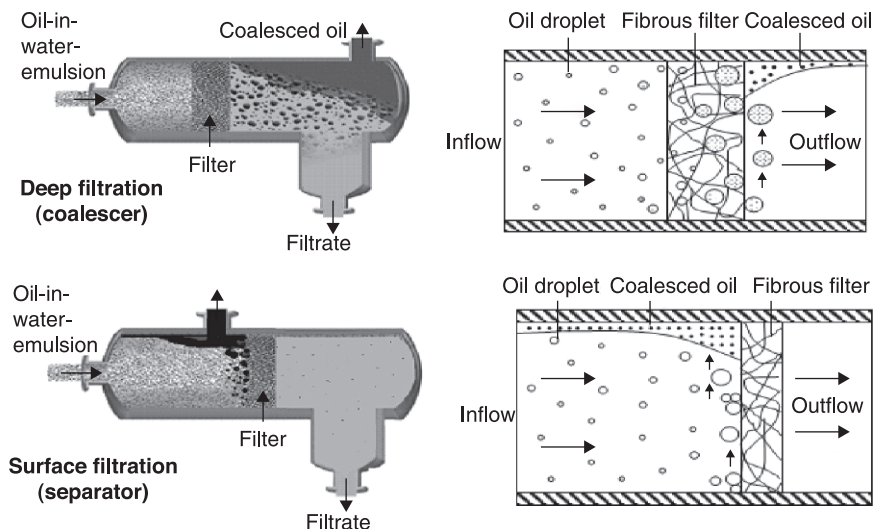
7.14 Removal of mist (liquid droplets) through coalescing media.

the fibres is high, liquid droplets will form film-wise collections on the fibres. In an extreme case, the medium will become waterlogged resulting in high pressure drop, medium plugging, re-entrainment, and low separation efficiency. On the other hand, if the fibres are not wettable, the collection will be drop wise. If the surface energy is too low to hold the droplets to the fibre surface, they will release and re-entrain into the fluid stream (Hutten, 2007).

In recent years, water in oil emulsion separation has received greater attention. In many applications, dispersions of water drop sizes of less than 100 μm diameter are very difficult to separate. The coalescence filter is economical and effective for separation of secondary dispersions (Shin and Chase, 2004). There are two very important and popular mechanisms to separate the liquid–liquid emulsions by means of porous media (Bansal *et al.*, 2011a):

1. *Coalescence by means of depth filter*: In this case, when the emulsion passes through the porous fibrous medium, the dispersed droplets adhere with the fibres of the filter medium. These attached droplets further coalesce with one another within the filter. Depending on emulsion inflow velocity and filter properties, these coalesced droplets leave the filter after attaining a certain size and are big enough to be separated by any mechanical or physical means.
2. *Separation by means of surface filter*: In this case, the emulsion passes through the porous fibrous medium of very small pore size and defined surface geometry (especially membranes). Therefore, the dispersed droplets are being retained at the filter surface and coalesce with one another there. Depending on emulsion inflow velocity and adhesive forces of the dispersed phase with the filter surface, these coalesced droplets separate themselves from the filter surface either by gravitational or buoyancy forces.

Figure 7.15 shows deep filtration (coalescer) and surface filtration (separator) (Bansal *et al.*, 2011b). In both the cases, a steady state is reached, in which oil accumulation and drainage rates balance out. Filters operate in such a steady state for almost their entire life. Multi-layer filters are typically used in industry, and their performance depends largely on the nature of the filter (oleophobic/oleophilic) (Kampa *et al.*, 2011). Coalescence filter performance depends on flow rate of feed, drop sizes in the feed, and filter bed properties (pore size, surface wettability and porosity of the fibre filters). Fibrous filter media provide the advantage of high filtration efficiency at an economical energy cost. At a similar surface energy, the droplet capture efficiency diminishes with increasing pore size and decreasing surface roughness of the filter. The coalescer should preferably be wetted by the dispersed phase to stimulate the droplet capture and coalescence. The emulsion separation efficiency also depends on influent droplet size, drop residing time in the filter (which is a function of filter thickness, inflow velocity and drop wettability at filter), fibre fineness and porosity of the filter (Bansal *et al.*, 2011a).

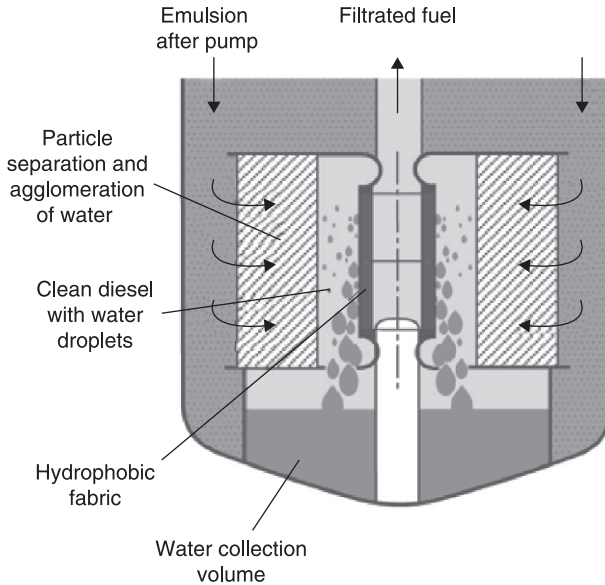


7.15 Deep filtration (coalescer) and surface filtration (separator) (Bansal *et al.*, 2011b).

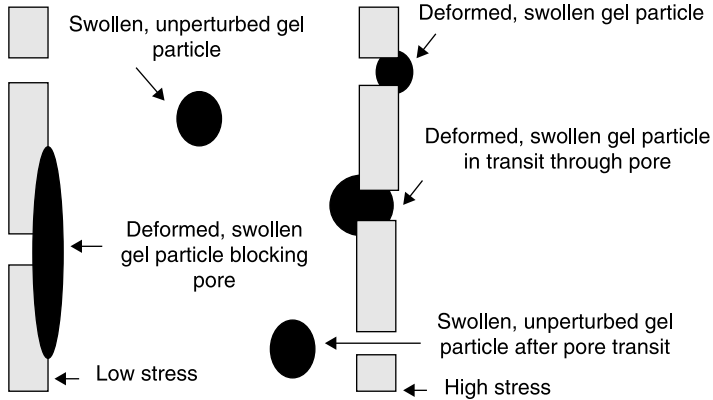
For newer generations with even higher requirements, a filter manufacturer (MAHLE, 2013) has opted for two separate filter stages during water separation (Fig. 7.16). In a diesel fuel filter, the first filter phase consists of a cellulose filter medium with an untreated melt-blown contact surface for increasing the contaminant absorption capacity. This melt-blown contact surface optimally causes many small droplets to coalesce into larger ones. The particulate filter in the shape of a pleated star even agglomerates the finest water droplets. The second filter phase consists of a water separator, whose hydrophobic fabric with a mesh width of $25\mu\text{m}$ divides the barely stable emulsion, thus separating the water. As this occurs on the clean side of the filter, it is referred to as clean-side water separation.

7.7 Media for gel removal

Removal of gel is an essential part of many chemical and pharmaceuticals processes. It is a complex problem as the gel deforms under stress. With low pressure (stress), gels can flatten and cause blockage of filter surfaces. This reduces filter life. At higher pressure, gels can begin to penetrate into the depth of the filter and can elongate and pass through the filter media. Figure 7.17 illustrates gel deformation with low and high stress. Depth cartridge filters are more effective in removing gels than surface filters, such as bags. Depth filters provide a thick, tortuous path increasing the likelihood of capture. Gels could work through if the medium deforms as the pressure increases. Therefore, rigid, resin bonded filters



7.16 MAHLE diesel fuel filters (MAHLE, 2013).



7.17 Filter/gel behaviour under stress. (Adapted from Schmitz (1998).)

are preferred because they provide a stable fibre matrix. To increase the efficiency of gel removal, lower than normal flow rates are recommended. This decreases the pressure drop through the media and increases their efficiency (Schmitz, 1998).

It is important to note that filtration is a key part of the paint manufacturing process, wherein it is necessary to remove transient dirt, agglomerated pigments,

gels ('fish eyes') and other contaminants which contribute to poor surface appearance properties. Use of finer rated filters is helpful to provide better gel removal capability. No matter what type of filter is used, it must have certain key properties (Schmitz, 1998):

- it must be silicone free;
- it must remove gels effectively;
- it should minimize the circulation time required before packaging;
- it should be capable of filtering a complete batch;
- it should not collapse or allow filter material to migrate into the paint, and
- it should not increase in efficiency during the filtration cycle so as to begin removing pigment particles.

7.8 Mechanisms of filtration: electro-filtration

In electro-filtration, dielectric materials are used as electrets. These materials exhibit an external electric field in the absence of an applied field. When used in air filtration applications, there are several benefits of imparting an electret treatment to filter media with a robust underlying mechanical structure. First, a well designed electret-treated media can provide high initial and high sustained efficiency over the filter lifecycle. Filters that are designed to provide only mechanical efficiency begin their life at their lowest particle removal efficiency and rely on the building of the dust cake in the filter to increase efficiency. Second, the electrostatic effects created in electret-charged media are particularly useful in increasing the capture efficiency for submicron particles. This is because, while submicron particles are much smaller than the void spaces present in most commercial electret media, the electrostatic forces within the media structure allow those particles to be removed with high efficiency. Third, filtration efficiency of electret-treated media is unaffected by relative humidity and by long-term warehousing at high temperatures (54.5 °C/130 °F). Therefore, the electret effect is very resistant to age-related decay under conditions relevant to its storage and use. Fourth, electro-mechanical media deliver lower airflow resistance in the same filter construction as mechanical filter media. This translates into a reduction in energy consumption and costs. The electret-treated filter media that have depth-loading media with a gradient density structure in which the fibres are more loosely packed on the upstream side and more densely packed on the downstream side is useful as an HVAC filter (Fedel, 2012).

Films, fibres, and nonwoven web structures are among the materials that can be formed into electrets. There are two distinct categories of electrets, viz. space charge electrets and dipolar electrets. Another way of classifying electret filter media is as follows: electrostatically spun fibres, fibrillated electret film, corona treated melt-blown fibres, and carded blends of triboelectric fibres (Hutten, 2007). It may be added that all colloidal and most biological materials have some surface charge. Glass, nylon and some cellulose materials have enough surface charge to

attract and bind the particles to the fibres. Nonwovens can be surface treated to produce or enhance the surface charge on the media. Charged cellulose media are good at reducing high particulate load from a fermentation process and colloidal material. Microfibre glass media are used as membrane pre-filters due to their high efficiency and long life but have low colloid removal. Meltblown polypropylene media have moderate efficiency and poor retention of colloids (Lydall Filtration and Separation, 2013). In the case of liquid filtration, the concept of electrokinetic filtration is prevalent wherein the medium is given a positive electronic charge that enables it to attract the mostly anionic particles in a polar fluid stream. It is therefore effective in biopharmaceutical filtration due to the inherent charge on biological material.

7.9 Separation by antimicrobial media

Antimicrobial filter media consist of an agent to protect the filter by inhibiting the growth of bacteria, fungi, and yeast (Hutten, 2007). In some cases they are also intended to prevent the migration of biological microorganisms into the filtrate or filtered product. The antimicrobial agent can be applied to a medium as a finishing step or it can be incorporated into the fibre. Antimicrobial activity in a filter medium serves the following basic purposes:

- It protects the filter and filter medium from biological decay and resulting failure.
- It can rapidly inactivate captured microorganisms and prevent further microbial growth inside the filter.
- It prevents the passage of biological organisms to the downstream environment of the filter.

7.10 Extraction

Extraction is a phenomenon that is not built into a filter medium, but rather the medium serves as a structural support for the extraction process. Teabag and tea filters act in a similar manner.

7.11 Key requirements for filtration media

For effective filtration, the filter medium has to be designed/selected based on the process gas/liquid requirements/application. In this regard, there could be wide variation in the type of fibres and fabric structure based on applications. There are various requirements of media characteristics based on the following:

- filtration-specific requirements;
- machine oriented requirements;
- application oriented requirements.

7.11.1 Filtration-specific requirements

Different performance indexes are used for gas filtration (filtration efficiency/emission, dust holding capacity, pressure differential, cake removal, etc.) and liquid filtration (filtrate clarity, filtrate throughput, low cake moisture content, resistance to blinding, good cake release, resistance to abrasive forces, etc.). However, the basic filtration requirements are similar for gas and liquid filtration systems. For example, a higher filtrate clarity signifies a higher level of filtration efficiency. Normally for higher clarity, filtrate throughput becomes lower in liquid filtration; whereas for gas filtration, higher filtration efficiency is often linked with higher pressure differential across the media.

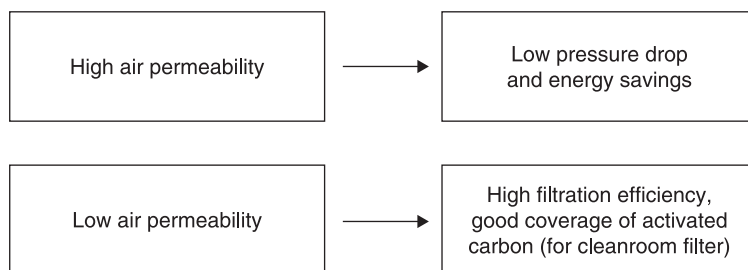
Improving the filtration efficiency of a fabric filter (through structural modification/higher material consolidation) leads to a higher pressure drop for the new state filter. The role of pressure drop is very important during the filtration process. It is important to note that higher pressure drop during filtration also indicates higher operational cost. In the industrial bag filtration process, the energy used by the downstream exhaust fan accounts for 60–80% of the baghouse total operation costs and, therefore, a stable and low range of differential pressure (ΔP) is of utmost importance in the highly developed filter unit. While designing the filter fabric, it is often very difficult to meet the two contradictory requirements – highest level of filtration efficiency and minimum level of pressure loss. In general, for aerosol filtration there is a need for composing filtration efficiency and pressure drop as illustrated in Fig. 7.18.

Through the use of composite material, it is possible to achieve higher filtration efficiency at lower pressure drop. In cleanroom filters, the term ‘Quality Factor’ is often used to judge filtration performance of the media (Hutten, 2007; Purchas and Sutherland, 2002) and is determined using the following equation.

$$QF = -\ln(1 - E)/\Delta P \quad [7.1]$$

E is the particle collection efficiency and is calculated by:

$$E = (C_u - C_d)/C_u \times 100 \quad [7.2]$$



7.18 Contrasting aspect for satisfying higher filtration efficiency and lower pressure drop for filter media.

where C_u and C_d are related to the particle concentration (number/mass) measured upstream and downstream of the filter cartridge, respectively. In fractional efficiency, the C_u and C_d are related to the single particle size. It is important to note that filtration efficiency may provide a gross picture about the performance of a filter since efficiency is not same for all size particles. Therefore, a rating system, beta (β) ratio (Svarovsky, 2000), is introduced with the object of giving both the filter manufacturer and the user an accurate and representative comparison amongst filter media (Svarovsky, 2000). It is determined by a multi-pass test which establishes the ratio of the number of upstream particles larger than a specific size to the number of downstream particles larger than a specified size, i.e.

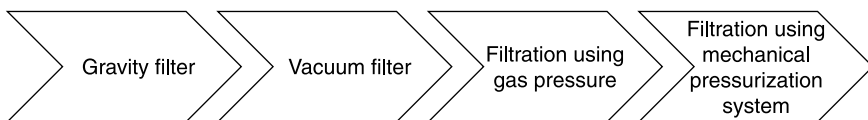
$$\beta_x = \frac{N_u}{N_d}$$

where β_x is the β rating (or β ratio) for contaminants larger than x μm , N_u is the number of particles larger than x μm per unit of volume upstream and N_d is the number of particles larger than x μm per unit of volume downstream.

It may be added that the expression (QF) may not be widely valid. Sometimes for meeting stringent particulate emission, higher filtration efficiency is chosen even at the cost of higher pressure drop. An ideal filter should remove all contaminants regardless of size. It is important to note that in case of liquid filtration similar compromise is needed in terms of filtration clarity and throughput. In many situations composite nonwoven can provide adequate solution of the aforesaid aspect. Further, composite material can greatly satisfy machine and application oriented requirements.

7.11.2 Machine oriented requirements

Machine oriented requirements involve properties of filter material encompassing mainly strength, rigidity, resistance to creep and stretch, stability of edges, resistance to flex fatigue, stability to vibration, resistance to abrasive forces, ability to be fabricated, and a sealing/gasketing function. In liquid filtration, stress operated on the fabric is much larger than in the gas filtration process, and pressure varies depending on the system design and filtration requirement. For example, cleaning by means of reverse-jet on industrial bag filter is milder than a pulse-jet cleaning system. In a liquid filtration system the stress level is progressively higher from gravity filter to filtration by the pressurization system as indicated in Fig. 7.19.



7.19 Progressively higher stress level among liquid filtration systems.

7.11.3 Application oriented requirements

Application oriented requirements involves chemical stability, thermal stability, biological stability, dynamic stability, absorptive characteristics, adsorptive characteristics, wettability, health and safety aspects, electrostatic characteristics, disposability, and suitability for reuse. The choice of fibre material primarily depends on application oriented requirements. For example, fibre material in the case of industrial filter bag is based on maximum operating temperature, physical (dry heat, moist heat, abrasion, flexing) resistance, and chemical (hydrolysis, acid, alkalis, organizing agents, organic solvent) resistance. Further, several nonwovens are available with a conductive surface to fulfill the requirements arising from explosive hazardous applications (Sievert, 2011). Table 7.2 shows the application of fibre material used in industrial filter bags.

Table 7.2 Fibre material used in industrial filter bags

Fibre material	Application examples
Cotton	Cement industry, pharmaceuticals, food industry, fibre board plant, wood plant (at present use is limited)
Wool	Cement industry, food industry, fibre board plant, wood plant (at present use is limited)
Polyester	Mining, cement, iron and steel, wood, ceramics, plastics and pigment
Nylon (polyamide)	Pharmaceuticals, food industry, fibre board plant, wood plant (at present use is limited)
Polyacrylic	Asphalt, spray dryer, lime, plastics
Polypropylene	Food industry (milk powder, sugar flour), detergents
Nomex	Asphalt, iron, cement/lime kilns, metal alloy smelting, ceramics
Teflon (PTFE)	Carbon black, coal fired boilers, incineration, cupola, ferro/silica alloy furnace
Glass	Coal fired boilers (FBC, PC), electro smelting oven, cement/lime kilns, industrial and small municipal boiler applications, furnace for metal melting, incinerators
Ryton (polyphenylene sulphide)	Coal fired boilers (FBC, PC), electro smelting oven, furnace for metal melting, biomass, waste incinerator
Polyimide P84	Cement kiln, metallurgy, biomass, waste incinerator, coal fired boilers
Ceramic Nextel 312	PFBC, IGCC and fuel cell technologies

FBC, fluidized bed combustion; PC, pulverized coal; PFBC, pressurized fluidized bed; IGCC integrated gasification combined-cycle; PTFE polytetrafluoroethylene.

7.12 Characteristics of nonwoven filters

Textile filter media have proved to be superior in many applications of gas and liquid filtration. In many cases the performance requirement can only be satisfied with textile filter media, among which the use of nonwovens is most prominent. In general, the nonwoven filter media can be grouped according to the following considerations:

- surface filters (cleanable) or depth filters (storage filters);
- the nature of the surrounding medium (dry and wet filtration);
- particle size to be filtered (e.g. micro-, ultra-filtration).

The first major distinction between the items listed above is whether the filter media or manufactured filters are single use, essentially storage filters, or whether they are cleanable and capable of regeneration by a backwash/reverse flow, shake or mechanical filter cake removal process. Synthetic fibre nonwovens have dominated the filtration industry since the 1970s because of five basic advantages (Scoble, 2011):

- performance in efficiency, pressure differential, durability and adaptability;
- high volume, low cost production processes producing lower cost media (compared to woven fabric);
- possibilities in achieving wide structural variability at ease (e.g., weight, permeability, surface characteristics, widths, and other basic characteristics);
- pleatability/moldability of material;
- availability (most serve multiple market segments).

