NC STATE UNIVERSITY
JTATM
Journal of Textile and Apparel, Technology and Management
Volume 6, Issue 1, Fall2008

Overview and Analysis of the Meltblown Process and Parameters

Kathryn C. Dutton, Graduate Student
North Carolina State University - College of Textiles

ABSTRACT

This paper is a comprehensive review of the meltblown process and parameters. The meltblown process is complex because of the many parameters and interrelationships between those parameters. Due to the competitiveness of the industry, process settings and polymers used are secretive, but there are several key researchers that have published studies on the interactions of meltblown variables. A majority of the research conducted has been on the relationship of process parameters and mean fiber diameter in order to understand how to produce smaller and higher quality fibers. This paper offers suggestions for future research on specific meltblown parameters.

Keywords: Meltblown, nonwovens, process parameters

1. Introduction

In general, a nonwoven fabric is a sheet, web, or batt structure made of natural or man-made fibers or filaments which are bonded mechanically, thermally, or chemically. Fibers and filaments are not converted to yarn as would be required to produce a woven or knitted fabric. The three general nonwoven categories are dry laid, wet laid, and polymer laid, see Figure 1. The dry laid processes originated from the textiles industry while the wet laid processes originated from papermaking, and the polymer laid processes originated from polymer extrusion and plastics (Wilson, 2007). The polymer laid webs, also referred to as direct laid, spunmelt, extrusion spinning, or an extrusion nonwoven, are formed directly from extruded polymer (Kittelmann & Blechschmidt, 2003; Lichstein, 1988; Wilson, 2007).

This paper will focus on the meltblown, polymer laid process defined as a one-step process in which streams of molten polymer is subjected to hot, high-velocity air to produce a web consisting of microfibers. The paper begins with a brief history of the process development, including common polymers used and leading end-uses, followed by a description of the process elements, and concludes with a discussion of the research conducted regarding meltblown process parameters.

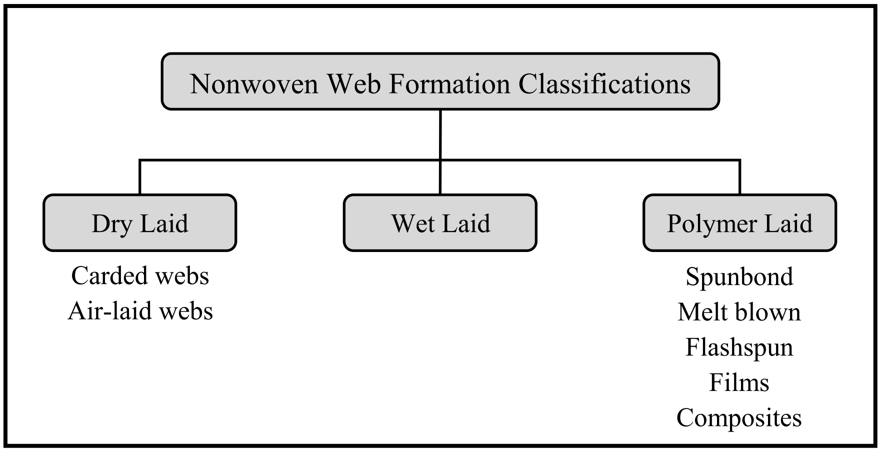

***Figure 1*. General nonwoven categories. Information adapted into figure from "Development of the Nonwovens Industry" (pp. 1-15), by A. Wilson, 2007, in *Handbook of Nonwovens*, by S. J. Russell (Ed.), New York: CRC Press.**

1.1 History of Meltblown Technology

The first attempt to develop microfiber was in 1939, by Carlton Francis, who pictured a spray gun as a process in which to develop textile like microfibers (Malkan & Wadsworth, 1993). Through the early 1940s, American Viscose (no longer in business) researched the development of microfibers using a spray spinning technique developed by Francis, and by the 1950s, had built a pilot plant to produce the microfibers (Mansfield, 1979). In addition, Dow Chemical Company was researching the development of microfibers using polystyrene during the late 1940s. In the mid-1960s, Chemstrand Company (now Monsanto Company) also worked on the development with spray spinning (Mansfield, 1979). However, American Viscose did not develop any commercial products, Dow did not see any potential, and Chemstrand thought the filtration market was not large enough. Therefore, all three companies discontinued research on the projects (Malkan & Wadsworth, 1993; Mansfield, 1979).

In the early 1950s, the United States Army Chemical Warfare Laboratories continued Dow's research to produce microfibers to collect radioactive particles (Malkan & Wadsworth, 1993; Mansfield, 1979). The first successful attempt to develop microfibers was in the mid-1950s by Van A. Wente and colleagues when they demonstrated the process that formed microfibers, or fibers less than 10 microns in diameter (Gahan & Zguris, 2000; Johnston, 1992; McCulloch, 1999). Wente et al. had conducted their research at the United States Naval Research Laboratory to develop microfibers (also known as microorganic fibers or superfine fibers) in order to produce filters to collect radioactive particles in the upper atmosphere as a result of US and Russian nuclear weapons testing (Gahan & Zguris, 2000; Johnston, 1992; Malkan & Wadsworth, 1993; Mansfield, 1979; Vargas, 1993; Wente, 1954).

In the 1960s, Esso Research and Engineering Company (now ExxonMobil Corp.) realized the significance of Wente et al.'s work. Research, led by Robert Buntin and Dwight Lohkamp, improved upon Wente's work to successfully produce low-cost polypropylene microfibers and scaled up the line from 3 to 40 inches wide (Gahan & Zguris, 2000; Malkan & Wadsworth, 1993; Mansfield, 1979; McCulloch, 1999). Furthermore, they improved Wente's die design to minimize flaws known as "shots" (Mansfield, 1979). A shot is a small, round clump of polymer on the web that is formed during the meltblown process (Vargas, 1989). By the mid-1960s, the process and technology was patented by Exxon and coined the "Meltblown Process" (Malkan & Wadsworth, 1993; McCulloch, 1999; Vargas, 1993). In the 1970s, Exxon realized the product's potential in filtration, hygiene products, adhesive webs, cigarette filters, specialty synthetic papers, and composites (Gahan & Zguris, 2000). They licensed the process out to companies which included Kimberley-Clark, Johnson & Johnson, James River, Web Dynamics, Ergon Nonwoven, Riegel, and Dewey & Almy so they could focus more on developing and producing the resins for the meltblown process (Kittelmann & Blechschmidt, 2003; Mansfield, 1979; McCulloch, 1999; Vargas, 1993). Exxon also licensed out to two equipment manufacturing companies (Accurate Products and Reifenhäuser) to supply precisely engineered equipment to the web manufactures enabling them to produce better quality webs (McCulloch, 1999). 3M developed a microfiber technology process (outside of the Exxon patents) that led to the development of a successful product known as Thinsulate (Mansfield, 1979). For a more detailed list of licenses, patents, and milestone products see McCulloch's article. In 1983, Exxon teamed with the University of Tennessee, Knoxville and built the first pilot line to ensure ongoing research for technological advancements in the meltblown process. In 1989, the research center became known as the Textiles and Nonwovens Development Center (TANDEC) (http://web.utk.edu/~tandec/).

1.2 Polymers Used in the Meltblown Process

There are many thermoplastic polymers used in the meltblown process although some more commonly used than others, see Table 1. Gahan & Zguris (2000) mentioned co-polymers known to have been used in the meltblown process, see Table 2. However, the most common polymer used is polypropylene, because it is relatively inexpensive and versatile enough to produce a wide range of products. Polypropylene has a low melt viscosity that allows the polymer to flow through the micron size holes, or orifices, and draw to as small as 1-µm in diameter. The polymer viscosity is measured by the melt flow index (MFI), or melt flow rate (MFR). This measurement indicates the amount, in grams, of a polymer that can flow through a given orifice, at a given load, and a given temperature in a ten minute time span (Gahan & Zguris, 2000). A high MFI indicates a low melt viscosity. In the 1950s and 1960s, when the process was just developed, the MFR of polypropylene was 12 MFR and within years was improved to 35 MFR. In the 1970s and 1980s, there were major strides and polypropylene with a MFR of 1200-1500 had been developed. The benefits of a higher MFR are reduction in extruder temperatures and an increase in throughput rates. Lower extruder temperatures reduce char, or totally degraded polymer, extends the die life, and reduces energy consumption (Vargas, 1989). Typical meltblown polypropylene fiber and web properties are listed in Table 3.

1.3 Meltblown Fabric End-Uses

Major markets for meltblown fabrics include medical, hygiene, industrial, filtration, sorbents & wipes; see Table 4 for an example of products within these markets. Many meltblown webs are often layered between two spunbond fabrics and bonded, see Figure 2. This fabric is called a spunbond, meltblown, spunbond composite (SMS) and typically used in medical fabrics because the meltblown provides good barrier properties and the spunbond adds support, comfort, and abrasion resistance.

Table 1
Polymers Used in the Meltblown Process

Common	Others
Polypropylene (PP)	EVA, EMA, EVOH
Polystyrene	Fusibles of copolymers
Polyesters	Polybutylene terephthalate
Polyurethane (PUR)	Polyphenylene sulfide
Nylon 6, 66, 11, 12	Polymethyl pentene
Polyethylene	Polyvinyl alcohol
Low and high density polyethylene	Polytrifluorochloroethene (PCTFE)
(LLDPE, LDPE, HDPE)	Polyethylene terephthalate
Polycarbonate (PC)	Poly (4-methylpentene-1)
	Poly (tetramethylene terephthalate)

Note. Polymers in the left column are more commonly used in production. Polymers in the right column have been reported to successfully melt blow. Compiled from Gahan & Zguris, 2000; Jirsák & Wadsworth, 1999; Johnston, 1992; Kittelmann & Blechschmidt, 2003; and Mansfield, 1979.

Table 2
Co-polymers Used in the Meltblown Process

Co-polymers
Ethylene/chlorotrifluoro-ethylene
Copolyesters
Polyurethane
Ethylene vinyl acetates
Polyamide polyethers

Note. Information adapted into table from "A Review of the Melt Blown Process," by R. Gahan and G. C. Zguris, 2000, *The Fifth Annual Battery Conference on Application and Advances*, pp. 145-149.

Table 3
Meltblown Polypropylene Fiber and Web Properties

Polypropylene Fiber Properties		Polypropylene Web Properties	
Length:	not able to tell	Basis weight:	5-1000 g/m^2
Diameter:	2-4 microns	Tensile strength:	1.379 N/cm^2 (2 lb/in^2)
Birefringence:	10 to 15 x 10^{-3}	Tear strength:	70 gm
Tensile strength:	to 2 grams per denier	Air permeability:	high, controllable
		Porosity:	75 to 95%
		Covering power:	Excellent
		Hand:	very soft, drapable

Note. Adopted from "Microdenier Nonwovens: Looking for Markets," by R. G. Mansfield, 1979, *Textile World*, 129(2), p.84.