In nonwoven fabric, filtration efficiency is quite high due to the role of constituent fibre (individual fibre acts as a filter element) and nature of fibre consolidation. Further, for similar application, total porosity of nonwoven filter media could be quite large as compared to woven fabric. For industrial filter bag, the porosity of surface filter media is between 70 and 80%, which is almost double that of woven fabric filter media (30–40%). This results in a lower pressure differential across nonwoven filter media. Further, special nonwoven structures can achieve three times more airflow than woven filters (Yang *et al.*, 2002). This implies a smaller size of filter unit and also lower fan energy consumption. In depth filtration application, tortuous and interconnected pores in nonwoven helps in better media performance in capturing solid particles.

A variety of nonwoven filter media can be produced with different manufacturing methods (e.g., needlepunching, spunbonding, meltblowing, spunlacing, etc.), laying techniques (e.g., wet lay, dry lay) and varying fibre type (e.g., glass fibre, polyester fibre), with their fineness ranging from the macro- to the nano-scale. Specifically, fibre diameter has a significant influence on the performance of the filter media. Nonwovens can feature characteristics such as chemical and water resistance, oil repellent, reduced flammability or fire blocking, electrical conductivity for usage in an explosive environment, preventing microbial growth,

being biodegradable and many more. This allows nonwovens to meet the increasing requirements from environmental legislation and from new safety standards. From the use of polymer fibres it is possible to heat weld or ultrasonically weld nonwovens allowing modern technologies to be used to manufacture filter elements such as pocket filters, cartridge filters and cassette type filters. The true engineering of the nonwoven fabrics gives them the chance to be incorporated in many types of filters, e.g. from coarse filter mats (filter class G1–G4) to high efficient HEPA filters (filter class H10–H14) (Sievert, 2011).

Although widely used in dust collection, needlefelts have found only limited use in liquid filtration because their thickness and density render them prone to blinding in many applications. However, they are found useful in some niche areas, e.g. filtration of metal ore concentrates such as copper on horizontal vacuum belt filters. These applications tend to be very aggressive on the filter fabric, and hence a suitably designed and finished needlefelt is often more cost effective than a considerably more expensive woven fabric. For such arduous applications, needlefelts are generally in the area density range $800\text{--}1000\text{ gm}^{-2}$. However, the uses of nonwovens in many liquid filtration applications are increasing in a steady manner. In general the growth of nonwovens over the last four decades is influenced by the following factors:

- the growth of a wide range of nonwoven processes;
- adaptation of nonwovens designed for other markets into filtration (e.g., spunbonded, spunlaced nonwovens);
- growth of pulse-jet collectors using needled felts vs shaker collectors using woven fabric;
- evolution of needling processes from scrim supported to self supported;
- expansion of pleated cartridges, pleated bags and filter elements into new filtration segments;
- application of membrane laminates effectively repurposed, less efficient nonwovens into high efficiency media (reverse osmosis, pleated cartridges, dust bags);
- environmental legislation forcing the use of more filtration equipment (1970, 1990, present day);
- development of micro-fibres and nano-fibres.

7.13 Types of nonwoven filter

7.13.1 Single-use replaceable filters

The largest use of nonwoven filter media is in single-use replaceable filter elements. Mostly, the filter material functions as a depth filter media. Three types of replaceable filter elements can be identified:

- panel, pocket, cassette and pleated cartridge filters for air filtration;

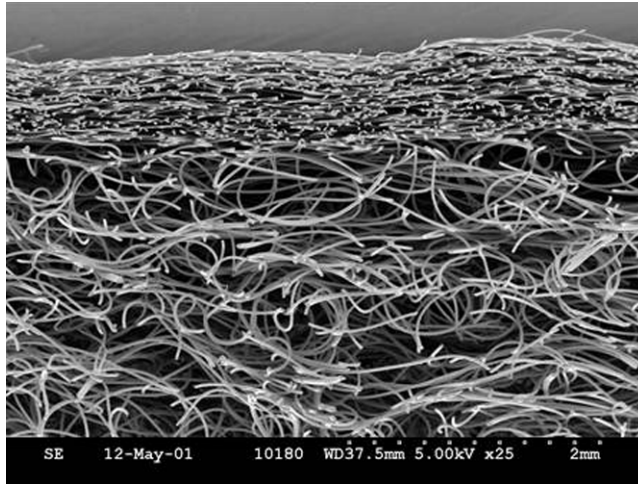
- bag filters for liquid filtration;
- cartridge filters for liquid filtration.

All these filter media are not regenerated during the process of filtration. It may be added that bag filters are in general designed for applications with a desired filtration rate from 1 to 1000 micron; whereas cartridge filters have a filtration rate from 0.1 up to 500 micron. However, in situation, a filter bag can work better than a filter cartridge. Nonwoven fabric with progressive density (PROGAF's) (Eaton, 2013) delivers high efficiency (>99.98%) through depth filtration, and long life with all the convenient features of a bag filter.

In comparison with other filtration technologies, filter media deliver lower operating costs while retaining the ease of change-out typical of a bag filter. Apart from the above, many other forms of filter are also used, such as a roll filter. Roll filters come in a variety of shapes and mechanisms (deep bed filters/pressure filtration systems). It may also be added that filter presses (mechanical pressurization systems) and belt filters (vacuum filters) account for a large proportion of the world's solid-liquid filtration activity, and have developed to become larger, more sophisticated and also more reliable. They are now found in applications ranging from small-scale, ultra clean medical laboratory applications to the largest, dustiest and heaviest applications of filtration. However, in these filters the use of nonwoven is restricted; but can have a potential future.

The disposable cartridge or element is one that is sufficiently inexpensive, so that any attempt to clean and reuse the cartridge would not be economically justified. Depth filter cartridges usually cannot be readily cleansed since the dirt is so well entrapped in the medium that cleansing would provide little benefit in restoring the cartridge for reuse. Eventually, even cleanable cartridges will have to be replaced. It is important to note that dirt-holding capacity is an important requirement for filter cartridges (Hutten, 2007). Ways to increase dirt holding capacity are shown in the following (Hutten, 2007).

- Increase the surface area of the medium: Pleating is the most popular way of increasing the surface area of a medium. It may be added that corrugation and, to a lesser degree, creping enhances the surface area of a filter medium.
- Use a prefilter: Prefilters would filter out the relatively coarse particles before the final filtration. There are filter designs where the prefilter medium and the final filter medium are contained within the same filter housing.
- Gradient density filter media: Gradient density media have a change in density as the flow passes from the upstream surface to the downstream surface. The change in density allows for a form of depth filtration so that larger particles are removed at the low density upstream surface and finer particles are



7.20 Cross-section of a gradient density filter medium. (Intrepid™ filter medium by courtesy of Kimberly-Clark Worldwide Inc.)

removed in higher density interior of the medium. Figure 7.20 is a photograph of a cross-section of a gradient density filter medium by Kimberly-Clark Worldwide Inc., marketed as Intrepid™ filter medium. It is a dual layer gradient density medium that is electrostatically charged. The medium contains two layers of polyolefin bicomponent fibres that are produced together by the spunbonding technique and thermally bonded in the process. The medium generally used is pleated air filtration application. This media construction, coupled with a proprietary electrostatic treating technology, allows filters made with Intrepid™ media to achieve high initial and sustainable filtration efficiencies. In addition this structure helps to reduce airflow resistance, enhance dust loading and prevent face loading of the filter. It is important to note that there are other ways of making gradient structure.

- Use bulkier and thicker media: The bulkiness of a filter medium is related to their dirt holding capacity. Bulkiness can be increased by increasing the weight of the filter medium or by increasing the pore structure or pore volume. Pore volume can be increased by using coarser fibres, crimped fibres, and higher modulus (stiffer) fibres. There are caveats in these approaches. Increasing bulk by increasing pore volume of the filter medium may increase the dirt holding capacity, however filtration efficiency may be compromised. Further, in a pleated medium cartridge, the additional bulk may restrict flow resulting in a loss of dirt holding capacity rather than the desired increase. Reducing the number of pleats in the cartridge reduces the surface area available for filtration and then what is gained by increased bulk is lost by reduced surface area. In addition to the above, a bulkier medium may have a snugger fit in the filter cartridge.

- Use of charged media: Use of electrets in the air filtration process is useful for greater dust holding. They are disposable and priced higher than fibreglass and pleated filters but less than washable/reusable filters. Their recommended replacement life is three months during seasons of normal use. In liquid filtration, molecules carrying a positive (cationic) charge are chemically bonded to the matrix components to form an interconnected, rigid filter sheet with positively charged electrokinetic capture sites. Since most contaminants found in fluid streams are negatively charged (anionic), they will be inherently attracted to the positive sites on the medium. The results in improved efficiency and dirt holding capacity. The Zeta Plus[®] media (composed of filter aids embedded in a cellulose fibre matrix) are used in a variety of industrial liquid filter applications, including pharmaceutical and bio-processing separations.

Panel, pocket and cassette filters

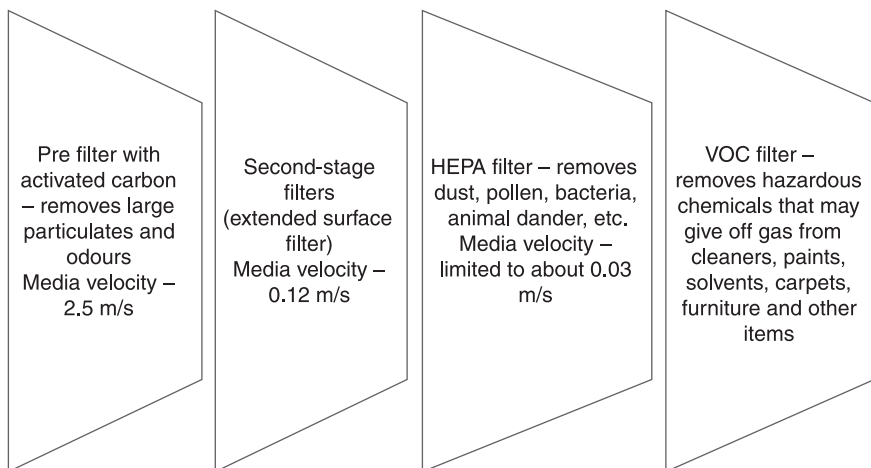
Air filters for cleanrooms are available in different forms and are named as pleated panel filters, pocket filters, extended surface v-style filters, cassette filters, pleated cartridge filters, etc. Square or rectangular panel filters are the most frequently used for air cleaning systems in the domestic residences and in the work place. Broadly, there are six main categories of in-duct air cleaning devices for residential air handling systems such as fibreglass filters, pleated filters, washable/reusable filters, electret filters, deep pleated filters and electronic air cleaners. Textile media are used in all cases except electronic air cleaners. For stricter requirement, HEPA/ULPA filters are used.

Cleanroom manufacturers pay strict attention to air particles, with most cleanroom design and manufacturing companies targeting the elimination of air particles 0.5 μm in size or larger, which has been generally the function of cleanroom air filters. However, some industries are now imposing even smaller air particle standards. Most indoor air pollution comes from the hazardous non-biological agents and biological agents. The cleanroom system must thus reduce the contamination entering with the air drawn into the room, and also remove that produced within the room to a suitable level to match the requirements of the processes being undertaken (Sutherland, 2008b). For applications in cartridge filters, extremely thin and stiff nonwovens are used. The thickness of these filter media varies between 0.1 and 5 mm and their basis weight is lower than for tube filters. They also have a paper-like appearance because they are mostly wetlaid and spunlaced. These filters are pleated and folded in a star form which helps to provide higher filter stiffness and higher filter surface area. This in turn works positively towards the pressure drop (lower pressure drop).

Filters designed for the treatment of air fall broadly into three categories (Sutherland, 2008a):

- Primary filters, designed to trap the majority of larger airborne dust particles of 5–10 μm in size, have high dust-holding capacity; these are usually of the dry panel type or roll filters, capable of working with relatively high airflow velocities.
- Second-stage filters, with finer media for trapping and retaining finer particles passed by the primary filter, such as particles of 5 μm diameter and smaller; these filters may be of the unit or panel, pocket or bag type, with extended depth of filtration; maximum air velocities are generally low, of the order of 0.12 m/s or less.
- Ultra-fine, or final stage filters, yielding very high efficiencies (99.95% or better) even with sub-micrometre particles; the chief types here being the HEPA and ULPA filters, employing a high density medium built up from synthetic spun fibres with a sub-micrometer diameter and made in the form of a closely pleated pack; air velocity in this case is limited to about 0.03 m/s.

HEPA filters and ULPA filters are designed to screen particles larger than 0.3 μm . HEPA filters are 99.99% efficient in removing particles 0.3 μm and larger. ULPA media exhibit a filtration efficiency of 99.999% or greater against 0.1–0.2 μm particles. ULPA filter media are usually wet laid and formed from glass microfibers of 0.2 μm diameter or less (Purchas and Sutherland, 2002). The final stage filter is therefore HEPA and ULPA filters, employing a high density medium built up from synthetic spun fibres with a sub-micrometre diameter and made in the form of a closely pleated pack; air velocity in this case is limited to about 0.03 m/s. Multi-stage filter systems with UV light sanitizing and gaseous absorber including VOC are also used.

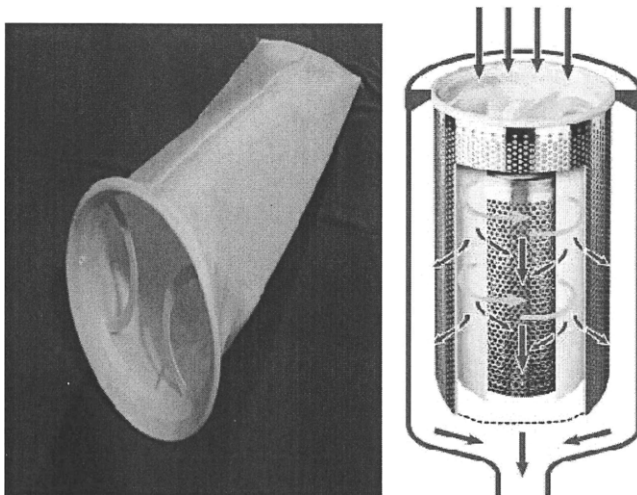


7.21 Multi-stage filtering system. NB. Media velocity reduces at second and third stage due to pleating of the structure.

Figure 7.21 shows a basic multi-stage filter system combined with VOC filter. A single-stage system using a low or medium efficiency filter has the lowest capital cost but will not filter very fine contaminants. A multi-stage system will filter virtually all atmospheric pollution but at higher capital investment. The filter cost itself will be low, because the cheaper primary filters prolong the life of, and protect, the more expensive filters. With a prefilter, HEPA filters and ULPA filters can last for several years in a cleanroom environment. Moreover, because airflow capacity decreases and static pressure increases over time, HEPA filters and ULPA filters can become more efficient as the filter loads.

Bag filters

Bag filters are used for a number of liquid filter applications including bulk chemicals and food industry applications such as vegetable oil, coolants, cleaning fluids, paints, varnishes, waxes, and plastisols. Bag filters may be as simple as a filter medium bag attached to the end of a pipe. For higher-pressure and larger volume applications, the bag is inserted into a housing and supported by a mesh basket (Fig. 7.22). Many filter bags are composed of woven materials, however nonwoven materials have made an entry into this market. Nonwoven material types used in bag filters include needlefelts, various forms of carded nonwovens, meltblown, spunbonded webs, and composite structures (Hutten, 2007). With a gradient density fibre structure, performance filter bag media provide premium depth filtration, trapping a wide range of particles for cleaner fluid streams.



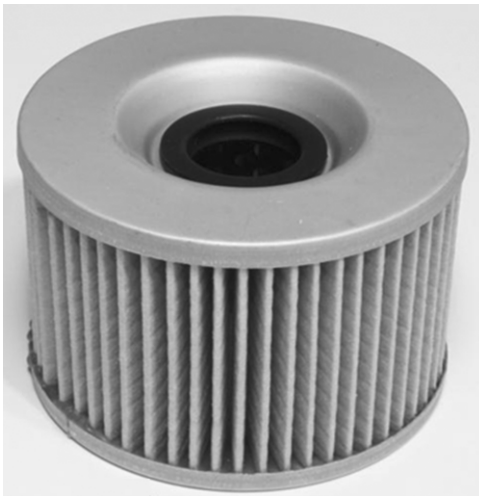
7.22 Bag filter in mesh basket for liquid filtration. (Courtesy of Trumpler-Clancy, Inc., 2013.)

Cartridge filters for liquid filtration

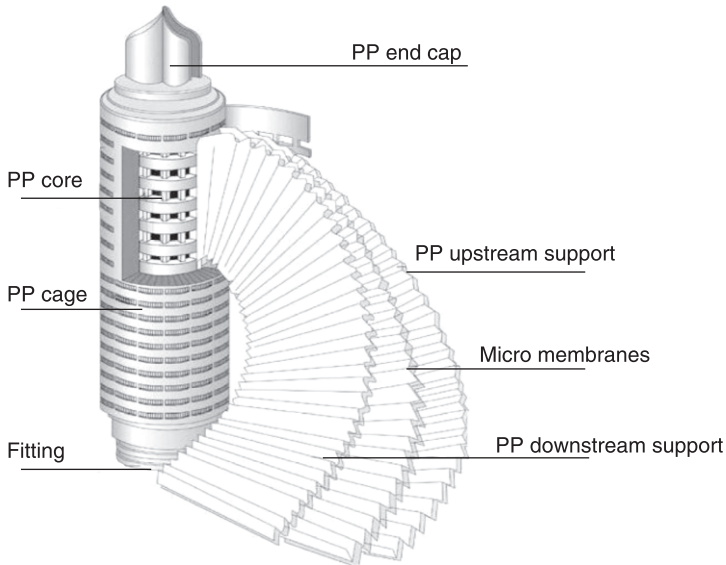
There is a wide variety of cartridge filters and a wide variety of filter media used in these cartridges. Engine filtration (lube oil and fuel) is one of the biggest users of liquid filter cartridges. It may be added that apart from nonwoven fabrics other media such as woven fabric media, sintered metal media, membranes, wound yarn and/or filament, mesh screen materials, and other novel media are also used. Most cartridge filters contain pleated media and are used in a variety of applications. The pleated medium as it comes out of the pleating machine is referred to as a 'pleat-pack'. Pleat-packs are not filter elements until they are stabilized with a support structure. It should be noted that cartridge filters are not always cylindrically shaped. Generally, they consist of housing and filter element. Figure 7.23 shows the configuration of a widely used filter element for the following applications:

- food and beverage – beer, flavours, juices, waters, syrups, spirits, wines;
- cosmetics – fragrances, lotions, creams, shampoos, toiletries, water;
- industrial – solvents, paints, inks, oils, chemicals;
- Electronics – reverse-osmosis and distilled water, solvents, coatings;
- pharmaceutical – pre filters and final filters for drug formulations.

Another form of filter element (Fig. 7.24) is a general purpose filter element containing multiple layers of pleated filter media. Versions of this cartridge incorporate various types of filter media including membranes of polypropylene, nylon, and PTFE sandwiched between protective layers of spunbonded media.



7.23 Pleated filter element.



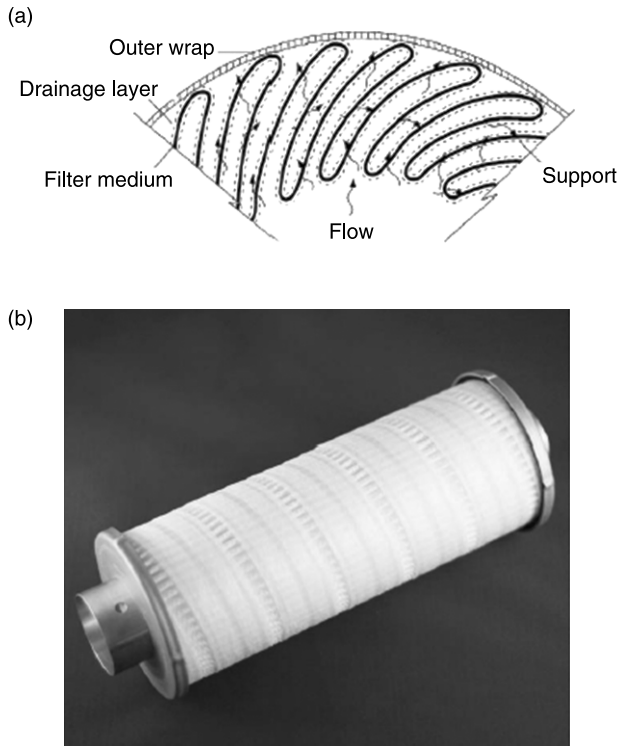
7.24 All-polypropylene (PP) general purpose composite filter element. (Courtesy of Yalida Filtration Equipment Co. Ltd, 2011.)