Table 4

Major Markets and Product Examples for Meltblown Fabrics

Filtration	Medical	Sorbents & Wipes	Hygiene	Industrial	Other
Air	Surgical gowns	Household wipes	Feminine hygiene	Protective apparel	**Electronics**
Clean rooms	Surgical face masks	Industrial clean up wipes	products	Face masks	Battery separators
Heating	Surgical drapes	Oil clean up (oil booms)	Diapers (cover stock,		Cable wraps
Ventilation		Food fat absorption	waist and leg		**Adhesives**
Air conditioning (HVAC)			reinforcement)		Hot-melt adhesives
Face masks			Incontinence products		**Insulators**
Respirators					Apparel thermal insulator
Gas masks					(3M Thinsulate®)
Vacuum cleaner					Acoustic insulation
Room air cleaners					(appliances, automotive)
Liquid					
Water					
Food & beverage					
Chemicals & solvents					
Blood					

Note. Compiled from Bhat & Malkan, 2007; Gahan & Zguris, 2000; Jirsák & Wadsworth, 1999; Johnston, 1992; Malkan & Wadsworth, 1993; and Vargas, 1989.

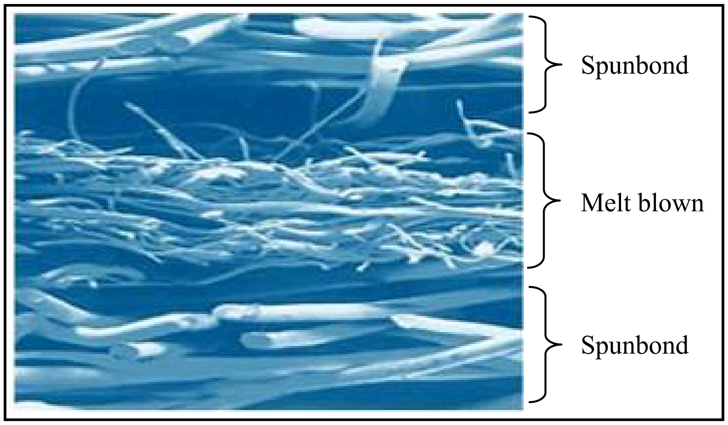

Figure 2. **A microscopic image of a SMS web. The larger fibers are spunbond and the smaller fibers are meltblown. Adapted from Decon Sciences, http://www.deconsciences.com/ds2bdp04sms.htm.**

2. The Meltblown Process

In general, the meltblown process consists of five major components: the extruder, metering pump, die assembly, web formation, and winding. The polymer resin is fed into the extruder where it is heated and melted until appropriate temperature and viscosity are reached. The molten polymer is then fed to the metering pump to ensure uniform polymer feed to the die assembly. The microfibers are formed when the molten polymer exiting the die is hit with a hot, high velocity air. The microfibers are collected on a moving screen, or drum, where the self-bonded web is formed. A moving screen is used in a vertical setup and a drum is used in a horizontal set up, see Figure 3. The web is then wound up and prepared for finishing, if required.

2.1 Extruder

The extruder is similar to the extruder used in the spunbond process (Malkan & Wadsworth, 1993). It is a heated barrel with a rotating screw, responsible for melting and feeding the polymer to the metering pump. The polymer, usually in the form of beads, pellets, chips, or granules, is gravity fed from the hopper into the extruder. The polymer may be mixed with additives, see Table 5, to improve web performance.

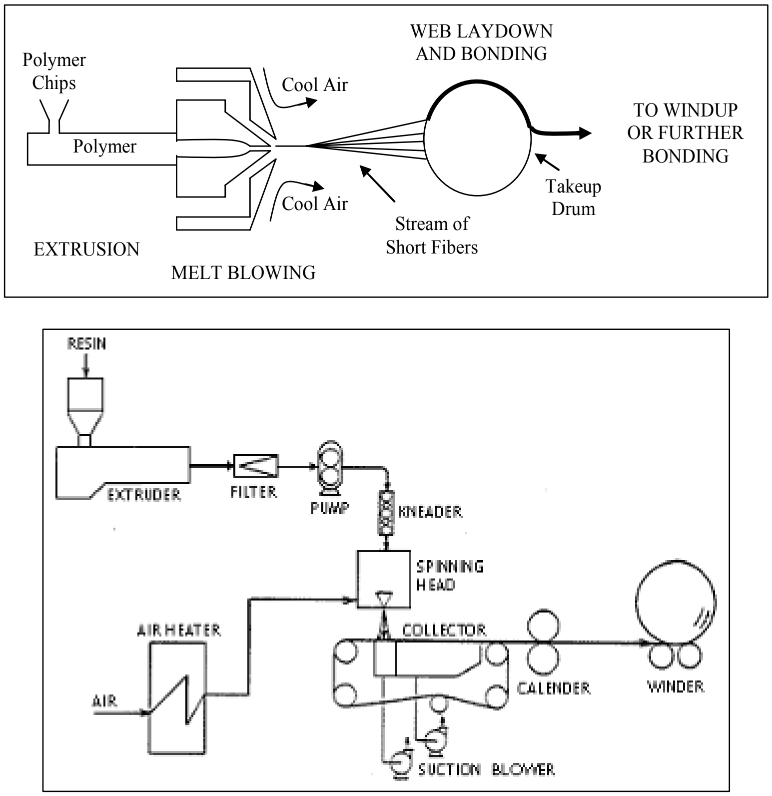

***Figure 3*. Schematic of the horizontal (top) and vertical (bottom) melt blowing processes. The top image is from *The Nonwoven Handbook* (p. 54), by B. M. Lichstein (Ed.), 1988, New York: INDA. The bottom image is from Nippon Kodoshi Corp.**

Table 5
Additives Used in the Meltblown Process

Additives	Function
Anti-oxidants	Prevents degradation of the polymer
Anti-stats	Prevents static build up
Blooming Agents	Materials which migrate to the surface Used to alter the material surface
Colorants (pigments or dyes)	Adds color to the polymer Adds special effects to polymer (metallic, pearlescence, fluouescence)
Flame Retardants	Reduces flammability
Lubricants	Used to lower melt viscosity for better polymer flow (internal) Used to prevent sticking between the polymer and equipment (external)
Peroxides	Controls degradation Often used in PP to obtain high MFR
Stabilizers	Provides extrusion stability by preventing large and uncontrolled changes
Heat Stabilizers	Provides thermal stability during normal use temperatures
Light Stabilizers	Prevents degradation when exposed to UV light
Wetting Agents	Agent added to increase wettability of the material

Note. Compiled from Gahan & Zguris, 2000; Lewin, 2007; Maier, 1998; and Vargas, 1989.

The extruder has three different zones – the feed zone, the transition zone, and the metering zone, see Figure 4. The feed zone is where the polymer mixture is preheated. The melted polymer is then pushed to the transition zone where it is compressed and homogenized. Finally, the polymer is pushed to the metering zone, where the polymer pressure is greatest, to push polymers to the metering pump. A breaker plate, or filter, near the end of the screw extruder helps control the pressure, remove dirt, foreign and metal particles, and polymer lumps (Malkan & Wadsworth, 1993). Details of the extruder, such as the length to diameter ratio, are determined based on the polymer being used (James, 2000).

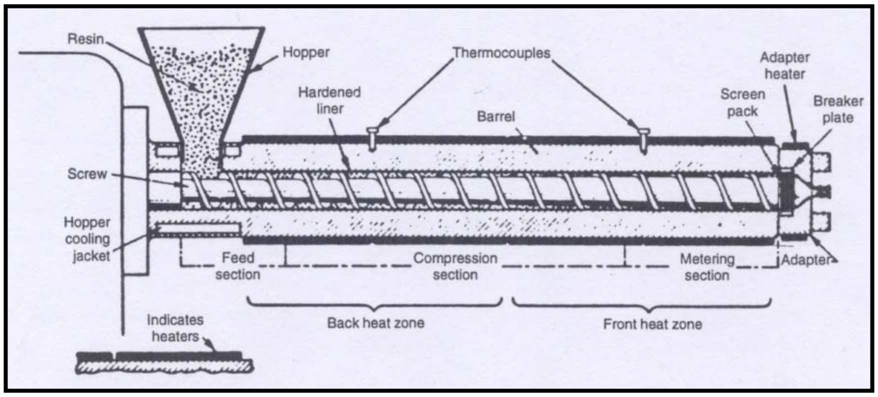

***Figure 4*. Schematic of an extruder. From "Polymer-Laid Systems" (p. 173), by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.**

2.2 Metering Pump

As with the extruder, the meltblown metering pump is similar to the one used for the spunbond process (Malkan & Wadsworth, 1993). A metering pump, also known as a gear pump, helps maintain the required pressure in the extruder which ensures the molten polymer is delivered uniformly and consistently to the die assembly under various process variations such as viscosity, pressure, and temperature (Gahan & Zguris, 2000; Jirsák & Wadsworth, 1999; James, 2000; Malkan & Wadsworth, 1993). As seen in Figure 5, the meter consists of two interlocking wheels, one rotating in the clockwise direction and the other in the counter-clockwise direction. The polymer is sucked in from the extruder, carried by to gear tooth, and discharged to the die assembly system (Malkan & Wadsworth, 1993).

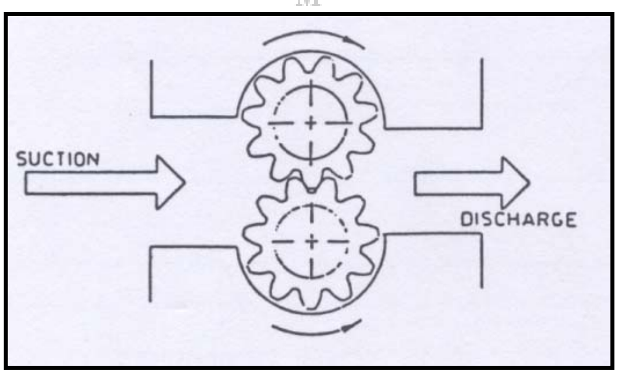

***Figure 5*. Schematic of a metering pump. From "Polymer-Laid Systems" (p. 173), by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.**

2.3 Die Assembly

Unlike the extruder and the metering pump, the die assembly of the meltblown process is different from the spunbond system. The die assembly is the most important element of the meltblown system and responsible for the production of quality fibers (James, 2000; Malkan & Wadsworth, 1993). The die assembly consists of three components; the polymer feed distribution plate, the die nosepiece, and the air manifolds, all of which are kept at a temperature of 215°C to 340°C. This temperature will variety depending on the polymer used. It is important to maintain the desired temperature in order to produce uniform, quality webs (Malkan & Wadsworth, 1993).

2.3.1 Feed Distribution Plate

The feed distribution plates are responsible for creating an even polymer flow across the plate. It is important to keep the plate heated at a consistent and proper temperature to keep the polymer flowing, and prevent the polymer properties from changing. The shape of the feed distribution is also important because it influences polymer distribution. There are two types of feed distribution plates, the coat hanger-type and the T-type (Malkan & Wadsworth, 1993). The coat-hanger is the most common distribution plate because of even polymer flow and residence time. There is a manifold, or pre-land, at the polymer entrance that ensures the polymer flows and distributes evenly across the plate instead of causing a large distribution of polymer in the middle and no distribution to the edges, see Figure 6 (Zhao, 2002). From the fed distribution plate, the polymer is feed to the die nosepiece.