Although most pleat configurations are in a zigzag shape, there are new technologies wherein a filter is constructed using crescent shaped pleats. The curved pleat configuration results in a more stress resistant filter media, thus improving the life of the filter. Figure 7.25 illustrates the pleat configuration with fluid flow patterns and the filter element.

Cartridge filters are that part of a filtration system that is removable from the main body of the system for disposal and replacement, or for cleansing and reuse. In some applications, they can be cleansed in place by procedures such as reverse flow and reused without being removed. There are filter cartridges that are reclaimed for reuse, as in the case of filters used in high pressure hydraulic systems that require very expensive filter elements. In this situation, it would be economically justifiable to reclaim both the element and the housing.

7.13.2 Cleanable filters

Gas cleaning is of prime importance in many process industries to control the particulate matter emission, maintain the work atmosphere and recover the valuable particles. There are a variety of dust collectors on the market available today ranging from cartridge dust collectors to baghouse designs; the latter one becoming more popular. Worldwide, needlepunched nonwovens are predominantly being used for filter bags (Fig. 7.26). The needlepunched filter media permit higher



7.25 Pall Unipleat® configuration: (a) pleat configuration with fluid flow patterns; (b) Unipleat® filter element. (Courtesy of Pall Corporation, USA.)

filtration efficiency at relatively lower pressure drop. Other than needlepunched fabric, spunbonded, chemical bonded and hydroentangled fabric are also used. Although there is a growing interest in spunbonded and hydroentangled fabric, in many ways needlefelts would still appear to be ideal for filtration, combining the possibility of greater flexibility and versatility in construction. A needlepunched fabric with weight of $450\text{--}500\text{ g/m}^2$ is very commonly used and provides adequate strength and life to the filter element. However, fabrics with weight of $550\text{--}600\text{ g/m}^2$ with equivalent pore diameter of $40\text{--}50\text{ }\mu\text{m}$ for abrasive and fibrous dust, and $25\text{--}30\text{ }\mu\text{m}$ for exceptionally high collection efficiency, are also used (Ray, 2004).

7.14 Conclusion

Understanding the theory behind the filtration process is essential for the development of composite nonwovens. It is also important to understand the application needs and forms of nonwovens for appropriate structural development.



7.26 Industrial filter bags with cage. (Courtesy of Testori Group, 2013.)

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Composite nonwovens in filters: applications

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Abstract: This chapter discusses the role of composite nonwoven filters in different structural forms such as combining mechanical support and durability with filtration, providing two or more layers of different filtration efficiency and combining different separation technologies/functionality into one filter medium. In many situations, composite nonwovens might fulfill multiple objectives. Applications of composite nonwovens are quite diverse and increasing in the area of air, liquid and engine filtration. The developmental objectives of composite filtering media are lower energy consumption, longer filter life, high filtration capacity, greater dust holding (in depth filtration) and easy cleanability (of surface filter), satisfying more than one functional requirement and easier maintenance.

Key words: applications, improved performance, role of composite nonwovens, structural variations.

8.1 Introduction

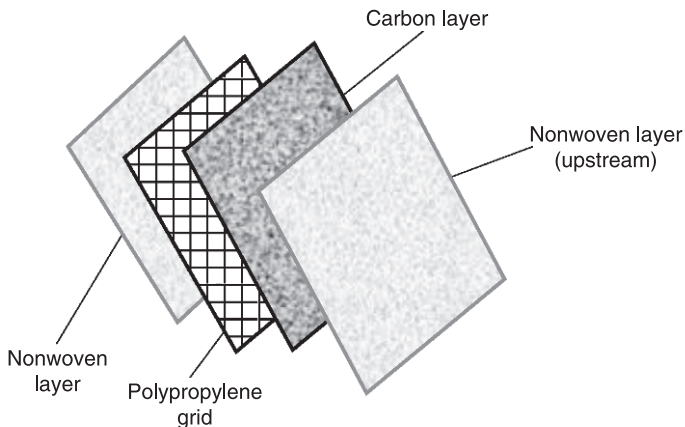
The developmental objectives of composite filtering media are lower energy consumption, longer filter life, high filtration capacity, greater dust holding (in depth filtration) and easy cleanability (of surface filter), satisfying more than one functional requirement and easier maintenance. Composite structures are usually multilayered filter media, each layer serving a specific purpose in the filtration/separation process. All the layers of a composite are not necessarily nonwovens. One or more of the layers could be a membrane material, a woven material, or a plastic or metal mesh material to provide structural support. Further, there are two contrasting styles of laminated structure, depending on whether the filter medium is intended to function by depth filtration or by surface filtration. With depth filtration, the medium should be graded so as to increase the fineness of fibers in the direction of flow. The upper, coarser layers will act as a prefilter, in which the larger particles are retained, with the smaller particles then being trapped subsequently in the finer layers. This will maximize the dirt holding capacity per unit area of medium, and hence its life before it is discarded. In the case of surface filtration, material consisting of finer pores/larger surface area should be at the upstream side, so that it can be cleaned intermittently for regeneration purpose.

In composite nonwovens, the structures usually serve one, or a combination of, the following purposes:

- Provide mechanical support for other structural or filtering layers, giving enhanced durability.
- Provide two or more layers of different filtration efficiency.
- Facilitating the combination of varied separation functions or technologies into a single filter medium.
- The outer layers serve as a containment to inhibit medium migration, dusting, and particle fallout from the inner layers.

In many situations, composite nonwovens might fulfill multiple objectives. For example, spunbond nonwoven can act as support layers for filter media (such as activated carbon, meltblown and nanofiber webs, microfiber glass and cellulose) as well as protection layer. Spunbond nonwovens in the higher weight range are used as filter medium for coarse filtration, and as a prefilter for finer filter media. Figure 8.1 shows that in many cases the composite filter media can satisfy multiple objectives such as particulate filtration (by nonwoven layer), absorption of gases (by carbon layer), and providing dimensional stability and strength to the media (by polypropylene grid).

Further, composite material may fulfill some other requirements not listed above. For example, the spunbond nonwoven can fulfill requirements other than support layer in pleated filter media for cabin air filters. It leads to stiffer and sharper (smaller radius of curvature) pleats, without losing overall mechanical properties, thus allowing a more efficient filter design (Maltha, 2011).



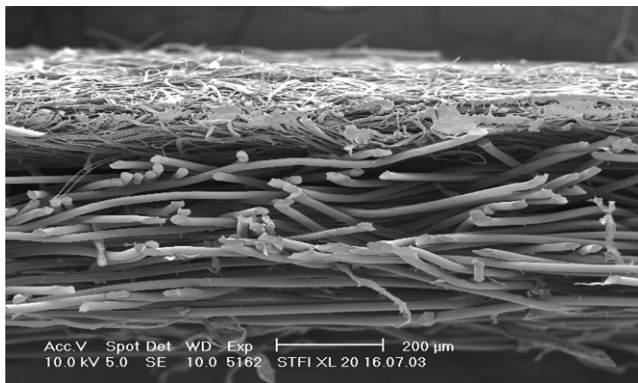
8.1 Configuration of the composite media HVAC filter.

8.2 The role of composite nonwovens in filters: combining mechanical support and durability with filtration

In many cases, the role of a component in a composite is to provide mechanical support and durability of the filtration layer. For illustration, although filtration capability by electrospun nanofibers and meltblown nonwovens is very high, they tend to be fairly weak and are generally too thin. The mechanical strength of nanofibrous layer/meltblown nonwovens are not sufficient to withstand macroscopic impact during filtration applications such as normal liquid or air flow passing through them. Stronger materials are therefore required for such applications, and materials which have been demonstrated to offer suitable mechanical strength include woven fabric, spunbond, spunlace (hydroentangled), needlepunch felt, or cellulose web. Figure 8.2 shows the cross-section of hydroentangled composite with meltblown layer for industrial application.

8.2.1 Use of finer fiber in composite structures

Fiber fineness is considered as one of the most important parameters while selecting/designing the filter media. Very fine fibers can be made from meltblown, bi-component and electro-spinning techniques. Nanofiber fabric possess extremely high surface to weight ratio from small fiber diameters (10–100 times smaller than those of meltblown and spunbond filaments), interconnected pore structure, very small pore size and potential for functional modification of the fiber surface, thus offering more possibilities for a wide range of applications,



8.2 Cross-section of a hydroentangled composite with a meltblown layer (HYCOFIL®) (used with permission from Sächsisches Textilforschungsinstitut e.V. (STFI), Chemnitz, Germany).

ranging from air cleaning for automotive to environment conditioning or liquid filtration (Yoon *et al.*, 2006; Barhate and Ramakrishna, 2007; Dotti *et al.*, 2007). In all these applications, finer fiber materials need to be supported by a stronger component in composite. There is another perspective of the use of thin layers of finer fibers. The media made out of finer fiber lead to higher filtration efficiency at the cost of higher pressure differential across the fabric. For a suitable balance between efficiency and levels of pressure, use of a thin layer of finer fiber component in a composite is required.

The finer fiber layer can be positioned upstream before the macro filtration substrate to enhance surface filtration performance or downstream of the macro filtration substrate to improve depth filtration in order to capture particles within the body of the media. Finer media at the upstream side of surface filters lead to better cake dislodgement and prevention of particle penetration inside filter media (Kothari *et al.*, 1993; Ciach and Gradon, 1998; Callé *et al.*, 2002), which in turn results in better long term performance of filter media. However, a thin layer of nanofibers on meltblown media has a weak bond and higher production costs (Lydall Filtration and Separation, 2013). The weak bond is a problem in the nanofiber layer in self-cleaning or pulse cleaning filter applications. The dust cake formed on the upstream side of the filter media can be removed by back-pulsing air through the media to rejuvenate it. As a great force is exerted on the surface during the back-pulse, nanofibers with poor adhesion to substrates, or comprised of delicate nanofibers, can delaminate when the shock wave moves from the interior of the filter through the substrate to the nanofiber. However, the new nanofiber technology was reported to provide excellent adhesion to the substrate, enabling longer life and improved efficiencies in pulse-cleaning applications because of greater particle collection and overall energy expended during the cleaning process. The plurality of nanofiber layers also provides superior durability (Wertz and Schneiders, 2009).

Studies have demonstrated that high efficiency composite filters made up of nano- and microfibers, when added to industrial gas filtration systems (such as dust-collecting pulse-clean cartridges) extend filter life (Kosminder and Scott, 2002). Researchers have also developed an industrial gas filter medium consisting of 70% polymers with a regular melting temperature and 30% polymers with a low melting temperature. This medium employs polyester felts as the base material for the polymer mix, with a prepared polyamide nano-sized web at the upstream side of the fabric (Yeo *et al.*, 2007). A thermal roller was employed to bond the overlapped filter medium. Subsequent work to evaluate filtration capability revealed greater collection efficiency and more stable filtration behavior in the medium with the nano-sized web showing more stable filtration behavior and improved collection efficiency. The levels of dust found to be left in fabric containing nanofiber web was also revealed to be far lower than those in fabric with no nanofiber web (Yeo *et al.*, 2007). One patent disclosure suggested that high filtration efficiency could be achieved by enhancing the upstream surface of

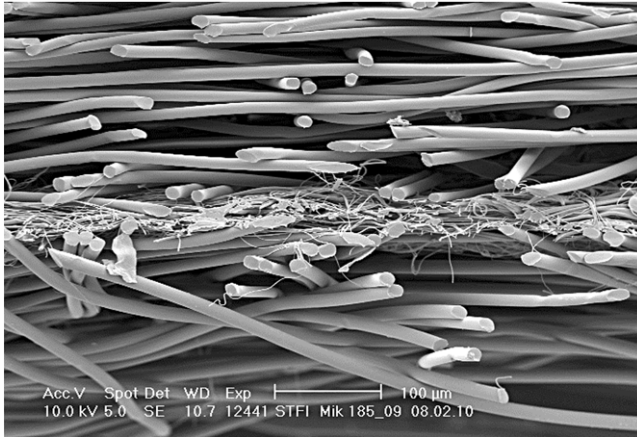
a spunbonded medium via use of a micro- or nanofiber structure on the upstream surface (Chung *et al.*, 2008).

Most often the combination of structure is made by heat bonding the process either by purely heating the process or by using hot melt adhesive. Combination is also possible by ultrasonic welding. Hydro-entanglement and needlepunching are also interesting options for the joining together of two layers to produce composite filtration materials. In one study, the needlepunching technique was used as the initial step in preparing P84 needlefelt. P84 needlefelt was then prepared by taking the upstream side of felt, constructed of standard 2.2 dtex fiber, and adding 1.0 dtex microfiber. This produces a medium capable of increasing gas filtration efficiency by preventing deep dust penetration, maintaining stable pressure drop, and facilitating good bag life. As well as being an effective filtration medium in gas filtration systems, P84 fibers can additionally be used as either a PTFE (polytetrafluoroethylene) fiber blending partner, or in the construction of surface layers on homopolymer acrylic, polyester or *m*-aramide felts (Connor, 1997). Varied combinations of medium have been tested in layered construction, leading to the formation of such composites as a felt-like layered construction of PTFE and glass paper (Fagan, 1982).

In the case of depth filtration, use of nanofiber was also reported. Finer media trap tiny particles of the order of $<0.5\text{ }\mu\text{m}$ at the final stage and therefore it is possible to achieve HEPA (high efficiency particulate air) grade regarding collection efficiency (Kattamuri *et al.*, 2005; Ahn *et al.*, 2006; Podgorski *et al.*, 2006; Yun *et al.*, 2007; Wang *et al.*, 2008a, 2008b). Problems of structural damage and delamination in depth filtration applications can be largely overcome by suitable composite development. In the combination of meltblown (M) and spunlaid (S) nonwovens (SMS, SMMS or SSMMS), the spunlaid component provides the required strength and abrasion properties and the meltblown component act as a barrier for liquids or particles. For the aforesaid reason, a major portion of meltblown material is used in composite form (Hutten, 2007). Figure 8.3 shows the cross-sectional view of an SMS fabric.

In a nanofiber composite, filter media were made where lighter layers of nanofibers were applied to the spunbond materials, then two layers of spunbond/nanofiber composite were laminated together in a face-to-face configuration, i.e. a structure of spunbond-nanofiber-lamination-nanofiber-spunbond.

The outer layers protect the nanofiber layer from abrasion and other mechanical damage, and therefore would also prevent the nanofiber layer from scuffing (Graham *et al.*, 2003). The material can be used for depth filtration situations in non-cleanable filters. A triple layer design of fibrous filters was reported (Podgorski *et al.*, 2006) wherein the middle nanofibrous layer was placed between the back support layer of densely packed microfibers and the front porous layer of fibers of a few micrometer diameter. The composite was found to be useful to remove the nanoparticles along with other polydispersed aerosol particles.



8.3 Hydroentangled composite HYCOSPUN® spunbond nonwoven with a meltblown fine fiber inside layer (used with permission from Sächsisches Textilforschungsinstitut e.V. (STFI), Chemnitz, Germany).

Composites with nanofiber layers find applications in many critical areas such as medical, hygiene, bioseparation, etc. (Gopal *et al.*, 2006; Barhate and Ramakrishna, 2007). It was observed that an electrospun membrane conveniently rejected the microparticles and acted as a screen filter without fouling the membrane especially when the particles were larger than the largest pore size of the nanofibrous membrane (Gopal *et al.*, 2007). Nanofibrous filtering media can be used where high-performance air purification is needed such as in hospitals, healthcare facilities, research labs, electronic component manufacturers, military and government agencies, food, pharmaceutical and biotechnology companies. The medium is very efficient for filtration of blood, water, air, beverages, gases, chemicals, oils, diesel and petrol, etc. Manufacturing and processing companies in food, pharmaceuticals, biotechnology and the semiconductor business require centralized air conditioning in the production environment, high purity water, clean gases and effluent/waste air and water treatment. Control over airborne and waterborne contaminants, hazardous biological agents, allergens and pollutants is a key issue in food, pharmaceuticals and biotechnology processes. Under these circumstances, nanofiber-based filtering media are very useful (Barhate and Ramakrishna, 2007). Nanofibers offer enhanced filtration performance in both mobile and stationary engines and industrial filtration applications wherein the nanofiber layer is used at the upstream side of the filter media.

With respect to engines, gas turbines and combustion furnaces, it is important to remove particulate material from the air stream supply that can cause substantial damage to the internal components. In other instances, production gases or off-gases from combustion engines and industrial processes may contain

damaging particulate material. The removal of these particulates is desirable to protect downstream equipment and minimize pollution discharge to the environment.

Recently, there was an attempt to functionalize the surface of filtering media with antimicrobial agents for long-lasting durable antimicrobial functionality (Lala *et al.*, 2007). An antimicrobial nanofibrous filter (Tobler and Warner, 2005; Jeong *et al.*, 2007) was found to be useful for improved antimicrobial functionality in HVAC (heat, ventilation, air conditioning) application. In a medical application, water resistant but water permeable coating of chitosan (antimicrobial) was applied over the polyacrylonitrile nanofibrous layer which was supported on the nonwoven microfibrinous substrate (meltblown polyethylene terephthalate mat). This three-tier approach is useful for flux and low fouling ultra filtration (Yoon *et al.*, 2006). High surface-to-volume ratio of nanofibrous media enhances the fouling. Therefore, surface modification of nanofibrous screen filter with suitable hydrophilic or hydrophobic oligomer is often recommended to reduce the fouling effect.

Applying a highly water and oil repellent nano-coating has shown to improve the performance of filtration products. By providing high liquid protection without compromising air flow, considerable performance improvements can be seen across a wide number of filtration products (Coulson and Evans, 2011). Through surface treatment, it is possible to achieve a high conductivity of the media. This allows putting these filters into hazardous applications even with an explosive gas atmosphere (Stoffel, 2011). Nanofibers do have potential as prefilters for particulate removal in various applications such as removal of micro-particles from waste-water, prior to ultrafiltration or nanofiltration membranes, to prolong the life of these membranes (Gopal *et al.*, 2006).

Since a fibrous filter medium with a large contact area per unit mass is expected to perform better in promoting coalescence, addition of polystyrene nanofibers to the coalescence filters (glass fibers) improves the performance of coalescence filters. The filtration experiments showed that the addition of a small amount of polystyrene nanofibers significantly improved the coalescence efficiency of the filter but also significantly increased the pressure drop of the filters (Shin *et al.*, 2005a). There is an optimum amount of nanofibers to be added to the coalescence filter media (Shin *et al.*, 2005b), which balances the desired improvement in coalescence efficiency and the undesirable increase in the pressure drop. Catalytic filters, adsorptive filtration and absorptive filters for highly selective separations (Gibson *et al.*, 2001; Zuwei *et al.*, 2005, 2006; Barhate and Ramakrishna, 2007) are also effective at nanoscale.

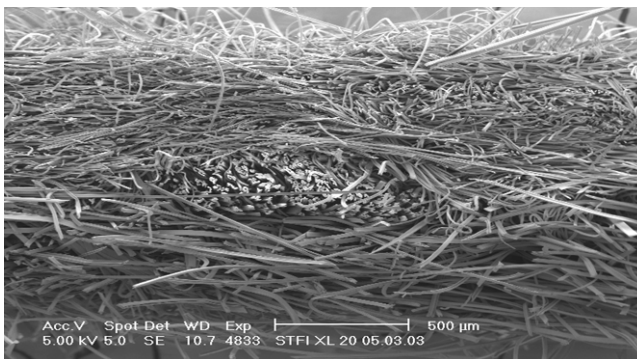
It is worth mentioning that manufacturing of nanofibers at commercial and economical scale has not yet been fully realized. The equipment required for nano technology manufacturing is rather expensive resulting in more expensive filter media. Nevertheless, nano technology-based filter media is catching on and will likely replace conventional filter media in near future. There is also growing

interest on bi-component fibers, which have a higher number of island fibers. With this island-in-the-sea formation, 1200 fine island fibers can be produced. Apart from the island-in-the-sea technology, the segmented pie technology also helps in producing fine fibers and has become more popular in recent years.