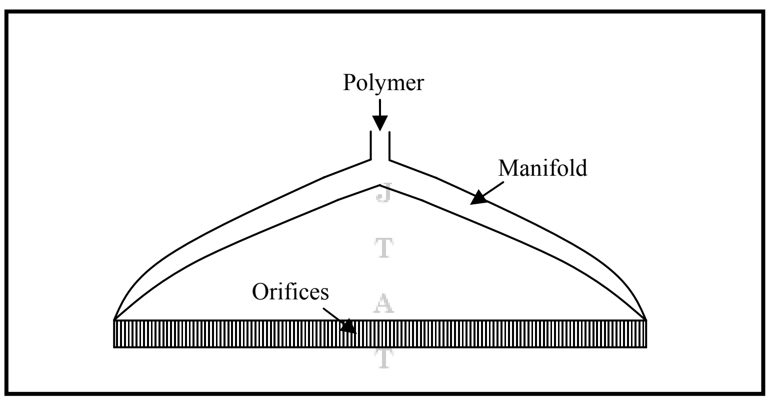

***Figure 6*. Schematic of the coat-hanger feed distribution plate. Adopted from "Analysis and simulation of non-Newtonian flow in the coat-hanger die of a meltblown process," by Q. Sun and D. Zhang, 1998, *Journal of Applied Polymer Science*, 67, p. 194.**

2.3.2 Die Nosepiece

The die nosepiece, or die tip, is the key component of the die assembly and largely responsible for fiber diameter and quality, uniform webs. Therefore, the design and fabrication of the die tip is important and requires precise measurement. The meltblown die tip is a very wide but thin piece of metal with each orifice typically measuring about 0.4-mm. However, the orifice can vary in size to allow anywhere from 1 - 4 orifices per millimeter (25 -100 per inch) according to Malkan & Wadsworth (2000), or 15 - 40 orifices per inch according to several authors (Batra, 1992; James, 2000; Vargas, 1989). James also states that these numbers have been known to be higher in special cases such as die tips designed by Biax Fiberfilm Corporation (http://www.biax-fiberfilm.com/pages/meltblown.html). When producing a die tip, where the distance between orifices is very small, there is less metal between the orifices and therefore the die tip is very delicate. This can lead to "zippering," where the metal between the orifices breaks, at which point the die must be replaced (James, 2000; Wilkie & Haggard, 2007). The molten polymer flows through these orifices to produce the filament strands (Malkan & Wadsworth, 1993; Zhao, 2002).

There are two basic types of nosepieces, a capillary type and a drilled hole type, see Figure 7. A capillary nosepiece is two flat surfaces with a semicircle milled into each flat piece. The pieces are placed together and precisely aligned to form the orifices. In 1974, Exxon was granted a patent for the capillary die which had longer holes and an easier and more precise alignment of the orifices than the drilled hole type. The drilled hole type, is one piece of metal in which holes are drilled to form the orifices. In 1974, Exxon was also granted a patent on their drilled hole design, which has the orifices located at the apex of the triangular configuration. Over the years, drilled hole dies have become less expensive due to the advancement in drilling technologies (Malkan & Wadsworth, 1993; Zhao, 2002).

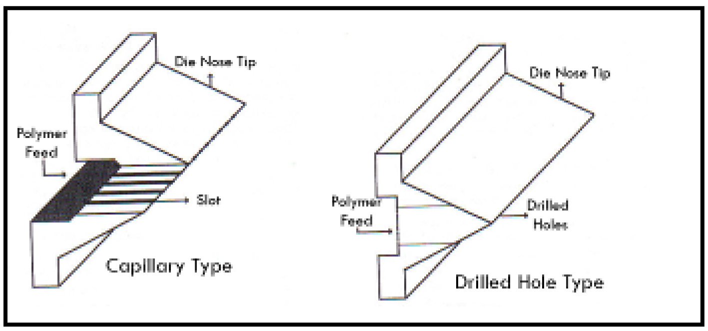

***Figure 7*. Schematic of a capillary (left) and drilled hole (right) die nosepiece. Adapted from "Polymer-Laid Systems" (p. 183), by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.**

In 1980, a patent by Schwarz revealed a die that included a near sonic air stream for each orifice, instead of the air stream coming in from the sides of the die. Therefore reducing air consumption as well as minimizing polymer degradation (Shambaugh, 1988). This die is used by Biax Fiberfilm Corporation and therefore known as the Biax Fiberfilm die, see Figure 8. This die increased productivity more successfully than traditional ways which include changing process conditions. Changing process conditions, such as increasing the polymer throughput, can decrease web quality. The die was also a better solution to placing die beams parallel to each other, which is extremely costly (McCulloch, 1999; Zhao, 2002).

A major problem with die tips is the clogging of the small orifices which causes shots and affects the uniformity of the web. In 1988, Kimberly-Clark patented a die tip known as the slot die. The die has a single slot that is continuous along the length of the die tip on one side; the other side of the slot has groves to form the fiber, see Figure 8. One side is designed to extend below the other side so that a lip is formed in the fluid stream (McCulloch, 1999; Zhao, 2002).

In 1989, Accurate Product Company patented a die that improved upon a weak region in the triangular apex of the original die design. The die is known as the bolt design die because the die tip is mounted to the die by bolting toward the orifices which applies equal and opposite forces to both sides of the die, see Figure 8. This helps resist internal extrusion pressure. The bolt design reduces down time, allowing engineers can easily and quickly remove the die. In addition, the bolt design allows for ease of disassembly and cleaning (Zhao, 2002).

In 1997, a modular die design was patented. This design allowed for modular dies to be added or removed from the structure in order to increase or decrease the width of the die, and ultimately the web. An advantage to this die is the easy replacement of one modular die offering improved maintenance and reduced cost in comparison to replacing the entire traditional die (Zhao, 2002).

The University of Tennessee patented an offset-hole die tip in 2000. The die tip is designed so that every other orifice is angled in the opposite direction at the exit point, see Figure 8. The patent claims shots are reduced because filament-to-filament interaction is reduced and filament attenuation is improved because of increased interaction between the filaments and the air (Zhao, 2002).

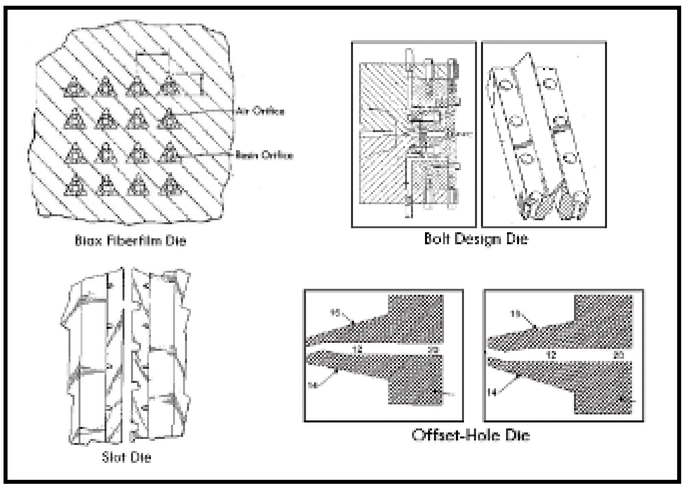

***Figure 8*. Schematic of various die nosepieces. From "Melt Blown Dies: A Hot Innovation Spot," by R. Zhao, 2002, *International Nonwovens Journal*, 11(4), pp. 39-41.**

Multiple dies can be placed on a meltblown line. The advantages of this included increased throughput and web-production rates, and more uniform webs. The disadvantage requires each die to need its own supply of cooling air. In addition, the layers of heavier basis weight webs are not well bonded together, and the increased number of die heads increases costs (Ahmed, 1982).

2.3.3 Air Manifold

The air manifold, or air knives, is responsible for supplying the high-velocity air, known as primary air, which assists in drawing, or attenuating, the polymer to form microfibers. Typically, the manifold is located on the sides of the die nosepiece and hits the polymer with hot, high-velocity air when it exits the die tip, see Figure 9. An air compressor is used to generate the high velocity air, typically 0.5 – 0.8 the speed of sound, which is passed through a heating unit to obtain the optimum air temperature, typically 230°C to 360°C (Malkan & Wadsworth, 1993). The air gap and set-back determine the angle and length of time the air hits the polymer stream. The air is hotter than the polymer in order to hold the polymer in a liquid state. At this point, web formation begins.

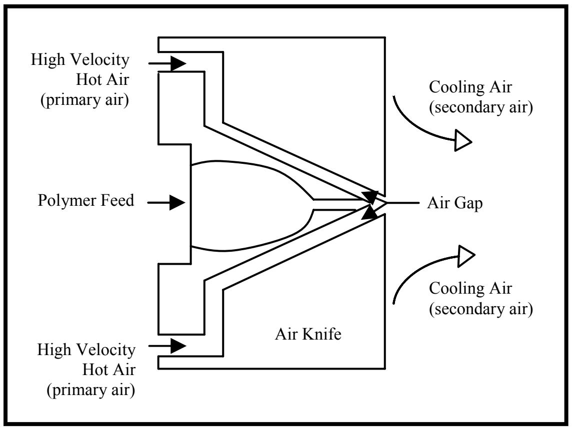

***Figure 9*. Schematic of the air flow in the die assembly. Adapted from "Polymer-Laid Systems" (p. 183), by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.**

2.4 Web Formation and Characteristics

As previously mentioned, the hot air steam (primary air) hits the molten polymer as it leaves the nose tip in order to draw the polymer. The turbulent air fractures the polymer stream and creates the microfibers which begin to entangle. Secondary air, or surrounding air, drawn into the fiber stream, cools the microfibers as they fall toward the moving collecting screen, or drum (Jirsák & Wadsworth, 1999; Malkan & Wadsworth, 1993). The fibers are still solidified and therefore, self-bond upon lay down without need for further bonding (Batra, 1992; Jirsák & Wadsworth, 1999; Malkan & Wadsworth, 1993; Vargas, 1989). A low to moderate strength web is produced because the fibers are drawn to the desired diameter while still in the semi-molten state, the fibers reach the collecting screen while in this state without any further fiber attenuation, and are rapidly quenched producing low crystallinity. The lower the crystallinity, the lower the fiber strength (Batra, 1992; Gahan & Zguris, 2000). At times, cooler air is used so the polymer is not sticky upon contact with the collecting belt and will not self-bond. Therefore, the web will need to be post-bonded before wind-up. The turbulent mixture of air contributes to the random lay down and entanglement of fibers. Due to the movement of the collecting screen, the web is slightly machine directional. A vacuum, located under the collecting screen, or in the drum, sucks the fibers down, helps hold the microfibers to the collecting screen, and removes the hot air (Malkan & Wadsworth, 1993). The collecting screen is generally a woven, wire mesh fabric as a plastic belt can melt during machine start up (Jirsák & Wadsworth, 1999; James, 2000). The die-to-collector distance (DCD) is generally 6-20 inches (15-50 cm) from the die (Vargas, 1989).