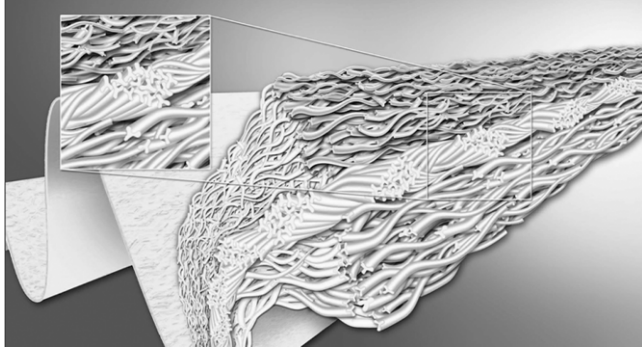
8.2.2 Use of scrim

In industrial pulse-jet filtration, scrim reinforced needlefelts are used for improving dimensional stability and greater durability. Figure 8.4 shows the sectional view of a hydroentangled composite nonwoven with scrim used for the industrial gas filtration process. Over the years, use of scrim becomes limited in gas filtration applications due to the improvement in the fiber consolidation process. However, scrim composites are often beneficial for high-temperature application. A range of scrim composite materials for high-temperature application are offered by EvonikFibres GmbH, such as polyimide (P84) fibrous batt with polytetrafluoroethylene (PTFE) scrim, P84 fiber nonwoven with P84 scrim, a fibrous blend of polyphylene sulfide fiber (PPS) and P84 with PPS scrim etc. Figure 8.5 shows the artistic view of P84 nonwoven with P84 scrim used for high-temperature application.

Research aimed at developing materials suitable for use in high-temperature applications has found that filter fabrics constructed from basalt-based composites produce some successful results (Johnson and Handy, 2003). The success of such materials lies in the fact that they combine the filtering characteristics of P84 with key properties of the basalt fabric used as scrim, including high chemical resistance, thermal resistance and strength. In scrim fabrics, if the nonwoven layer shrinks it does not cause any change in the dimension of filter bags, meaning there



8.4 Hydroentangled composite HYCOFIL® nonwoven with scrim (used with permission from Sächsisches Textilforschungsinstitut e.V. (STFI), Chemnitz, Germany).

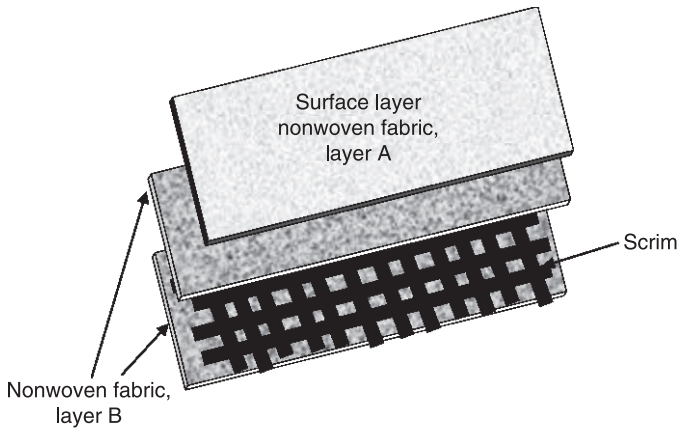


8.5 Composite nonwoven with P84 fibrous batt with P84 scrim (used with permission from Evonik Industries, Austria).

is no deterioration of filter ability, and some research suggests that the bags remain operational at temperatures of up to 300°C. By assessing retention of fabric strength, the service life of both P84/basalt filters composite (meteor bags) and membrane laminated glass fiber bags have been estimated and found to be comparable. Ensuring functionality at high temperatures is an extremely desirable characteristic for some applications, and even at temperatures over 800°C basalt composite filter fabrics can successfully clean corrosive hot gases or waste air containing hot particles.

Studies from around the world have suggested that meteor fabric has been successfully used to clean air with 1500 ppm of sulfur dioxide at 160°C and a high moisture content (South African Republic), to filter carbonyl of nickel from waste gas generated by nickel film production (Canada) and to filter stack gas after molybdenum powder production in Russia. The use of *LD-Mobile/HEC* monitoring and cleaning technology has also been used to significantly increase basalt composite filter bag lifespan (Medvedyev and Tsybulya, 2005).

A sandwich structure has been used to improve filtration performance, with two nonwoven fabrics and a polyester grid (C)-laminated together to form a nonwoven composite for use as filter bags (Lin *et al.*, 2006) (Fig. 8.6). One nonwoven component (A) was made up of polyester fibers of various levels of fineness, with a surface layer of ultra fine fibers of low melting-temperature (T_m). A second component (B) was constructed from 2.22 dtex polyester fibers, and the two materials were then used to compose the nonwoven composite using layers in an A/B/C/B order, forming a sandwich structure with a basic weight of 500 g/m². In order to bond the layers firmly, forming a composite nonwoven fabric, the material was then thermal calendared and needle punched. It has been claimed that in order to suit varied filtering media, the sandwich-structure could be molded into varied shapes.



8.6 The conformation of a nonwoven composite fabric.

8.2.3 Use of membrane over support layer

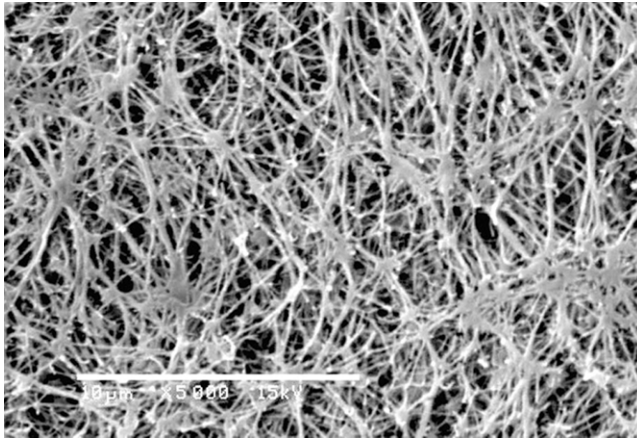
Recent emphasis on extremely high-efficiency removal of very fine particles during filtration has led to the demand for very fine porous surface layers, and this demand has been met by the lamination of a membrane on to a suitably robust substrate. Because the membrane used is extremely thick ($12\text{--}75\text{ }\mu\text{m}$) it is essential that special adhesives or, where possible, flame bonding are used to combine it with a suitable substrate. Nonwoven materials have proved to be very suitable as substrates, especially for the support of PTFE membranes. Depending upon the intended application, substrates range from lightweight spunbonded polypropylene or polyester, to substantial fabrics such as thick needlefelts. Membrane-based filtration media offer unique properties that make them suitable for a wide number of applications. This includes pulse-cleaned industrial applications (bag house, airborne pollution control and gas turbine), applications in respirators, consumer and industrial vacuum cleaners, medical, biopharmaceutical and aggressive chemicals.

It is important to note that membrane filtration technology was greatly limited by membrane fouling. Membrane fouling leads to higher operation and maintenance costs by deteriorating membrane performances (flux decline vs. time, zeta potential changing during time, etc.) and eventually shortening membrane life. Hence it is sensible to use nonwoven porous support which generally has the superior dirt-holding capacity and does not have a much wider pore size distribution. Such quality, along with reinforcement of mechanical

strength to the membranes, gives better performance with decreased fouling. In a research work (Hegde *et al.*, 2011) on a polysulfone blend nanoporous membrane with nonwoven support consisting of fine polyester fibers, it was observed that nonwoven support minimizes membrane fouling apart from providing mechanical strength to the membrane during the filtration process. Hence it helps in better membrane performance in terms of salt rejection, improved flux, thermal stability and proton conductivity. The membrane is essentially a surface filtration device, with little or no depth filtration involved in its use. In practice, many membranes are of asymmetric structure and effectively comprise two layers. The active, surface layer is a very thin skin, the permeability of which is of critical importance. The lower, thicker layer is of more open structure, its role being to serve as a mechanical support for the active layer. One of the most popular membranes is PTFE. The advantages of the PTFE (naturally hydrophobic) membrane are its superior chemical and temperature resistance and its non-sticky nature. Apart from PTFE, another most widely used acrylic copolymer membrane is inherently hydrophilic, and offers low extractability. The laminated product with nonwoven polyester fabric is employed in semiconductor water, pharmaceuticals, food and beverages.

Besides the most popular ePTFE membrane, UPE membranes are also reported to be inert and compatible with harsh industrial environments. The inherent structural properties of these membranes enable flexible composites, enhanced pleat processing and new high performance filter designs. While used in cleanrooms, HEPA and ULPA filters, they provide absolute protection. They are designed to be installed for the lifetime of the cleanroom. Prefilters are used to capture the majority of particles in the airstream and reduce the load on the membrane filters. High alpha membrane filters lower the pressure drop, leading to significant savings in energy consumption during cleanroom operations. Over the typical five-year useable life of a filter, the resulting savings easily outweigh the added cost for the membrane filter (Galka and Saxena, 2009).

Most often the membrane filter operates at face velocities of 10 to 20 cm/s while used for cleanroom applications. The composite with ePTFE and UPE membranes provide high efficiency at these higher airspeeds and the low pressure drop enables the high airflow rates with reduced power consumption. The low pressure drop, ULPA efficiency and hydrophobic membrane properties are essential in surgical and hospital airway management, protecting both the patient and equipment. Those same properties are ideal for venting applications such as ostomy bags. The membrane can also be typically laminated to a carbon impregnated nonwoven. The combined filter provides for pressure relief, an absolute barrier to liquid flow through the filter in both directions and odor reduction. Depending upon the particular requirements, the membrane may be treated to enhance its oleophobic properties. In biopharmaceutical manufacturing, ePTFE and UPE filters can be used to vent gases produced during fermentation and cell culture. These vent filters require an absolute barrier to microorganisms

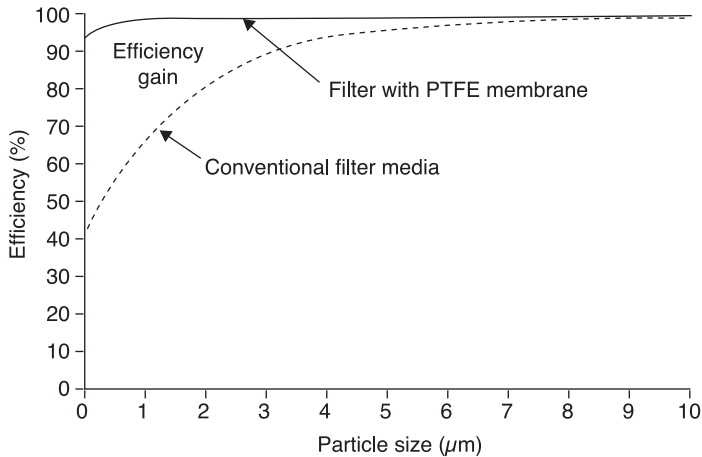


8.7 A photomicrograph of expanded PTFE membrane (reprinted with permission from Mukhopadhyay (2010), Taylor & Francis, UK).

in aerosols and to bacteria in the event the filter is wet out. The gamma stable properties of UPE membranes provide significant benefit in single-use applications in the medical and biopharmaceutical fields (Galka and Saxena, 2009).

In industrial gas filtration, higher efficiency is provided by filter membranes than by conventional fabrics. An expanded PTFE membrane is shown in Fig. 8.7. The size of the pores trap any particles below $2.5\mu\text{m}$ in diameter whilst still allowing air to pass through, thereby proving more effective for filtering, particularly for small particles, than conventional filters (Fig. 8.8). This membrane is attached to needlepunched felts, spunbonded or over spunlace nonwovens. Different fiber polymers, including homopolymer acrylic, torcon, nomex, static conducting polyester, polyester and polypropylene, can be used to make the substrate, as can woven fabric of PTFE yarn/glass yarn. The chemically inert PTFE membrane can withstand high temperatures of up to 260°C . When selecting the base material, the filtration operating temperature and chemical environment must be taken into account. High efficiency and exceptional flow capability are provided by uniquely engineered microstructures in the PTFE membranes (Martin, 1999; Griffin, 2003; Menardi Filters, 2013; Mueller sales, 2013; Simatek A/S, 2013; W. L. Gore & Associates, 2013a). In comparison to the plain spunbonded media, a slightly higher filtration efficiency of 99.999% (99.9975% efficiency without lamination) was given by lamination of a PTFE membrane to the spunbonded polyester media. This result was obtained while operating at a slightly higher pressure drop. Such spunbonded media have been employed in bag houses, ventilating many applications (Martin, 1999).

In industrial gas filtration process, membrane filters also help in removal of cake. In this regard, the cake adhesion force determines efficacy of removal of



8.8 Comparison of fabric with and without PTFE membrane (reprinted with permission from Mukhopadhyay (2010), Taylor & Francis, UK).

cake from the filter media. When the filtration cake is formed during the filtration process, the resistance to air flow through the filter increases, as a result the pressure drop increases. The cake must be removed by cleaning processes, once the pressure drop is considered relatively high, in order to minimize resistance to gas flow and, consequently, reduce costs. Therefore, improvements in the cake removal process may represent substantial economic gains, as well as significant contributions to a greater improvement of the filtration process.

However, complete removal of cake is not desirable as primary cake also takes part in filtration and protects the fabric. Particularly, problems occur in sugar particles where a stable primary cake formation is difficult due its particulate nature.

Membrane filters may offer numerous advantages, including:

- reduced maintenance costs;
- increased plant utilization;
- increased filter life;
- meet and exceed environmental compliance;
- reduced particulate matter and down time;
- reduced energy costs;
- reduced cleaning cycles;
- increased throughput.

However, membrane applications are fairly expensive, meaning their use is usually limited to applications which are particularly difficult. Such applications include cases where filtration of extremely fine dust particles or particularly

hazardous contaminants is required, or where unique advantages (such as cake release) may be offered by interaction with a membrane surface. As an example, hybrid technology which combines electrostatic charges with fabric filtration offers improved efficiency when utilizing membrane fabrics with lower air to cloth ratios, thanks to the substantial reduction in the burden of particulates on the fabric filter (Mukhopadhyay, 2009).

In a study by Fritsky (2013) based on particulate emissions at a municipal solid waste combustion facility, the performance of GORE-TEX® membrane (PTFE)/TEFLON® B fiberglass fabric filter bags was assessed. This technology is made up of two key elements: a pulse-jet fabric filter collector, which is additionally equipped with a lime slurry spray dryer absorber. Some factors attributable to the success of the fabric filter collector include: superior operation of the boiler and spray drier absorber; infrequent and low pressure pulsing; prevention of the penetration of particulate matter into and beyond the GORE-TEX membrane (wear of abrasive dust can otherwise cause fiberglass fiber breakage); and excellent bag-to-cage fit and bag design to minimize flex fatigue of fiberglass fibers against cage wires, whilst allowing adequate bag movement for efficient cleaning (Fritsky, 2013). It may be added that membrane-less glass fiber fabrics are unable to meet current emission requirements.

However, filtration performance is degraded by premature membrane failure. Particularly during cleaning pulses, filter bags are subjected to continual stresses and flexing which may lead to breaking of the membrane's bond, causing fibrils structure and the development of cracks. Various factors, including the frequency of cleaning pulses and the amount of pulse pressure used, affect the severity and extent of this crack development. Pulse pressure and pulse-on-time during membrane filter use, should be kept below 550 kPa and 350 milliseconds, respectively (Hardman, 2000; Savage *et al.*, 2013; W. L. Gore & Associates, 2013b). Innovative development and re-engineering of PTFE membranes can achieve higher strength levels and increased air flow, whilst maintaining filtration efficiency.

8.2.4 Coated filters

A coated filter can be considered as composite, as it consists of two different materials in a single structure. Sometimes the application of resin to a nonwoven filter medium is wrongly referred to as coating. The resin is applied as saturant (sometimes referred to as an impregnate). Unlike coating, which is intended to cover the surface of the substrate, a saturant is expected to penetrate the media and form bond points in the interior as well as at the surfaces. Because of the need for penetration, low viscosity is a very desirable property in liquid resin systems for filter media.

It is a little more complex to coat needlefelt fabric surfaces, and it can occasionally be difficult to establish the difference between coated fabrics and

bonded media. Water repellency is important to a filter medium, particularly air filtration media, because it helps to prevent it from being wetted out and damaged when exposed to water. Wetting of HEPA filter media leads to degradation of filter strength to a large extent and could reduce resistance to medium breach. Water repellency is incorporated into a filter medium by the use of hydrophobic material in the media surface. This can be done by the use of water repellent fibers or by water repellent coatings. Polyester and polyolefin are examples of fibers that are hydrophobic in nature and will impart water repellency to a filter medium. Waxes, silicones, and fluorocarbon resins are examples of water repellent coatings that can be applied to filter media. Some binders such as styrene acrylates also impart a degree of water repellency (Hutten, 2007). There are various methods for coating filter media, including surface coating, steeping, foam coating and coating with inert powders.

Surface coating

To achieve finer particle filtration and improve cake discharge during the industrial gas filtration process, microporous polymer coatings can be applied to the face of nonwoven fabrics. In addition to improving filtration efficiency and cake release, this process improves the efficiency of heat, chemical and abrasion resistance (Goosens, 1993). When applied to the needlefelt surface, coatings form a quasi-membrane structure. The addition of a Teflon B coating on the surface of glass fiber fabric for boiler applications is common (Carr and Smith, 1984). During the late 1980s Ravensworth Ltd developed a range of coated materials, under the trade name of Ravlex, for achieving superior filtration performance. Three main product groups are generally used for the coating process: Ravlex MX, Ravlex PPC and Ravlex YP. Ravlex MX is a PTFE microporous embedded coating which is applied to the carrier needlefelt filtration surface. Ravlex MX is generally used for the filtration of fine particles in the chemical, pharmaceutical and food industries. Formulated from PTFE, the Ravlex PPC coating offers higher permeability than the Ravlex MX due to its larger pore size, thereby making it suitable for the filtering agglomerating or sticky dusts. With a pore structure similar to Ravlex PPC, Ravlex YP is formulated from polyurethane (PU), whilst another recent product, Ravlex CR, is formulated from PTFE coating. As previously outlined, all such coatings usually offer such benefits as high abrasion resistance, effective cake release, increased air permeability, reduced operational pressure drop (resistance to blinding), reduced cleaning frequency and extended filter operational life (Gibbons, 2002; Lydon, 2004; Ravensworth Ltd, 2004a, 2004b).

MicroWeb 2000 and MicroWeb II media, which comprise polytetrafluoroethylene (PTFE) and acrylic coatings, respectively, on a polyester needlefelt, have been introduced by Webtron and are designed to provide reasonably high permeability. Similarly, a number of treatment processes are produced by

Fratelli Testori. These include *Novates*, which is a coating of polyurethane (PU) on polyester or acrylic felts to provide hydrophobic and oleophobic characteristics; and *Mantes*, which gives enhanced chemical resistance via application of a resin chemical treatment containing PTFE to acrylics and high-temperature fibers. Tuf-tex™ thermosetting resins have been developed by Madison Filter for the coating of polypropylene, polyamide and polyester substrates. Once sprayed or knifed onto the surface of the filter fabric, these provide good abrasion resistance and enhanced dimensional stability (Lydon, 2004).

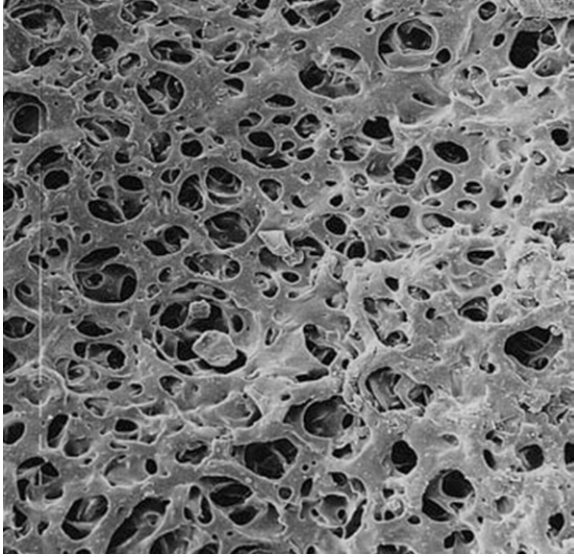
Steeping

During application, fabric is steeped in a chemical solution containing high concentrations of PTFE and fluoride resins. The fluorides are then fixed on the fibers by drying and heating the fabric. Application of this process to polyester or acrylic fiber fabrics enhances both cake release properties and protection from chemical activity (Hardman, 2000). When treating glass fiber fabric, the fabric is immersed in an emulsion of water, silicon, silicon graphite or colloidal graphite or fluorocarbon compounds, before excess liquid is removed by squeezing the material through a roller, and the fabric is then dried (Ray, 2004).

Foam coating (Goosens, 1993)

Aqueous-based acrylic latex is usually the principle ingredient of the treatment. In order to ensure that a fine, regular, stable pore structure is formed and that any specifically required characteristics (such as antistatic or hydrophobic properties) are produced, a range of chemical agents may constitute the precise formulation. Surface chemistry factors are the key factors governing the selection of polymer for coating, and the final product must feature effective chemical affinity between the contiguous materials involved. Figure 8.9 shows a foam layer electron photomicrograph.

Using this approach in the production of acrylic foam-coated needlefelts produces such materials with the capability of operating continuously at temperatures up to approximately 120°C. These materials are not, however, usually resistant to hydrolytic conditions, which can potentially lead to structural collapse and premature pressurization. The specific density of the foam when applied to the material is also essential for successful application. If the density is too high, the substrate is wetted excessively. This leads to inadequate penetration and poor mechanical bonding as a result of the unacceptable air permeability and too low a density, increasing the risk of delamination.



8.9 Electron photomicrograph of a foam layer on a nonwoven fabric (reprinted with permission from Mukhopadhyay (2010), Taylor & Francis, UK).

Use of inert powders (Goosens, 1993; Menardi Filters, 2013)

Uniform, smaller sized pores can be achieved on the fabric surface via the use of powders, which are chemically inert additives. By pre-coating the new fabric filters with this powder, the filter surface develops a protective coating. Calendaring can help achieve effective powder coating, thanks to the lower melting point of the powder in comparison to the nonwoven fabric. The powder, which is scattered onto the surface of nonwoven fabric, melts together with the fibers to form a layer of smaller pores.

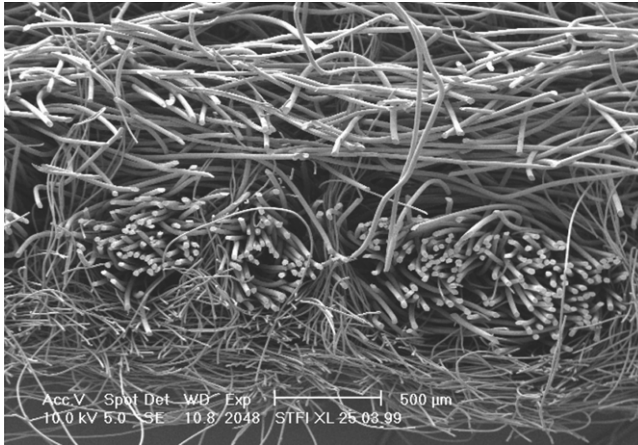
It is interesting to note that the improvement of composite material performance via the use of low pressure plasma for coatings is gaining increasing interest. Filter media producers adopt plasma coating to improve the quality of their products. Innovative plasma processes allow depositing coatings with high levels of hydrophobicity and/or oleophobicity for use in gas filtration, or coatings with permanent hydrophilic effect for liquid filter media and battery separators. The use of low pressure plasma for surface modification of filter media becomes more widespread because it is a dry and clean technology. The coatings applied by low pressure plasma polymerization also give good resistance to abrasion and washing. At the same time, it helps these companies to save costs because of a lower consumption of energy and chemicals (Legein, 2011). A well-known application of plasma coating is found in the production of blood filter media, respiratory mask, filter for HVAC, etc.

8.3 The role of composite nonwovens in filters: providing two or more layers of different filtration efficiency

In this case, composite nonwoven filter layers may be used in one of two forms: an upstream layer may be used as a prefilter for the final filtration layer, or, alternatively, gradient density depth filtration may be provided by arranging composite nonwoven layers of increasing densities. The outer layers can also serve as a containment to inhibit medium migration, dusting, and particle fallout from the inner layers. It may be added that process air from machining operations can have high concentrations of liquid aerosols, up to 100 mg/m^3 , and can cause several types of serious health effects on workers. A good drainage capacity is a vital requirement in a multistage filtration system.

The SMS fabric as referred to earlier (Section 8.2.1) works under the aforesaid philosophy wherein the meltblown middle layer provides higher filtration performance as compared to spunbonded side layers. As the meltblown layer conducts the final filtration, the spunbonded layer acts as a prefilter. In the gradient density medium, the differing bulk of each layer provides an increasingly efficient level of filtration; as the fluid moves through these increasingly fine layers, smaller and smaller contaminant particles are removed. Better filtration has been found through producing a unique gradient structure made in two steps. In the first step, a pile stitch-bonded nonwoven with a one loop surface is manufactured. In the second step, the one loop surface of pile stitch-bonded nonwoven is compressed by putting a hydroentangled nonwoven on it (Smithies and Zimmerman, 2005; Lin *et al.*, 2006). The result is a gradient density medium and a photomicrograph of the structure is shown in Fig. 8.10. The product is unique in that the fibers of the upper pile surface are oriented in the direction of flow. This is in contrast to the conventional filter media where the fibers are generally perpendicular to the direction of flow. The share in pile ranges from 98% to 99% and the number and size of cavities between the fibers depend on the fineness of fibers used and the fabric thickness. The product is found to be useful for depth filtration applications.

In another development, wet lay technology can be used to create pore gradient in the media for the manufacture of air filtration media for many different applications, including HVAC, heavy duty air intake, automotive air intake, gas turbine and cabin air. Due to the gradient pore size, these media have a high dust-holding capacity and low pressure drop. The multilayer construction can combine mechanical filtration (a prefilter that removes most particles), electrostatic filtration (the middle layer allows high initial filtration efficiency) and the last layer/filter that allows high efficiency for all filter life. The triple-layer construction makes it possible to create different kinds of products by simply modifying the grammage or the fiber composition of the layers. The composite can be pleatable on different kinds of pleating machines. It is also possible to mix different fibers (a wide range of natural, mineral, synthetic and man-made fibers of varying



8.10 HYCOKNIT® – high efficiency cleanable pile fiber stitch-bonded nonwoven composite (used with permission from Sächsisches Textilforschungsinstitut e.V. (STFI), Chemnitz, Germany).

length) and obtain a wide range of fiber orientation ranging from random to parallel with the consequent differences in filtration performances and applications. The system is flexible to incorporate gas adsorption media (for example activated carbon granules) on-line in the middle layer, obtaining an efficient filter for gas odor removal. This innovative concept of wet lay technology can create nonwovens with special properties, i.e. high efficiency filter media (or gas-adsorption filter media) combined with a very low pressure drop. These advantages make these nonwovens extremely useful for applications such as cabin air or HVAC where high permeability assures a consistent air-flow into the filtration system (Ahlstrom Technical Specialties, 2001; Montefusco, 2005). It may be noted that there are other ways of creating a gradient structure, for example the Intrepid™ filter medium by Kimberly-Clark Worldwide, Inc. (discussed in Section 7.13.1 under the subheading Gradient density filter media).

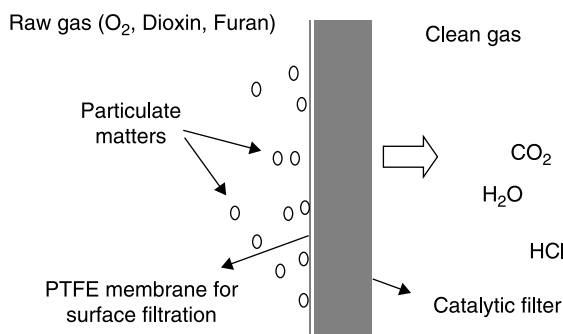
8.4 The role of composite nonwovens in filters: combining different separation technologies/ functionality into one filter medium

8.4.1 Conversion of gases with simultaneous control of particulates via catalytic filter

As demands to meet energy and space-saving requirements increase, chemical engineers have had to develop new multifunctional reactors which have the ability to conduct multiple functions in addition to the necessary chemical reaction, including functions relating to separation, heat exchange, momentum transfer and

secondary reactions amongst others (Agar, 1999; Dautzemberg and Mukherjee, 2001). One feature common to all multifunctional reactors is their facilitation for the substitution of a single process unit in place of at least two, allowing all necessary operations to be carried out simultaneously. The catalytic reactions occurring in catalytic filters have been found to be useful in one such application, as they are able to remove particulates from flue gases (from, for example, waste incinerators, diesel engines, boilers, pressurized fluidized bed coal combustors, or biomass gasifiers, amongst others) whilst also abating chemical pollutants (including nitrogen oxides, dioxins, volatile organic compounds, tar and carbonaceous material). A thin layer of the catalyst is applied directly onto the filter material, which may either be rigid (consisting of filter tubes made of sintered granules) or flexible (nonwoven fabrics) (Matatov-Meytal and Sheintuch, 2002; Fino *et al.*, 2004). In applications such as incinerators, pyrometallurgical and cement kilns, the combination of surface filtration and catalysis (ALSOM Power, 2008) has created new methodologies which destroy gaseous dioxins and captures solid phase emissions, leading to operational cost savings.

Efficient particle, NO_x and VOC removal can be achieved via the use of fabric filters or ceramic hot gas filter elements (foam candles) which combine a fine filtering outer membrane with an integrated catalyst in the support structure (Spivey, 1993; Bonte *et al.*, 2002; Hackel *et al.*, 2005; Nacken *et al.*, 2007; ALSOM Power, 2008; Heidenreich *et al.*, 2008). The combination of a filter and an SCR (selective catalytic reduction) reactor in one unit (Fig. 8.11) is facilitated by such elements. PTFE lamination is able to function at a continuous temperature of 260°C , so the development of a catalyst capable of the selective catalytic reduction (SCR) of NO_x with ammonia and simultaneous combustion of VOCs at such a temperature is also useful (ALSOM Power, 2008). One such innovative catalytic filter concept has been reported by Fino and co-workers (2004). This concept for reduction of NO_x and the combustion of PAHs (polycyclic aromatic

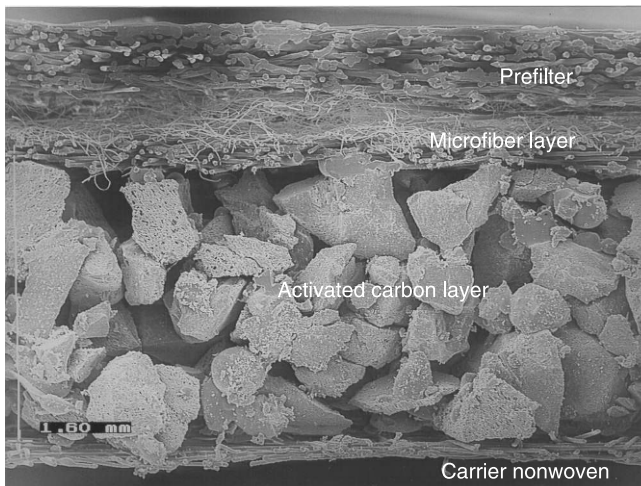


8.11 Combining the principles of surface filtration and catalysis (reprinted with permission from Mukhopadhyay (2010), Taylor & Francis, UK).

hydrocarbons) present in incinerator flue gases, was based on a structure combining catalytic foam with a laminated fabric filter for fly-ash filtration.

8.4.2 Contaminants adsorption with simultaneous removal of particles

As well as collecting particles, the removal of gaseous components such as odors or corrosive gases from air becomes increasingly important in filtration, specifically in air filtration. There are many applications where adsorption of odor/gases are important while removing particulates such as medical and surgical source capture (laser odors, disinfection odors, etc.), industrial vacuum cleaner filters, personal protection (masks, cabin-air filters, military environments, etc.), smoke/fume exhaust filters, etc. Zeolites, ion exchange resins, alumina, baking soda (sodium bicarbonate), activated carbon and other materials can be used as adsorbents and are available as powders, irregularly shaped granules, extruded granules or in the form of fibers. The majority of the nonwovens used for gas adsorption consist of carrier nonwoven layers covered with activated carbon and a prefilter nonwoven layer (Fig. 8.12). The nonwoven layers perform particulate filtration and the activated carbon layer separates molecular contaminants by adsorption. With average surface areas of around $1000 \text{ m}^2/\text{g}$, the activated carbon surface is very irregular, with pore sizes ranging from 0.5 to 50 nm. This feature allows the surface to absorb substances with widely varying particle sizes. In addition, water vapor is not favorably adsorbed by activated



8.12 Nonwoven filter medium with activated carbon for gas adsorption (reflection electron microscope, REM) (used with permission from Freudenberg Filtration Technologies, Weinheim, Germany).

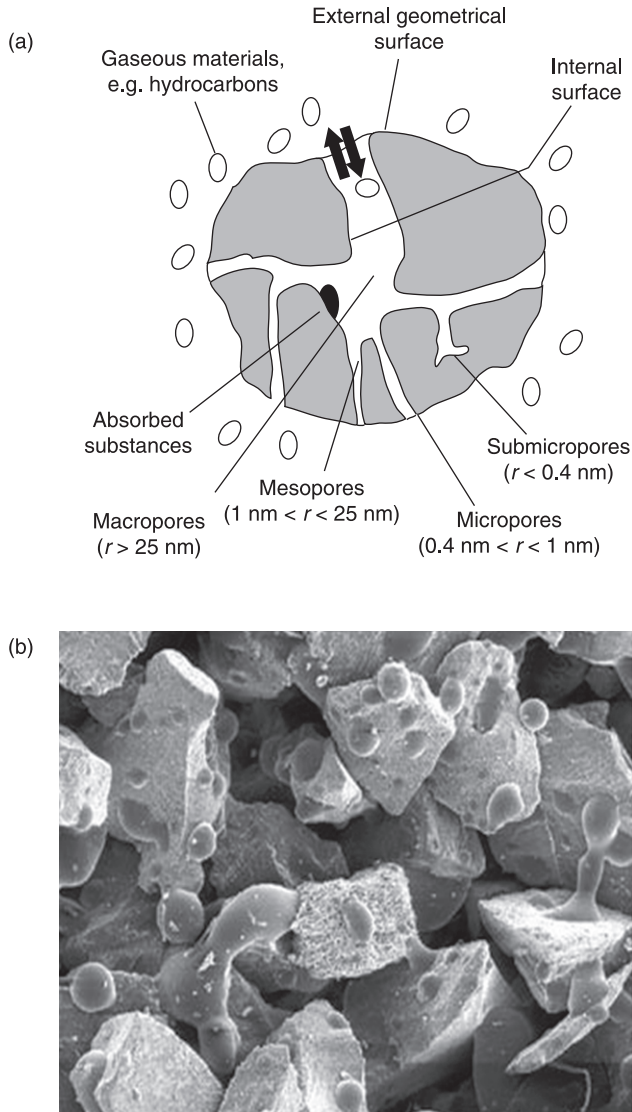
carbon, as activated carbon is nonpolar. Due to this the surface can capture organic vapors at relatively high humidity. In addition, carbons with smaller pore sizes facilitate the increased capture of high-volatility vapors, due to having a greater affinity for them.

A variety of different technologies exist to adjoin activated carbon powder or granules with the nonwoven filter medium. This could be printing, impregnation, applying a chemical binder or thermal bonding resin or spraying fine hot-melt fibers. All technologies have common aims, to keep the surface of the activated carbon as free as possible to enhance the adsorption mechanism and to maximize the loading capacity for gaseous components or odors (Fig. 8.13) (Sievert, 2011). In a study, sorbent particles (active carbon, aluminium oxide, chitosan, etc.) are caught by microfibers in meltblown nonwovens. These nonwovens do not contain any additional agent to bind sorbent particles, hence the durability of binding sorbent particles is the key issue in this technology. Organoleptic assessment is useful to determine the durability of active carbon particle bonds in the composite nonwovens. The assessment of one part of a filtration face mask made out of composite nonwovens with active carbon showed that sorbent particles had a tendency to drop off (Nowicka, 2003).

Adsorbent media are increasingly being used for the removal of unpleasant odors and emission fumes in automotive cabin air filters, with great success. Absorbent media are also frequently employed in the removal of toxic and obnoxious chemicals from air in applications such as respirators and gas masks. Active carbon and similar adsorbents are used to combat the toxic effects of chemical agents in military affairs, to protect both military personnel and civilians. Liquid and soluble contaminants are also removed from fluid streams by filter media containing adsorbents, via surface adsorption, i.e. the medium surface attracts the contaminants and the physical chemical effects hold them.

Filter media are used in liquid filtration for the removal of unpleasant-tasting contaminants and hydrocarbons from drinking water. In home water filters, activated carbon filter papers (a form of wet laid medium) are used extensively to remove undesirable taste and odor contaminants. Adsorbents have become a key element of HVAC (heat, ventilation, air conditioning) systems in both the home and workplace in recent years. As activated carbon is extremely efficient at adsorbing most organic chemicals, it is unsurprising that it has become the most regularly used sorbent in HVAC systems. Figure 8.14 shows the filter with activated carbon for HVAC application. The filter (Austin air filter) is composed of a prefilter (to trap larger particles such as dirt, lint and hair), a layer with a carbon and zeolite mix (to adsorb odors and gases), and HEPA filter paper (to remove harmful airborne particles).

One of the commercial grade nonwoven composites, known as PLEKX[®], contains active ingredients greater than 82% of the media by weight to maximize adsorption and performance. A carbon layer is sandwiched between two nonwoven

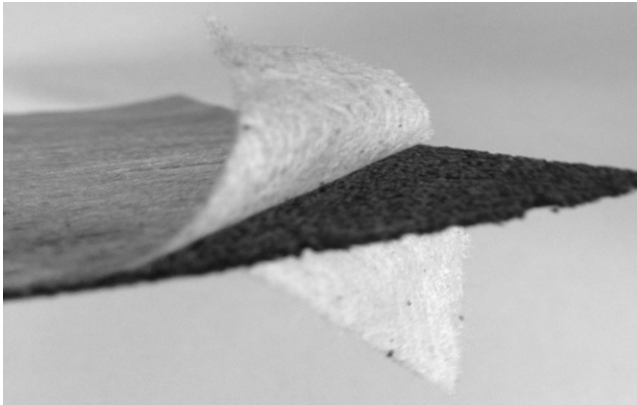


8.13 (a) Structure of activated carbon; (b) REM image (reprinted from Sievert, J. (2011)).

layers of PET substrates (Fig. 8.15) in which the inner layer is activated carbon particles held together with a thermal bonding resin (10% microbinder) top and bottom. The conventional adsorption product is coconut shell carbon, but this can be boosted with chemical impregnation for higher efficiency in critical gas applications. It is possible to use commercial carbon fiber of 5–10 μm diameter which offers a possible alternative to organic fibers and glass fibers for filter pads



8.14 Filter with activated carbon for HVAC application (courtesy of Austin Air Filters, 2013).



8.15 PLEKX[®] adsorption medium wherein an activated carbon layer is sandwiched between two nonwoven layers (used with permission from KX Technologies, LLC of West Haven, Connecticut).

and felts for extreme chemical and temperature use and to dissipate electrical charges, with additional advantage that the material can be activated as an adsorbent filter. The main limitation of carbon fiber as a filter medium has been its expense, coupled with the fact that the current fiber diameter sizes are higher resulting in reduced performance of current HEPA filters using microglassfibers. However, carbon fibers down to nanometer diameters are now becoming commercially available and these are going to be an exceedingly important component of the fiber filter media business.

The application of chemical impregnates can also be used to supplement physical adsorption via additional chemical reactions, increasing the range of vapors that activated carbon can adsorb. Recent work has led to the development of chemically impregnated fibers (CIF) which use smaller, more active sorbent particles than previously employed. Such CIFs allow the incorporation of such material as carbon, permanganate/alumina, or zeolite into a fabric mat. Types of impregnate based on chemical contaminants are well documented in readily available source material (Centers for Disease Control and Prevention, 2003).