The microfibers produce a web with high surface area and small pore sizes which give the fabric good barrier, insulating, and filtration properties (Gahan & Zguris, 2000; Jirsák & Wadsworth; Malkan & Wadsworth, 1993). There appears to be some disagreement among researchers with regard to the average fiber diameter. Some state the meltblown process can produce an average fiber diameter as fine as 0.5 microns to as coarse as 30 microns (Bhat & Malkan, 2007; Johnston, 1992; Malkan & Wadsworth, 1993). Others state an average diameter of 90 to 100+ microns can be produced for coarse filtration end-uses (McCulloch, 1999; Vargas, 1989). Under certain conditions the average diameter can reach 0.1 microns which is considered a nanofiber, fibers with a diameter less than 1-μ, or 1000-nm (Shambaugh, 1988; Vargas, 1989). Several researchers have successfully produced nanofibers (Ellison et al., 2007; Hills, 2007; Podgórski et al., 2006). However, the typical range for the average fiber diameter in the meltblown process is 2 - 4 microns (Jirsák & Wadsworth, 1999; Vargas, 1989). Average diameters are reported, because the diameter varies along a single fiber and there is a wide fiber diameter distribution within the web (Gahan & Zguris, 2000; Malkan & Wadsworth, 1993). The average fiber diameter is typically affected by the throughput rate; melt temperature and viscosity; and air temperature and viscosity, see Table 10 (Gahan & Zguris, 2000). The fiber length ranges from less than 1 inch to 11 inches (2.5 – 28-cm) with 5 - 11 inches (12.7 – 28-cm) being more typical (Johnston, 1992). Web basis weights can range from 8 – 350 g/m^2, but typically range from 20 – 200 g/m^2 (Bhat & Malkan, 2007; Jirsák & Wadsworth, 1999; Malkan & Wadsworth, 1993). However, Gahan & Zguris state that a web can range from 1 – 400 g/m^2. The basis weight of a web can be increased by reducing the collector speed or increasing the throughput rate (Ahmed, 1982; Gahan & Zguris, 2000).

Uniformity is important in web characteristics. The uniformity of a web is affected by the uniformity of fiber distribution in the air stream and the vacuum levels. A poor die design and/or non-uniform ambient air will negatively affect the air stream and fiber distribution resulting in a non-uniform web. The vacuum level should be set to hold down the fibers and remove the air. If improper levels are set, it will result in poor web uniformity (Vargas, 1989). The meltblown process creates webs with a wide range of characteristics, see Table 6.

Table 6
Meltblown Web Characteristics

Web Characteristics	
Smooth surface texture	Low to moderate web strength
Favorable hand and drape	Highly opaque web (high cover factor)
Low abrasion resistance	Random fiber orientation
High surface area (good filtration, insulation, & absorption)	Wide range of fiber diameter
	Difficulty distinguishing fiber length (sometimes considered continuous)

Note. Compiled from Bhat & Malkan, 2007; Gahan & Zguris, 2000; Johnston, 1992; and Malkan & Wadsworth, 1993.

There are three major defects that can develop while producing a meltblown web – shots, roping, and fly. A shot is a small, round clump of polymer in the web that can be caused by excessively high temperatures, too low of a polymer molecular weight, or poor equipment cleanliness (Gahan & Zguris, 2000; Vargas, 1989). Roping is a long, thick “streak” of polymer in the web caused by turbulence in the airstream or fiber movement during and after lay down (Vargas, 1989). Fly is a collection of very short, fine fibers that do not collect on the screen, or drum, and therefore do not affect the web as with the other two defects. Instead, the fly contaminates the surroundings. This defect is caused by extreme and excessive blowing conditions (Vargas, 1989). A fourth defect known as fiber splitting, branching, or bundling, has been mentioned in the literature. Fiber branching occurs when fibers collide in the airstream near the die tip and fragments the filaments. These fiber are therefore not smooth like the fibers that have not been effected by fiber branching. The cause of this defect is unclear (Bhat & Malkan, 2007; Gahan & Zguris, 2000).

There are many process parameters that can affect the average fiber diameter and web properties, including the polymer used, process temperatures, and die geometry. The meltblown process is secretive, therefore limiting information published on these parameters. However, some research has been published on the affect of various process parameters which will be discussed later in this paper.

2.5 Winding and Finishing

Fibers, typically hot when laid down, produce an already bonded web ready for wind-up. However, some finishing and/or bonding may be done before or after wind-up depending on the end-use requirements, see Table 7. Calender bonding, the type most often used, creates a smooth or patterned surface (Malkan &Wadsworth, 1993). This bonding typically increases the strength, abrasion resistance, and density, and reduces thickness of the web; however, the web becomes stiffer and looses its fabric-like appearance and feel. Just before wind-up, the edges of the web maybe trimmed, the roll may be split to specific widths, or wound up at full width (Vargas, 1989).

Table 7
Benefits of Finishing, or Bonding, on Meltblown Webs

Finishing	Benefits
Antistat agents	Static control
Calendering	Reduced thickness Reduced pore size Increased web density Increased strength Increased abrasion resistance Creates smooth or pattern surface Laminate to other substrates
Coloration	Adds aesthetics through dyeing
Composites	Strengthens MB webs
Electrostatic charging	Improves particle filtration
Embossing	Decorative Functional
Flame retardants	Reduced flammability
Laminated with other substrates	Extends range of properties
Printing	Decorative Functional
Rewet agents	Modified water wetting
Super absorbent powders	Absorbency
Surface modification	Printability Dyeability Barrier properties

Note. Compiled from Gahan & Zguris, 2000; Malkan & Wadsworth, 1993; and Vargas, 1989.

3. Process Variables

The meltblown process appears simple; however, the number of variables and the interaction among the process variables makes the process very complex. The process consists of two types of variables: operational, or machine variables, and material variables. Quality of the fibers and web relies on the proper selection of these variables.

3.1 Operational Variables

Operational variables, also referred to as machine variables or parameters, include on-line and off-line variables, see Table 8. On-line variables can be adjusted while the machine is in operation but off-line variables can only be fixed when the machine is not operating. In general, on-line variables such as the polymer throughput rate and air throughput rate control the fiber diameter and entanglement while the polymer/die temperatures and the air temperatures, along with the air flow rate, affect fabric appearance, hand, uniformity and the amount of defects. Fabric openness and fiber-to-fiber bonding are affected by the die-to-collector distance (DCD) (Jirsák & Wadsworth, 1999; Malkan & Wadsworth, 1993).