8.4.3 Removal of microbes during removal of particles

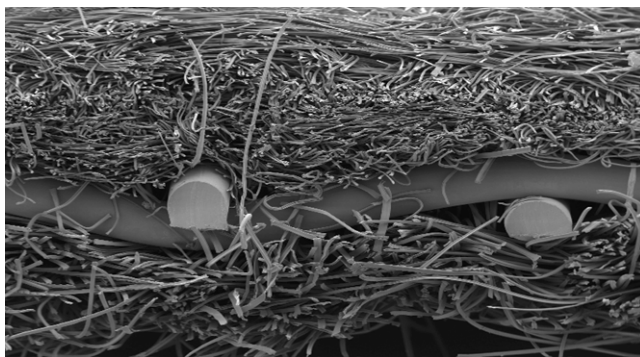
A number of filter medium and filter manufacturers are incorporating antimicrobial agents into their filter media for removal of microbes. It is worth mentioning that although HEPA filters are designed to filter out microorganisms, the arrested microorganisms can grow inside the filter medium under certain conditions such as sufficient nutrients, proper humidity and temperature (Maus *et al.*, 2001). Some organic media such as cellulose provide nutrition for microbiological growth. A function of activated carbon media in the HVAC filter is to adsorb organic material, which in turn makes the medium vulnerable to being a nutritional haven for microorganisms. In aqueous and high moisture air environments, biological activity can cause serious degradation of the filter medium and be a source of contamination downstream of the medium (Price *et al.*, 1997). Apart from being widely used for cleanroom filters (particularly in the food processing industry, hospitals, etc.), swimming pool and spa filters are logical candidates for removal of microbes in aqueous filtration.

It is important to note that silver is the most adopted antibacterial agent due to its strong antibacterial activity (Spadaro *et al.*, 1974), high biocompatibility (Joeger *et al.*, 2001), relatively nontoxicity, excellent resistance to sterilization conditions, and long-term durability of its antibacterial effect. There have been many reports utilizing several silver-doped polymers and, maybe the most worked polymer embedded silver nanoparticle and electrospun is polyacrylonitrile (PAN) (Hoda *et al.*, 2012). Antimicrobial nanofibrous filters (Tobler and Warner, 2005; Jeong *et al.*, 2007; Lala *et al.*, 2007) are found to be useful for improved antimicrobial functionality. In a report, a silver nanoparticles–chitosan composite was prepared by using a microcrystalline chitosan gelatinous water dispersion at ambient temperature and its aqueous solution was applied to the antibacterial finishing of Tencel/cotton nonwoven fabric. The finished nonwoven fabric showed excellent water absorption ability, air permeability and antibacterial activity against *E.coli* (Di *et al.*, 2012). There is also an application of enzyme type antimicrobial agents for the HEPA filter. The primary characteristic of the enzyme filter is to exterminate the captured microorganisms with the lytic action of immobilized enzymes to the filter (Taiwan Nitta Filter Co., Ltd, 2013).

8.4.4 Elimination/retention of static charge during filtration

Depending on application, there is a need of either elimination or retention of static charge during filtration. For cleanroom application, retention of static charge is beneficial; whereas in an industrial environment (e.g., the sugar industry) dissipation of static charge is most often required. Several nonwovens are available with a conductive surface to fulfill the requirements of static dissipation arising from explosive hazardous applications (Sievert, 2011). The high resistivity exhibited by the majority of synthetic fibers makes them a potential source for static build up, which can lead to arcing and explosions. In order to reduce such risks, a range of methods have been employed to increase the conductivity of filter media and facilitate the movement of any static build up directly to the ground. Such methods, which have varying degrees of durability, cost, efficiency, practicality and contamination potential, include the use of epitropic and stainless steel fiber admixtures, chemical coatings, aluminized coatings, carbon/resin coatings and carbon lines printed on a media. At the time of writing there is a clear market potential for the development of an efficient, durable, convenient conductive fiber which can be successfully applied to a wide range of filtration applications (Scoble, 2011). Mesh materials are frequently used in sandwich formations, primarily for static dissipation and also for structural support. Figure 8.16 illustrates the cross-section of a filter medium that contains a stainless steel mesh.

In HVAC application, retention of the static charge is useful for separating small particulates. Statically charging fibers can enhance the particle collection efficiency of the filter media used in HVAC. However, it is important to relate the operating behaviours of filters to their charging state. A good filter is one that is capable of preserving a high level of charge for as long a time as possible, and hence a high collection efficiency. The decay of the electric potential at the surface of combined nonwoven media is accelerated when the design of the air filter includes an activated carbon layer (Dascalescu *et al.*, 2010).



8.16 Nonwoven filter medium with reinforced scrim (used with permission from Sächsisches Textilforschungsinstitut e.V. (STFI), Chemnitz, Germany).

8.4.5 Removal of unwanted fluid/vapor during removal of particulate contaminants

Nonwovens are often employed in absorbent structures in order to contain the absorbent material during particulate contaminant removal. However, because structures such as those in diapers, hygienic pads, and wipes do not involve an element of separation, they are not considered as filter media. Although hydrophobic, polyolefins, have an affinity for oil. As such, they are frequently used to absorb oil from water, for example to control oil spills at sea. It should be noted that absorbency is often an undesired quality affecting a filter medium. Cellulose media has a tendency to absorb water, leading to softening and weakening of the filter structure and subsequently a reduced filter life. Furthermore, filtration performance may be inhibited by the fiber swelling caused by moisture absorption.

Air-laid nonwoven structures, largely based on cellulose material, or short staple synthetic fibers, including polyester, polypropylene, nylon or rayon along with super absorbent polymers (SAP), for example carboxy methyl cellulose (CMC), are frequently used for formation of composite structures. Within a composite, fibers are inherently more effective because of their complementary structure. They also outperform super absorbent powders in handling (Dewsbury, 1990). If a considerable amount of long synthetic fibers feature in the web produced, it can then be spunlaced (hydroentangled). The media can be effectively used for different application areas such as water removal from oils and fuels, air filtration, blood treatment filters and personal protective equipment.

In aviation fuel treatment, composite filter media consisting of super absorbent fiber (SAF) has found wide acceptance. They are used in the form of monitor cartridges which incorporate multi-layer nonwoven composite. These cartridges are capable of reducing particulates to <0.3 mg/liter of solids in effluent and reduce free and dispersed water to <5 ppm in effluent. Cartridges are based either on outside to inside or inside to outside fuel flow and offer excellent filtration rate capability. The flow through the system is halted when hit with a localized slug of water because of super absorbent gel block. Presence of water/solids in the incoming fuel will give rise to an increase in pressure differential, or a decrease in the flow rate, as the cartridges reach their maximum capacity for solids, water or a combination of both (Dewsbury, 1990).

8.5 Applications of composite nonwovens

The usage of composite nonwoven filter media in filtration is very popular worldwide. They are being widely used in industrial air filter bags, industrial fume cartridge dust filters, residential ventilation panels and pocket filters, air purifiers, automotive cabin air and air intake, to name a few. Some applications of composite nonwovens along with their constructional details are given in Table 8.1. It is important to note that both new requirements and novel products are continuously

Table 8.1 Uses of composite nonwovens in filters

Applications	Type of nonwovens
Industrial air filter bags	Membrane laminated over needlefelts Scrim reinforced needlefelts Scrim reinforced spunlace felts
Industrial fume cartridge dust filters	Membrane laminated over spunlace Membrane laminated needlepunch
Residential ventilation panels and pocket filters	Spunboded with meltblown composite (e.g., SM or SMS composites) Electrospun composite
Air purifiers	Glass nanofiber or glass microfiber/synthetic blends with cellulose or synthetic fiber support Nonwoven (spunlace) with activated carbon air filter fabric
Automotive cabin air and air intake	Meltblown composites with electrostatic material Meltblown composites with activated carbon Electrospun nanofiber composites
Automotive air intake	Meltblown/cellulose composites with fire retardant additives
Surgical face masks	Laminated meltblown composite Laminated glass microfiber
Respiration	Electrospun nanofiber with spunbond support Spunbonded with meltblown composite Spunbond composites with activated carbon
Vacuum bags	Electrospun nanofiber with wet-laid support
Fuel filtration	Resin treated blend of cellulose, polyester fiber and glass microfiber (wet-laid) Meltblown cellulose composites
Fuel filter coalescer	Resin treated blend of cellulose and glass microfiber (wet-laid) Layer of borosilicate fiber supported by two inner and outer stainless steel structures
Fuel filter coalescer separator	Resin treated cellulose with teflon or silicone treatment (wet-laid) Glass nanofibers and microfiber composite
Turbine and rotating machinery (bag)	Needlefelt supported nanofibers – electrostatic
Belt filters	Scrim reinforced needlefelt Double layer mono filament filter cloth clipped by stainless steel at both ends (potash fertilizer filtration)
Micron rated filed bag	Meltblown/needlefelt composite
Reverse osmosis prefilters	Laminated meltblown/cellulose composite Composite with activated carbon
Swimming pool filters	Spunbonded pleated with antimicrobial material

evolving as a result of market development and demand and this need for new products and technologies continues to grow. Disruptive technologies such as nanofibers are essential to growth and new product development across a range of fields, fueled by market responses, and the development of any new composite filter media would also originate from market needs or ideas. Looking at current market needs (Scoble, 2011) such developments may include:

- Non-polytetrafluoroethylene (PTFE) membranes.
- Fibers capable of communication through alteration (for example by changing color) to highlight potential problems such as exposure to toxins, excess temperature or dangerous wear levels).
- Fibers which could convert and/or neutralize pollutants, toxins, CO or other harmful gasses or solids.
- Fibers which could be charged and have polarity reversed, creating a textile electrostatic precipitator.
- Increased use of nanofibers, microfibers and splitable fibers in an attempt to fill the gaps between standard, fine, micro- and nanofibers.
- A longer-lasting, activated carbon coating for fibers to rival A/C depth filters.

8.6 Applications in air/gas filtration

8.6.1 HEPA filter

The primary issues that are always being pursued with particulate filter improvements are: (i) higher efficiency at lower energy consumption, (ii) longer filter life, (iii) greater dust load capacity, (iv) gaseous absorption and (v) easier maintenance without compromising filter efficiency. In all these improvements, development of the composite filter media is of prime importance. Usually, ultra-fine filters such as HEPA and ULPA elements use a sheet form of medium produced with glass microfibers with a graduated matrix to provide very high dust retention capacities. Nonwoven media, made from progressively structured thermally- (meltblown and spunbonded) and resin-bonded synthetic fibers, are gaining in use over glass fiber media. PP melt blown supported by spunbonded material are also used as HEPA filters. HEPA filter performance is found to be improved through appropriately structured meltblown nonwovens (Hassan *et al.*, 2012). There are many other variants of filter media composite structure such as the SMS (spunbond/meltblown/spunbond) process and variations thereof. The layered construction enables a gradual removal of finer airborne particles. In addition to being less expensive, filters exhibit greater durability, performance, safety, and environmental friendliness than their nonwoven glass fiber counterparts (Thiele and Badt, 1996). In addition, some designs offer varied separation modes within a single filter media. In automotive cabin air filters, for example, a nonwoven particulate filter layer is often combined with an activated carbon layer, offering further removal of odors and fumes.

For higher efficiency at lower energy consumption, the use of the layered fabric concept is also reported, where layers of finer denier fibers or even nanofibers can be incorporated in the fabric structure. Various finer fiber layers can be positioned at different locations within composite filter media to enhance the performance of HEPA filters. With Hollingsworth & Vose's (2013) nanoweb process, nanoweblayers (thickness in the range of 15 to 30 μm) can be applied directly to a filtration substrate, such as glass, cellulose or synthetic fibers. A second nanofiber layer of a similar or different polymer can also be applied as a coating (Leung and Hung, 2012). NanoWave®, extended surface synthetic media has been reported to meet ASHRAE bag standards and HEPA/ULPA challenges (Anon, 2008; Wertz and Schneiders, 2009).

In recent years, developments in fibers and process technologies have expanded the applications of stitch bonded, hydroentangled composite nonwoven fabrics in filtration (Schmalz, 1998). The use of composites in filter cartridges (pleated cylindrical shape) which exhibit a fabric outer filter and a PTFE inner membrane is also reported (Dotti *et al.*, 2007). In another development, polymeric fibers are mixed with glass fibers which can make the structure pliable and can add a significant amount of structural strength that allows pleating to be effective (Larzelere, 2006). This will enhance the filtration performance of HEPA filter media in a smaller space.

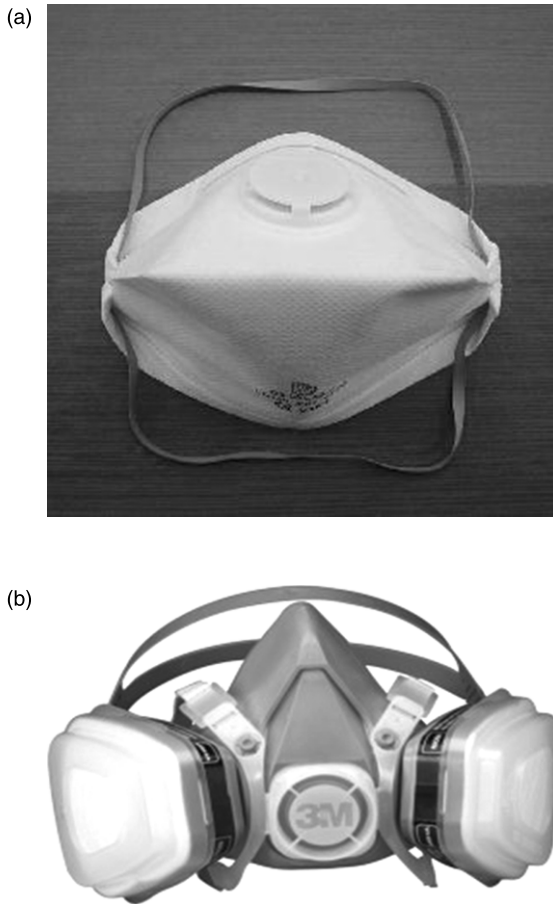
8.6.2 Industrial filters

Investigating methods for enhancing surface filtration is a common approach taken in developing industrial filter media. Although there have already been great improvements to the basic nonwoven structure, various methods to further enhance surface filtration are also available, in addition to the layered nonwoven fabric of membranes or coatings, fine/nanofibers, or trilobal/multilobal fibers at the upstream side. Of the several available techniques, membrane filters are becoming most frequently used for controlling fine particulates. As well as PTFE filter membranes increasing production costs, further research is still needed into their mechanical strength and subsequently their lifespan. As such, research and development related to this membrane arguably represents the fastest growing area of the filtration media market.

A variety of other composite forms are also being employed in industrial gaseous filtration. Use of metallic wire mesh inside the nonwoven structure is prevalent for dissipation of static charges in some specific industries. There is growing interest of using scrim needlefelt fabric, particularly in high temperature applications. Advanced composite products of this type will undoubtedly feature strongly as a future trend in this field, and the development of such products will facilitate the formation of structures that are not only more efficient in particle capture, but also have an increased filter life and enhanced performance capability in more chemically and thermally challenging environments. Combined, these benefits translate into operational cost savings and greater control of environmental pollution.

8.6.3 Respirator filters

Respiratory equipment is used throughout the world to provide personal protection from a variety of noxious gases, vapors and aerosol hazards which could cause harm and even death to humans, if inhaling wood dust, chemicals, coal dust, pesticide spraying, spray painting and aerosol transmissible diseases such as influenza, diphtheria, SARS (severe acute respiratory syndrome) and swine flu. In contrast, surgical face masks have not traditionally provided protection to the wearers but have been used to keep mouth generated particles from harming a patient in a healthcare situation. Two key types of respirators, air-purifying respirators and air-supplying respirators, are shown in Fig. 8.17. The latter either



8.17 An example of typical respirators available in the market (courtesy of Focus Technology Co., Ltd, 2013, and 3M Collision Repair, 2013).

have a self-contained air supply or are supplied by an external air source. Air-purifying respirators are constructed from three key parts: a facemask; a filter or cartridge filter to remove dust, smaller particles and mists; and cartridge filters to remove chemical gases and fumes. Air-supplying respirators, in contrast, directly draw clear air from either an external source or a self-contained air supply.

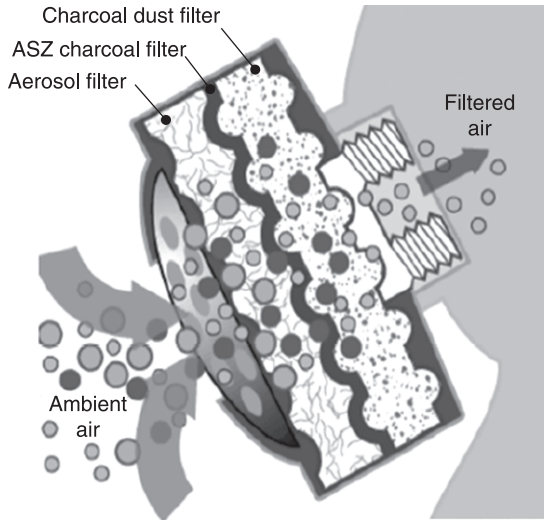
In yet another classification scheme, respirators can be graded as non-powered air-purifying particulate arrestors, powered air-purifying respirators, chemical cartridge respirators and surgical and healthcare facemasks. In each case there are varied requirements based on application. For illustration, facemasks help in stopping large-particle droplets, splashes, sprays or splatter that may contain germs (viruses and bacteria) from reaching the wearer's mouth and nose and may also help to prevent the wearer's saliva and respiratory secretions reaching those who happen to be nearby. The medical facemasks have five specific performance characteristics (Graham *et al.*, 2003):

- bacterial filtration efficiency;
- submicron particulate filtration;
- differential pressure (an indicator of breathing comfort);
- fluid penetration resistance (to protect the wearer from blood spurts);
- flammability.

To meet these varied requirements, a layered composite structure is used, which is typically SM/SMS or a more complex structure comprised of an inner cover, one or multiple meltblown fiber layers, a porous film layer, and an outer cover. The meltblown fiber layers provide the aerosol filtration performance, while the porous film layer provides the fluid resistance. The remaining layers are incorporated to improve wearer comfort by minimizing abrasion and to allow for high-speed processing of the composite material. Polymeric nanofiber webs are a relatively new addition to the range of materials that may be used in a composite structure design for protective apparel applications (Graham, 2003). When using sorbent particles, bonding durability of the particles with nonwovens is important for its effective functioning (Nowicka, 2003).

The cartridge respirator can provide careful protection against multiple hazards. It can handle not only dust and mist, but also threat agents. The cartridge filter normally has multiple layers for different functionalities as shown in Fig. 8.18. The removal of the agent was brought about by its physical adsorption onto activated charcoal having an extraordinary large surface area as high as $300\text{--}2000\text{ m}^2\cdot\text{g}^{-1}$. Further increased protection can be achieved by impregnating the charcoal with substances such as copper oxide since it reacts chemically with certain threat agents (Verdegan *et al.*, 2007).

In air-purifying respirators, filter media is usually a composite with meltblown nonwovens as a middle layer responsible for filtration and spunbond or needlepunching nonwovens used as internal and external layers. The improvement of filtration efficiency can be achieved with the composite of nanofiber electrospun



8.18 Illustration of cartridge respirator filter structure.

material with a meltblown layer (Krucińska *et al.*, 2012). In the case of respiratory tracks, protection against bioaerosols, additionally antimicrobial properties of fibers used in filtering material, plays a very important role (Rengasamy *et al.*, 2004). Bioactive fibers can show biostatic or biocidal activity against microorganisms. Silver ions, antibiotics, *N*-halamines and quaternary ammonium are cited as bioactive agents used in antimicrobial modification of nanofibers (Yang *et al.*, 2003; Jeong *et al.*, 2007; Lala *et al.*, 2007; Tan and Obendorf *et al.*, 2007).

Performance of respirators is largely dependent on the removal of nanoparticles and agglomerates since the special properties of nanoparticles give rise to concerns about the potential health hazards posed to workers or users that are exposed to them (O'Hern *et al.*, 1997). The respirator is also adaptive to the environment it exposes, to not only remove particulates at high efficiency and high capacity, including the threatening aerosols (toxic agents and bioaerosols), but also to detect the kind of toxins that are captured or inhaled, so quick and correct medical response can be initiated in case of an emergency.

8.6.4 Miscellaneous filters

Vacuum cleaners

One of the newer ways to categorize vacuum cleaners is bagged or bagless. The bags are both reusable and disposable (Cox and Healey, 2003). In the past few years, there have been significant new developments such as synthetic ultra-fine fiber media, electrets, and composite media (Hsieh, 2001). Vacuum bags with the



8.19 Vacuum filter (used with permission from Graver Technologies LLC).

filter papers enhanced by the inclusion of a meltblown substrate lining has been one such popular form of composite medium developed in recent years. Once filled with dirt, the filter bag is usually disposable (Hutten, 2007). In a patent disclosure, the composite includes an outermost support layer and a filter media in the form of a multi-component sheet having a first spunbond layer contacted to the outermost support layer, with a second spunbond layer forming the innermost portion of the vacuum cleaner bag. In between the aforesaid spunbonded layers, preferably four layers of meltblown webs, made up of electret polymer fiber with charge stabilized additives (fatty acid amide), are placed. Generally, all layers are composed of polypropylene. The composite filter media have enhanced filtration performance characteristics, particularly suitable for vacuum bags. Apart from particulate separation, vacuum filter can also remove gases/odors. Typical bagless industrial vacuum cleaners which simultaneously remove both gases and particles are shown in Fig. 8.19. The filter medium (PLEKX[®]) is a composite filter exhibiting adsorption of high levels of gases and/or odors.

Air purifiers

Air purifiers, which may also be referred to as room air cleaners or residential air cleaners are usually portable units designed to provide clean air in residential environments. Such units usually contain activated carbon or a similar adsorbent to facilitate particulate and odor removal. In order to increase the efficiency of the particulate removal, an electrostatic charge is often induced in the media. Other forms of filter media include glass microfiber HEPA, synthetic fiber and glass microfiber blends, or composite media backed by cellulose or synthetic fiber nonwoven supports.

Air demisters

Air demisters can be classified in two distinct groups: (1) air-moisture demisters which are used to remove moisture from industrial, commercial, and residential air streams; and (2) air-oil demisters which are used to clear airstreams of hydrocarbon and oil mists. In both cases the coalescing mechanism is an important part of separation. The layered nonwoven composite is useful in these applications.

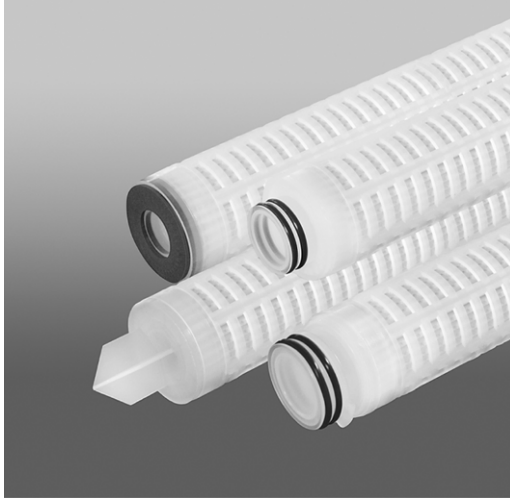
8.7 Applications in liquid filtration

In liquid filtration, composite structures are often used to provide gradient density filtration. They are also used as prefilters to membrane filtration and reverse osmosis. Needlefelts for liquid filter applications are usually scrim reinforced to provide adequate strength. Use of welded liquid filter bags containing a layer of meltblown polypropylene microfibers is quite common. It also contains laminated multiple layers of graduated nonwoven material; the polypropylene microfibers being secured by ultrasonic means. Another application for composite structures is taste and odor adsorbing media in drinking-water filters. These contain an activated carbon layer. A few uses of composites in liquid filtration are given below:

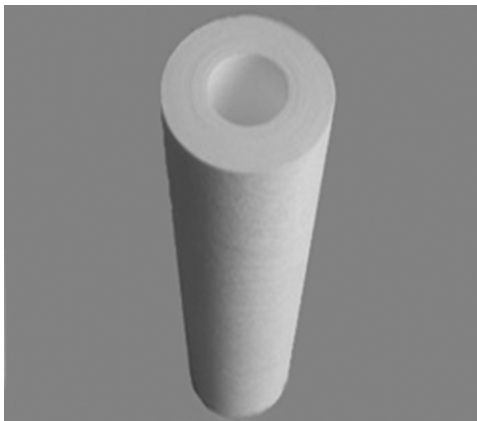
- In absolute rated filter cartridges, the filter media can consist of three layers: a glass fiber web between polyester filter layers for superior removal performance, strength and stability. In another design, PTFE membrane laminated composite media (pleated form) are used in cartridge (Fig. 8.20). The filter cartridge can be used in completion fluids, work over fluids, gravel pack fluids, waste-water treatment, diesel, fuel oil, process water, prefiltration RO, acids, solvent, gels, etc.
- In spunbond filter cartridges (Fig. 8.21), the spunbond graded density filter matrix (lower density at the surface of the filter with progressively higher density toward the center) can be used in many applications such as oil and gas, fine chemicals, petrochemicals, food and beverage, electronics, metal, etc.
- An advanced fuel filter utilizes nanofiber composite media to meet the challenge for water and particle control. The high pressure common rail fuel injection system (HPCR) requires fuel cleanliness levels far more demanding than past fuel systems or even high pressure hydraulic systems. Compared to existing fuel filters, the advanced fuel filter exhibits better water and particle removal. This results in reduced wear of HPCR components and reduced engine downtime (Wieczorek *et al.*, 2012).
- In a study by Doh and co-workers, poly-vinylidene fluoride (PVDF) was fabricated using electro-spinning technology onto Kapok nonwoven and tuned into composite filtration/separation media. PVDF polymers possess excellent mechanical properties and resistance to severe environmental stress, good chemical resistance, good piezoelectric and pyroelectric properties.

These specific properties can be utilized for separating oil and water in various filtration/separation media systems. Whereas Kapok is natural fiber as a form of seedpod, the characteristics of this fiber are light, very buoyant, resilient and resistant to water. Composite nonwovens showed good oil/water separation performance (Doh *et al.*, 2012).

- Dewatering of industrial sludge by geotextile tubes is found to be economical and environmental (Lin *et al.*, 2012). The geotextile tube can be made out of woven–nonwoven composite.



8.20 Filter cartridge (used with permission from Graver Technologies LLC).



8.21 Spunbonded filter cartridge (courtesy of Krishna Filters and Fabrics, 2012).

8.8 Applications in engine filtration

The major uses of engine filtration are cabin air filtration, fuel filtration, lube oil filtration and air intake filtration.

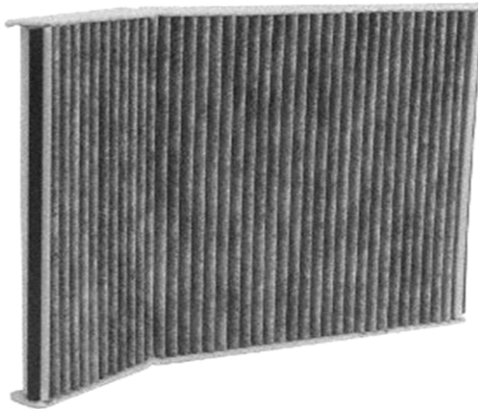
8.8.1 Automotive air and cabin filter

Cabin filter

Providing comfort and protection for passengers is the main function of the cabin air filter. In addition to preventing passengers taking in particulates such as pollens, spores and allergens, cabin air filters can also protect against odors and harmful gas pollutants. A typical cabin filter is shown in Fig. 8.22. The composite structure can be made by combinations of several types of media (Bräunling *et al.*, 2000) as enlisted below:

- Electrospun nonwovens, which combine electrostatic effects with nanofiber filtration.
- Triboelectrically charged needlepunched nonwovens.
- Split charged fiber media.
- Meltblown media.
- Spunbonded nonwovens.
- Dry laid webs.
- Wet laid webs.
- Adsorptive media (activated carbon and activated alumina).

In general, there are two types of cabin air filters: particle filters and combi-filters. The former consists of one or more layers of synthetic nonwovens such as a PP meltblown in combination with a spunbond, whereas the latter consists of a



8.22 Cabin filter.

composite of synthetic nonwovens (particle filter and support layer) and activated carbon (Maltha *et al.*, 2012). In order to apply spunbond nonwovens as a support layer or prefilter for cabin air filter media, the following important performance requirements must be satisfied:

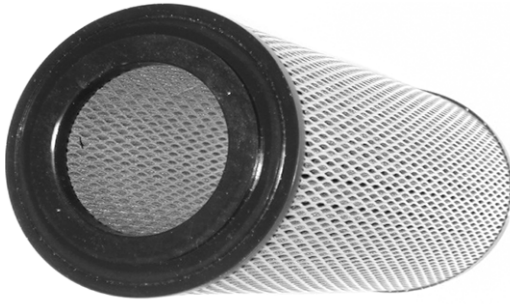
- high air permeability for the lowest pressure drop (energy savings);
- good coverage in the case of activated carbon filters;
- high stiffness to get optimal pleats;
- high dimensional stability for good processing and stable pleats;
- good adhesion to the filter medium such as a PP meltblown.

All these performance requirements are important for good filter media efficiency. Because of the unique manufacturing process of the bicomponent nonwoven, it is possible to tune its properties in such a way that the nonwoven gets optimal properties for specific filtration applications (Maltha *et al.*, 2012). Recently, more and more nanofiber/bicomponent/meltblown media are combined for particle filtration, whether purely mechanical or electrostatically charged or a combination thereof, with the benefits of activated carbon. These combined filters not only stop particles but also absorb a multitude of gasses and odors. New developments in the manufacturing of nonwoven media containing activated carbon, which tightly encapsulates the carbon particles, now allow manufacturers to easily pleat these media and hence design filters for a wide variety of shapes and sizes. By means of activated carbon applied over flat and even layers on various textiles (Diederich, 2011) odors and VOCs in the automotive interior can be controlled. Different activated carbons can be used according to what substances and how much gas and odor filtration are required to be adsorbed. As typical cabin air filters cannot catch emissions in the car interior, especially when the car is stationary, car interiors can be made out of the composite containing activated carbon. The increasing public awareness of air quality is expected to move cabin air filters into more and more cars, therefore further expanding this market (Barrillon, 2005).

The Hollingsworth & Vose Company, Inc. (2013) promotes adsorptive filter media with multilayered structures that remove vapors and gases from the air space. Their media can be combined with almost all particulate filtration media and scrims. Ahlstrom products (2013) has designed its Trinetex® technology for particulate filtration of cabin air. This unique technology employs a gradient density effect to increase dirt-holding capacity, through a design consisting of a three-layer wet-laid medium. In order to provide optimized filtration efficiency, mechanical and electrostatic filtration are combined, whilst flame retardancy and antimicrobial treatments are also available to further enhance the filter media.

Engine air filter

The purpose of an engine air induction system is to deliver clean air to the throttle body of the engine, while providing engine sound tuning with minimal power



8.23 Car engine air filter.

loss. A typical engine air filter is shown in Fig. 8.23. Automotive air filtration and heavy duty air filtration are the two main air intake filter categories for engine powered vehicles, and require media with quite different properties to meet the very different demands of each system. As the automotive air-intake filter is frequently exposed to the high temperatures generated by a running engine, heat and temperature resistance are important requirements of the filter medium used, whilst additionally being expected to be flame retardant in some cases. For such applications the filter elements are single use, and once they have come to the end of their useful life they are disposed of.

The most commonly used filter media is resin treated cellulose from the wet lay process. Synthetic fibers may be used to provide reinforcement for applications where higher burst strength and enhanced durability are required, such as for use in military vehicles. Filter media with a nanofiber coating have also generated much recent interest. These nanofibers also show very high initial efficiency compared to standard cellulose media which only achieve their targeted efficiency level after they have built up a sufficient dust cake on their surface. However, there are still challenges such as cost, chemical compatibility, durability, nanofiber layer adhesion and uniformity, and some hazards associated with solvent removal and disposal (Chuanfang, 2012).

8.8.2 Lube oil filtration (Hutten, 2007)

Within an engine, particle build-up may develop from various different sources. In protecting the engine from the wear and abrasion caused by such contaminants, lubrication oil filters (Fig. 8.24) play a key role. Ensuring oil is sufficiently clean is key to preventing damage, particularly in areas where the oil operates in the narrow gaps between moving parts (for example at the bearings and annular spaces between the piston and wall). The advent of composite structures for lube oil filtration can greatly enhance the performance of an engine.



8.24 Lube oil filters.

8.8.3 Engine fuel filtration

The two key vehicle engine fuel systems are based on either gasoline or diesel fuel, and varied filtration media have been produced for the filters in these systems. Different media offer a variety of useful characteristics so can be selected for use depending on the required performance and environmental conditions of a particular system. Gradient density cellulosic media, gradient density/dual-phase cellulose-microfiber glass, and cellulose-microfiber meltblown glass are all used as filter media in engine fuel systems.

8.8.4 Transportation systems for fuel

From ocean tankers, barges and rail to trucks and pipelines, there is currently a varied range of distribution systems that distribute oil and fuel to varied locations (Hutten, 2007). The contaminants include particulate matter, moisture, and micro-organisms such as bacteria and fungi. Apart from the particulate filter, a separate coalescing filter medium can be used for removal of moisture from fuel. The typical coalescing media for the filter inlet element is usually a resin-treated wet-laid medium composed of a blend of cellulose fibers and glass microfibers. Sometimes synthetic fiber such as polyester is added for greater flex resistance. In filters, a fairly hydrophilic fiber surface is desired that attracts water droplets and holds on to them as they grow in size by being struck by additional droplets. Media treated with phenolic resin generally have the right surface properties for good coalescing and separation efficiencies. Eventually, the coalesced water particles will be of sufficient size to be blown off the fibers by the fluid stream passing through the medium. Downstream of the medium, the water droplets are of sufficient size to settle gravimetrically in the settling sump. It is key that the exit

element or separator is extremely hydrophobic, rejecting any small water particles entrained in the fuel stream. The addition of very low energy media (such as a fluorocarbon or silicone) as a coating for the exit elements can enhance this.

8.9 Conclusion

The development of composite nonwovens leads to improved performance of nonwovens in many areas of filtration.

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Composite nonwovens in medical applications

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Abstract: This chapter reviews the role of composite nonwovens in medical applications. It covers surgical gowns, clinical wearable products, wipes, wound dressings, pads, swabs, scaffolds for tissue engineering, hernia meshes, filtration materials, and incontinence products. Commercially available, innovatively designed composite nonwovens for various medical applications are improving the quality of life of many people. Specific research needs have been highlighted to further improve the effectiveness of these products. The chapter ends with some perspectives for the use of composite nonwovens in medical applications in the future.

Key words: composite nonwoven, fibre, cell, wound, scaffold.

9.1 Introduction

Composite nonwovens are fibrous materials, in which several layers of different fibres are either bonded together or combined with other textile components, while their felt characteristics remain predominant. Composite nonwovens are generally prepared by combining multiple fibrous layers of different types of polymers, fibres or textile components. Integration of multiple fibrous layers can be achieved by passing them through a set of hot rollers, needle-punching, stitch-bonding, ultrasound treatment or high-frequency welding. Such nonwoven products can be tailored to meet the requirements of the following specific clinical applications:

- personal healthcare/hygiene products, such as surgical gowns, masks, wipes, surgical drapes and bedding;
- non-implantable medical dressings, including wound dressings and bandages;
- implantable medical products, including scaffolds for tissue regeneration and orthopaedic structures.

Nanofibrous nonwoven matrices, made by using the electrospinning technique, are beyond the scope of this article. However, extensive research work is being conducted in the development of electrospun matrices made up of composite nanofibres for medical applications (Soliman *et al.* 2011; Zhang *et al.* 2009; Kai *et al.* 2013).

9.2 Surgical gowns

The main function of a surgical gown is to provide an appropriate level of hygiene, comfort and protection for surgeons and healthcare workers from blood-borne pathogens. The recent prevalence of infectious diseases such as AIDS, hepatitis, and severe acute respiratory syndrome (SARS) demonstrates the critical need to develop efficient surgical gowns, gloves and masks to ensure the highest level of protection.

A critical performance factor in protective surgical apparel relates to the ability to provide a barrier to microbial transfer from a non-sterile to a sterile side of the fabric. Microbes and pathogens can pass through the fabric, carried by dust particles or liquids such as body fluids (blood, perspiration, etc.). According to the definition of the Centers for Disease Control and Prevention (CDC, USA), liquid-resistant apparel allows minimal amounts of liquid to penetrate when pressure is applied. Liquid-proof apparel does not allow any liquid to penetrate at all (Mangram *et al.* 1999).

There is great demand for cheap disposable gowns in the cost-conscious healthcare sector. Over the last few years various strategies for developing single-use fabrics have evolved, using spunbonded-meltblown-spunbonded (SMS), spunlace hydroentangled, triplex or bicomponent fibrous webs, with or without chemical finishes to resist liquid penetration. Disposable SMS fabric can be formed by sandwiching an inner thermoplastic meltblown microfibrinous web between two outer nonwoven webs of substantially continuous thermoplastic spunbonded filament, where the spunbond layer provides strength and dimensional stability while the meltblown layer provides the barrier property. The microfibrinous nonwoven meltblown layers provide a barrier impervious to pathogens in the composite nonwoven fabric. However, various surgical procedures entail an extent of splashing, liquid strike-through, aerosol generation, or applied pressure, and can be of long duration. Care should therefore be taken in selecting single- or multiple-use gowns during specific procedures.

Leonas and Jinkins (1997) compared eight commercially available surgical gowns, among which five were disposable nonwovens and three were reusable woven fabrics. Four of the five nonwoven fabrics investigated were made from polypropylene-based SMS nonwoven fabrics and hydroentangled wood pulp and polyester of spun-lace fabrics. SMS nonwovens showed better efficiency in preventing the transmission of *S. aureus* and *E. coli* in a saline solution, as compared to woven fabrics. Lankester *et al.* (2002) studied the extent of bacterial penetration through disposable gowns made of spun-bonded polyester and wood pulp, as compared to reusable woven polyester gowns; the results clearly showed a comparatively inferior barrier property for reusable woven polyester fabrics. Taken together, as a very generalized conclusion (McCullough and Schoenberger 1991), polypropylene-based gowns (for example, 97–100% polypropylene, SMS laminates) provided the greatest protection against blood strike-through and

microbial penetration. Gowns composed of a single layer of nonwoven fabric provided the next highest level of effectiveness. Reusable gowns composed of 100% woven cotton provided a minimal level of protection.

9.3 Surgical facemasks and other clinical wearable products

Other than surgical gowns, several other wearable products are currently demanding attention from researchers, such as shoe covers, caps, facemasks to be worn by surgeons during surgery, facemasks for patients or caregivers, facemasks for health workers handling outbreaks of airborne diseases (SARS virus, H1N1 flu, bird flu, etc.), and masks for sanitation workers working in dusty environments. Previously, all such reusable hospital garments were made using conventional textiles (cotton, cotton-polyester, etc.), but these have now been linked to increases in so-called 'Hospital Acquired Infections'. Pathogenic bacteria present on the scalp and skin are reported to have caused epidemics (Dineen and Drusin 1973); it is therefore highly important that efficient coverings are available during surgery. All over the world, major care is being taken to reduce patient-to-patient transmission of resistant pathogens such as methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant *Enterococcus*. Nonwoven products remain the most common choice for protection, sometimes with an additional active coating.

Surgical facemasks are usually composed of three layers of an SMS nonwoven fabric, where the meltblown material acts as a filter. The design of most surgical masks includes three pleats/folds to allow the user to expand the mask to cover the area under the nose and under the chin. This design may be sufficient to protect the wearer in dusty environments, but these products are not particularly effective in offering protection from airborne pandemic diseases or in environments full of aerosols.

Several new designs of respirator mask that use advanced strategies are currently coming in the healthcare markets. For example, the multiple-use respirator mask introduced by Carey International Ltd, Westerly, RI, USA, consists of a needle-punched, four-ply nonwoven fabric in which two outer layers contain silver/copper zeolite compounds permanently embedded onto the fibres, and two inner filtration layers are designed to prevent microbial or particulate penetration (complying with the National Institute of Occupational Safety and Health standards N95 and N99). The outer layers have been demonstrated to kill *Streptococcus pyogenes* and methicillin-resistant *Staphylococcus aureus* and deactivate strains of H1N1 and H5N1, as well as common flu and other viruses. The N95 masks offer 95% or higher particle filtration efficiency.

The main limitation in the performance of shoe covers for clinicians and healthcare professionals is frequent rupturing during use (Carter 1990; Jones and Jakeways 1998). Blood easily soaks through many commercially available shoe covers, and better bacterial and liquid barrier properties are needed.

Although all these products have been commonly used for many years (Eisen 2011), there is scope for innovation in their design. For example, facemasks for health workers involved in flu pandemics must remain effective for at least a few weeks, but the standard single-use masks currently available remain effective for only a few hours. Efficient pathogen monitoring and detection mechanisms should be available for these masks.

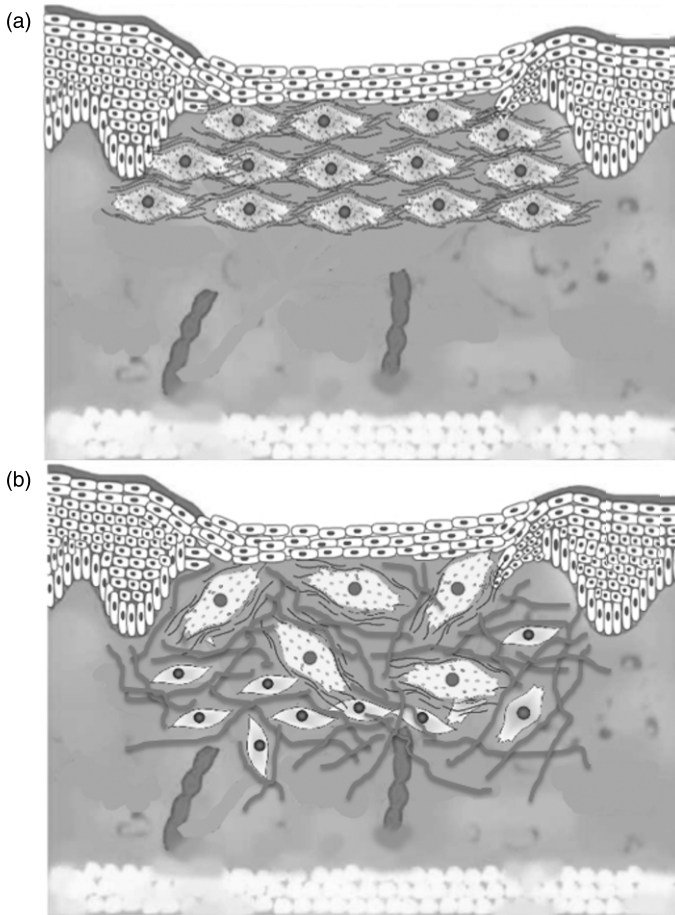
9.4 Wipes

The wipes market is experiencing massive growth, and there has been a constant stream of new nonwoven products across a number of categories, which have been innovatively applied. Examples include Procter & Gamble's 'Swiffer' household floor wipes and L'Oreal's make-up removal wipes 'Revitalift'. An extensive review of wipes is given in Chapter 6 of this book.

9.5 Wound dressings, pads and swabs

Mammalian embryos and some amphibians can spontaneously regenerate their tissues after severe injury. Adult mammals typically recover from such injuries by a 'repair' process, eventually developing scars. At the price of wound closure, severe wound contraction and scar tissue formation often cause serious clinical complications and life-long disfigurement for the survivor. During healing of skin wounds, a group of contractile cells (myofibroblasts) migrate in the wound bed. These cells express cytoplasmic bundles of microfilaments (stress fibres), using which they apply contractile forces to shrink the injured site. Eventually the wound site is filled by an irregular dense collagen fibrous matrix (Tomasek *et al.* 2002). When a nonwoven matrix is implanted within the wound bed, those contractile cells migrate randomly, following the randomly oriented fibrous architecture of the nonwoven matrix. This can result in disorientation of major axes of contractile cells and the disruption of organized cell contraction at the edges of the wound. Thus, randomization of individual force vectors of contractile cells will reduce rapid contraction of wound edges (Fig. 9.1). A significant reduction in the number of contractile cells has also been reported when the wound is treated with a nonwoven scaffold during dermis regeneration (Murphy *et al.* 1990). Despite detailed understanding of wound healing mechanisms, scarless healing in adult humans still remains a utopian concept, but extensive research is ongoing to develop bioresponsive fibrous material, such as collagen-glycosaminoglycan bicomponent fibrous web, which will be able to inhibit scar formation and cause controlled contraction (Yannas 2013).

Many basic composite nonwoven dressings are commercially available and are regularly used. These are relatively inexpensive, readily available, and versatile enough to treat several types of wounds. The simplest form is as a single nonwoven layer with a transparent waterproof backing (generally polyurethane film), which



9.1 (a) Skin wounds without nonwoven myofibroblasts get oriented to form scar tissue; (b) in the presence of nonwoven fabric, random scattering of myofibroblasts inhibit scar tissue formation.

forms an attachment to the skin to keep the dressing in place while the nonwoven absorbent layer contains medication to promote healing.

Strategies to induce fast clotting are critically needed for wound dressing materials to achieve minimum blood loss and absorption of exudates. Numerous commercial wound dressing products use composite nonwoven adhesive tape (usually polyester) as an absorbent pad/wound contact layer. In some dressings, these absorbent pads are placed continuously edge-to-edge, whereas in some products they are located as an island in the central region of the dressing. Such dressings can handle low-to-moderate exudate. In some dressings, such as Kendall's Viasorb, super-absorbent polymers may be added for handling moderately- to heavily-exuding wounds.

9.6 Scaffolds for tissue engineering

Tissue engineering is a rapidly developing multidisciplinary field and holds great promise for the repair and reconstruction of tissues and organs damaged by disease, accidents, congenital abnormality and defects. There are numerous methods of scaffold fabrication, but porous sponge-like scaffolds made using porogen-leaching techniques and nonwoven-based structures are the two most common. These offer much in terms of high surface area, porosity and pore size distribution, ease of preparation, and fibrous randomness, as per anatomical requirement. High porosity and pore interconnectivity are needed for cell attachment, migration and uniform distribution throughout the scaffold.

In the early stages of embryogenesis, trophoblast cells form an outer layer of blastocyst to provide nutrients to the embryo. Culturing human trophoblast cells on needle-punched nonwoven polyethylene terephthalate fabric has shown that metabolic activities and proliferation rate are dependent on the porosity of the nonwoven scaffold. However, a higher extent of cellular differentiation has been observed with high-porosity mesh than with low-porosity mesh, as evidenced by the expression of specific biomarkers (Ma *et al.* 2000). These findings are important, as a critical balance between cell proliferation and differentiation can govern tissue development.

Human embryonic stem cells have the potential to differentiate into all three germ layers and develop into any tissue types found in our body. These cells can proliferate in long-term culture *in vitro*. However, until recently, undifferentiated embryonic stem cells needed culture on a layer of feeder cells, such as mouse embryonic fibroblasts. Feeder cells produce some important soluble factors, such as the cytokine Leukemia Inhibitory Factor (LIF), which are critically needed for embryonic stem cells to maintain their undifferentiated, pluripotent phenotype. Cetinkaya *et al.* (2007) generated carboxylic acid groups on poly(ethylene terephthalate) fibrous nonwoven material by hydrolysis reaction, which helped in immobilizing LIF via ionic interaction with amino groups. LIF-immobilized scaffold supported the growth of embryonic stem cells, but undifferentiated morphology was not retained as anticipated.

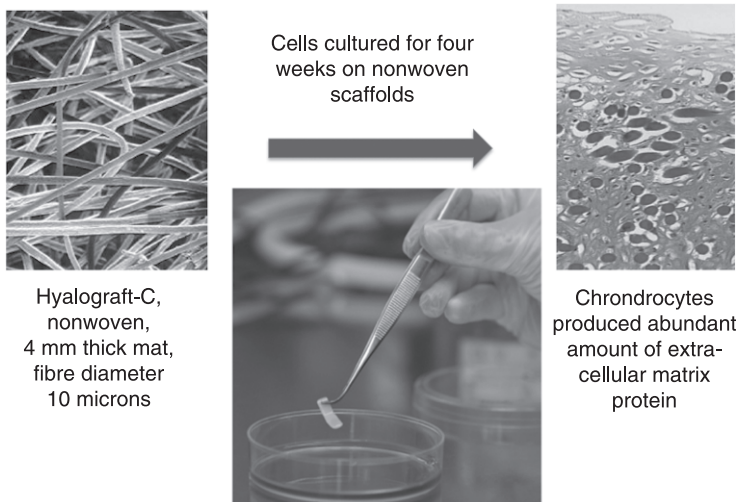
First-generation tissue engineering experiments targeted cartilage regeneration using poly lactic acid/poly glycolic acid (PLA/PGA)-based nonwoven matrices. For example, Shieh *et al.* (2004) used PGA nonwoven fibrous scaffolds, where fibres were treated with poly-L-lactide (PLLA)-chloroform solution; a human ear-shaped architecture was developed using a negative mould. Sheep chondrocytes were then cultured to develop tissue-engineered auricular cartilage.

Hyaluronic acid is an important molecule in the maintenance of the physicochemical characteristics of the cartilage extracellular matrix. Sodium hyaluronate salt is water-soluble, so sodium hyaluronate is esterified in order to impart water insolubility. Esterified hyaluronic acid fibres show easy processability and enhanced residence time *in vivo*. Esterified hyaluronic acid-based nonwovens

(e.g., Hyaff-11, Fidia Advanced Biopolymers, Italy) have been extensively used for knee-joint cartilage tissue engineering (Moretti *et al.* 2005) and nose reconstruction (Farhadi *et al.* 2006). Statistically, chondrocytes produced a significantly higher amount of glycosaminoglycan and collagen in the nonwoven scaffold (Fig. 9.2) as compared to porogen-leached poly ethelene glycol terephthalate/poly butylene terephthalate (PEGT/PBT) scaffolds (Miot *et al.* 2006). Nonwoven porous polymer tubes fabricated from nonwoven meshes of polyglycolic acid fibres have been seeded with rat hepatocytes and the constructs successfully implanted in small intestinal submucosa (Kim and Mooney 1998).

Spinal cord damage can cause paraplegia or quadriplegia. Attempts have been made to fill gaps in the spinal cord by seeding adult rat spinal cord-derived cells in a polyglycolic acid nonwoven mesh (Albany International, Albany, NY, USA); in these experiments, the construct was implanted into a 3–4 mm-long gap. Cells gradually differentiated into neurons, astrocytes, and oligodendrocytes and contributed to the restoration of function to the lower limbs. After six months, coordinated gait in hind limbs and motor control of the tail were noticed. This work demonstrated the fascinating promise for spinal cord repair by incorporating undifferentiated neural progenitor cells into implants to fill gaps in the damaged spinal cord (Vacanti *et al.* 2001).

Wakita and colleagues developed siloxane-poly(lactic acid)-calcium carbonate composite fibrous structures so that mineral components are agglomerated within the PLA fibre matrix. Such nonwoven scaffolds release calcium and silicate ions, and have potential for bone regeneration (Wakita *et al.* 2011). However, most



9.2 Cartilage tissue engineering using nonwoven scaffold.

nonwoven scaffolds reported so far have poor compressive strength and are hence unsuitable for bone tissue engineering. For the purpose of bone regeneration, attempts have been made to develop fibre-reinforced polymer foam. The reinforcing effect of fibres within a matrix becomes effective when fibres are uniformly distributed throughout the matrix, the degree of fibre-polymer contact is maximized and fibre-fibre contact is kept at a minimum. Generally, this type of scaffold is made using a solvent-casting technique. Mandal *et al.* (2012) attempted to develop a silk-fibre-reinforced scaffold to simulate the compressive modulus of bone. Interfacial bonding between the silk fibre and the silk matrix resulted in an compressive modulus of 10 MPa in hydrated conditions. Such matrix stiffness and surface roughness support osteogenic differentiation of mesenchymal stem cells to prepare bone-like tissue (Mandal *et al.* 2012).

There is no successful clinical option available for patients suffering from end-stage liver disease. Bioartificial liver support systems based on hollow fibre technology have undergone clinical trials and have been demonstrated to be promising (Watanabe *et al.* 1997). In this system, hepatocytes are placed inside a chambered cartridge. When patients' blood is passed through, cells process toxins from the blood and synthesize proteins and metabolites. This plasma is then returned to the patient's body. In such systems, oxygenated plasma flows through the fibre capillary, but hepatocytes are attached in extracapillary spaces. As a result, the oxygen supply to the hepatocytes is inadequate because the oxygen-binding ability of plasma is less than one-tenth of that of whole blood. This limited oxygen supply leads to insufficient function of hepatocytes.

Li *et al.* (2006) used a roller pump in which polysulfone hollow fibres were spirally wound with polytetrafluoroethylene nonwoven fabric. Nonwoven fabric allowed attachment and aggregation of hepatocytes, and semipermeable membranes of hollow fibres served as gas exchangers and immuno-protective barriers. Whole blood passed through the intra-luminal space of the hollow fibres and was exposed to the hepatocytes for effective oxygen supply, CO₂ removal and exchange of metabolic waste and nutrients. Hence, the diffusion distance was reduced and mass exchange took place akin to that in the sinusoids of the liver parenchyma.

9.7 Hernia meshes

A hernia is a protrusion of a tissue through the wall of the cavity in which it is normally contained. Nonwoven meshes should be easy to use in both laparoscopic and open hernia repair. Fibrous capsule formation, cellular attachment and mesh contraction result in the recurrence of hernias in most patients. Woven polypropylene meshes frequently form adhesion and fistula when transplanted intra-peritoneally. Polypropylene nonwoven fabric has been demonstrated to overcome such complications due to its microporous structure giving a high capacity for tissue in-growth and integration (Langenbach *et al.* 2003).

Raptis *et al.* (2011) implanted woven as well as nonwoven polypropylene fabrics into 12 pigs to compare ease of incorporation and removal by histology and adhesion formation 90 days after implantation. Intraperitoneally, woven polypropylene fabric became fully peritonealized, but generated thick and abundant adhesions. Interestingly, polypropylene nonwoven fabric became fully peritonealized and generated only very thin adhesions, and to a strikingly lesser extent. Woven meshes formed comparatively dense adhesions that could only be detached with greater difficulty than with nonwoven meshes (Raptis *et al.* 2011).

Weyhe *et al.* (2006) and Dubova *et al.* (2007) investigated the inflammatory response in rats during abdominal wall reconstruction using polypropylene fabrics, at different time points after surgery. One group of rats received heavy woven polypropylene meshes with macro-dimensional pores, and the other group of rats received light nonwoven fabrics with micro-dimensional pores. A more severe inflammatory reaction was noticed in the group which received nonwoven fabrics. Interestingly, however, Dubova *et al.* (2007) noticed less intense fibrosis in the nonwoven fabric, with uniform tissue growth after 28 days, while Weyhe *et al.* (2006) reported a decline in the concentration of inflammatory cells over time in both groups. Fibrous tissue formation took place in both types of hernia mesh after 45 days, with no statistical difference between the groups.

9.8 Filtration materials for medical applications

Red blood cell concentrates and platelet concentrates are commonly transfused to patients. It has been observed that the presence of white blood cells (leukocytes) in blood during transfusion may cause several adverse reactions, including recurrent febrile nonhemolytic transfusion reaction with high fever and vomiting, platelet refractoriness, graft versus host disease, and transmission of viruses (e.g. cytomegalovirus and HIV). The preferred method is therefore to reduce leukocyte-counts before storage of peripheral blood at the blood bank.

Kim *et al.* (2009) developed meltblown poly(butylene terephthalate) nonwoven and graft-polymerized acrylic acid onto it by oxygen plasma glow discharge treatment. They then immersed the nonwoven fabric in an aqueous solution containing high concentrations of phosphate and calcium ions to produce a thin layer of hydroxyapatite. This composite nonwoven was found to successfully remove 98.5% of leukocytes and recovered 99.5% of erythrocytes. This strategy seems promising compared to the standard procedure of removing cell populations by centrifugation.

Bone marrow-derived mesenchymal stem cells are regularly used for regenerative medicine strategies. Isolation of these stem cells from total marrow is usually conducted using a sucrose-based density gradient column, which is a time-consuming process. After screening 200 biomaterials, Ito *et al.* (2010) selected rayon–polyethylene nonwoven fabric for the development of a filter for the collection of mesenchymal stem cells from bone marrow hematopoietic

mononuclear cells. Mesenchymal stem cells adhered tightly to highly hydrophilic and rough surfaces as compared to hydrophobic and smooth surfaces, resulting in a rapid and efficient method of cell isolation filtration.

9.9 Incontinence products

Healthcare and hygiene products for incontinence tend to basically consist of an absorbent pad and skin contact layer and a transparent (waterproof) film adhesive tape. Composite nonwoven based incontinence and hygiene products can be classified as follows:

- Babycare products: baby nappies and baby wipes (dry or moisturized).
- Feminine hygiene products: sanitary napkins, panty shields and liners.
- Adult incontinence: adult nappies, nursing pads, disposable underwear, bladder control pads.

These products are discussed in detail in Chapter 5 of this book.

9.10 Conclusion and future trends

Advances in the development of composite nonwovens for various medical applications are significantly changing the lives of many people. However, the emergence of drug-resistant microbial strains demands more efficient detection mechanisms for surgical drapings and masks and better anti-viral, anti-microbial strategies. The detection, prevention and killing of viruses and bacteria such as methicillin-resistant *Staphylococcus aureus*, hepatitis, SARS or H1N1, remain permanent challenges in the development of protection for healthcare workers.

Although significant progress has already been made in research on nonwovens, structure–function relationships still need to be elucidated. Moreover, in order to face up to such challenging problems, researchers should not be afraid of blurring the boundaries of traditional textile technology. A multi-disciplinary approach is required to develop the next generation of products – for example, electronics-embedded nonwovens for efficient detection of viral particles on a facemask – to improve understanding of the interaction of the nonwoven matrix with cells and the related cellular signalling process to induce organ regeneration. As boundaries between disciplines blur, multi-disciplinary research will become the norm rather than the exception, stimulating further growth in the nonwovens sector.

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9.12 Appendix: recent patents based on composite nonwovens for medical applications

Table 9.1

Serial no.	Patent no.	Name of patent	Invention	Date of patent	Inventor name
1.	US8341768 B2	Surgical garment with means for affixing a glove thereto	Surgical garment was developed with a front portion, back portion and two sleeves, with each sleeve having at least one adhesive region for affixing a donned surgical glove thereto	1 January 2013	Molnlycke Health Care ABNewsRx.com
2.	US8361913	Nonwoven composite containing an apertured elastic film	Composite nonwoven material were used for diapers, absorbent underpants, incontinence articles, feminine hygiene products, baby wipes, medical absorbent articles, underpads, bedpads, bandages, absorbent drapes, and medical wipes	29 January 2013	Kimberly-Clark Worldwide, Inc.
3.	US8283029	Multilayer microporous films and composites for barrier protective materials, and methods	A breathable composite non-woven multilayer microporous film was designed with controlled pore size which provided adequate barriers to blood and blood-borne pathogens (viruses)	9 October 2012	Clopay Plastic Products Company, Inc.
4.	WO2011078442 A1	Medical nonwoven fabric, and preparation method thereof	Medical nonwoven fabric was developed, with improved dimensional stability and adhesion barrier. This invention was further used for anti-adhesion, anti-air injection shield	30 June 2011	Korea Institute of Industrial Technology
5.	WO2009081421 A1	Composite material made of non-woven fabric with a high absorbing capacity	The composite non-woven fabric was used for medical products and hygiene products, including napkins	2 July 2009	Achille Costamagna, Sogetec S.P.A

(Continued)

Table 9.1 Continued

Serial no.	Patent no.	Name of patent	Invention	Date of patent	Inventor name
6.	US6723892	Personal care products having reduced leakage	The products to be used in absorbent articles for personal care (diapers, bandages, feminine hygiene) or wound care to promote rapid absorption and retention of fluids with comfort to the user and optimum dryness	20 April 2004	Kimberly-Clark Worldwide, Inc.
7.	US6774069 B2	Hot-melt adhesive for non-woven elastic composite bonding	Composite non-woven material used as medical garment, feminine care product, adult incontinence garment and diaper	10 August 2004	Kimberly-Clark Worldwide, Inc.
8.	US6610163 B1	Enhanced barrier film and laminate and method for producing same	Composite nonwoven material developed for use as surgical drapes and gowns having soft outer cover and breathable properties	26 August 2003	Kimberly-Clark Worldwide, Inc., Michael P. Mathis
9.	EP 1364773 A1	Composite nonwoven fabric for protective clothing and production method thereof	Composite nonwoven fabric used for protective clothing such as medical underwear and gowns due to excellent water vapour permeability, water resistance and strength	26 November 2003	Chori Co., Ltd, Kuraray Co., Ltd
10.	US6410464 B1	Hand-tearable tape	Pressure sensitive adhesives developed for constructing medical tapes which are physically and biologically compatible with human skin	25 Jun 2002	Robert H. Menzies, Robert J. Maki
11.	WO2001015898 A1	Breathable multilayer films with breakable skin layers	Breathable multilayer films for use in absorbent articles, medical garments	8 March 2001	Kimberly-Clark Worldwide, Inc.

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