Off-line variables such as die hole size, die design parameters, and set-back affects fiber size while the air gap affects fiber breakage. Depending on the angle of the air, multiple properties are affected. If the angle is approximately 90-degrees, fiber distribution is more random due to a more turbulent air flow. If the angle is 30-degrees, defects, such as roping, occur. Therefore, an angle of 60-degrees is considered desirable (Malkan & Wadsworth, 1993).

Table 8
Operational Variables for Meltblown Processing

On-line Variables	Off-line Variables
Polymer (resin) throughput rate	Die hole size
Air (gas) throughput rate	Die set-back
Polymer temperatures	Air gap
Die temperatures	Air angle
Air temperature	Web collection type
Die-to-collector distance	Polymer/air distribution

Note. Information adapted into table from "Polymer-Laid Systems" (p. 184), by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.

3.2 Material Variables

The option of using a variety of polymers and polymer blends is an advantage of the meltblown process. However, there are a number of material variables which affect fabric quality, see Table 9. While a range of polymers can be meltblown, polypropylene has been the most widely used polymer because of its melt flow index. A low molecular weight is desired in the meltblown process. Low molecular weight indicates low melt viscosity, or high melt flow index (MFI), which produces a more uniform web. Using a higher MFI and lowering the operating temperature, increases the throughput rate and decreases manufacturing costs. In addition, the use of polymers in a granule form is preferred because they melt better and faster than those in pellet form (Malkan & Wadsworth, 1993).

Table 9
Material Variables for Meltblown Processing

Material Variables
Polymer type
Molecular weight
Molecular-weight distribution
Melt flow rate (MFR)/Melt flow index (MFI)
Melt viscosity
Polymer additives
Polymer degradation
Polymer forms (pellets, granules, chips)

Note. Information adapted into table from “Polymer-Laid Systems” (p. 184-185) by S. R. Malkan and L. C. Wadsworth, 1993, in *Nonwovens: Theory, Process, Performance, and Testing*, by A. Turbak (Ed.), Atlanta: TAPPI Press.

3.3 Related Literature

The meltblown industry is competitive, therefore the process settings and polymers used are secretive. This has led to a plethora of patents on the process and equipment. However, there is research published that attempts to understand the relationship between the process variables and the interactions among these variables. Researchers have also studied these variables to develop mathematical models to predict the meltblown process (Chen, Li, & Huang, 2005b; Rao & Shambaugh, 1993; Uyttendaele & Shambaugh, 1990). The most common studies look at the affects of the process parameters on the mean fiber diameter. The specialty of the meltblown process is to produce micron size fibers, hence the interest on the parameters effects on fiber diameter. Other studies have researched the affect of process parameters on variables such as fiber entanglement, pore structure and size, air permeability, strength, and elongation. A review of the literature showed there are three key researchers, or principle investigators, conducting research on meltblown technology, Randall Bresee, Robert Shambaugh, and Larry Wadsworth. See Tables 10 and 11 regarding their research, and others, on the meltblown process parameters. For a general overview of research conducted by various authors see Wadsworth and McCulloch’s article and part one and two of Wadsworth and Malkan’s articles.

3.3.1 Process Variables Effect on Fiber Diameter

Table 10 displays various studies on process variables and mean fiber diameter. Independent variables studied include polymer throughput, polymer temperature, polymer melt index, air flow rate, air velocity, air pressure, air temperature, die temperature, and DCD. Other independent variables studied include collector speed, capillary and annulus orifice diameter, nozzle dimensions, and the use of oscillating and crossflow air.

The effect of polymer throughput, also referred to in literature as resin throughput, polymer flow rate, resin flow rate, and melt throughput, was studied by several researchers. Results all tread the same; there is a direct relationship between polymer throughput and mean fiber diameter. Researchers who studied the effect of polymer temperature, also referred to as melt temperature, on mean fiber diameter found an increase in polymer temperature decreases the mean fiber diameter. Two researchers studied the effect of the MFI, or melt flow rate (MFR), on mean fiber diameter and found different results. Chen, Wang, and Huang’s (2005) research showed an increase in MFI, decreased mean fiber diameter. However, they stated the diameter only decreased less than 1 micron from 150 to 2000 MFI. It is questionable if the MFI affect on mean fiber diameter is significant after 150 MFI. Straeffer and Goswami's (1992) research found that MFI did not decrease fiber diameter as expected. One possible reason for the disagreement between the two studies is that Chen, Wang, and Huang used the same air temperature for each MFI where as Straeffer and Goswami used different air temperatures.

Research by several authors show an increase in the air flow rate decreases the mean fiber diameter. A similar trend is also seen with the effect of air velocity and air pressure because the three variables are all closely related. However, Milligan et al. (1992) indicated that at higher air velocities (approximately 275 – 300 mps and higher), the mean fiber diameter is no longer affected. Several researchers stated that an increase in air temperature resulted in a decrease in mean fiber diameter. However, Chen, Wang, and Huang (2005) stated that the air temperature's affect on mean fiber diameter is insignificant. Several studies show that an increase in die temperature, decreases mean fiber diameter. There are also several studies that show an increase in DCD decreases the mean fiber diameter. However, Lee and Wadsworth (1990) state that after 30-cm, the DCD has no affect on mean fiber diameter.

The other independent variables shown in Table 10 were only found to be studied by one research group. Bresee and Qureshi (2006) found that an 83% increase in collector speed only increased fiber diameter 0.1 micron, indicating that collector speed did not significantly influence mean fiber diameter. Kayser and Shambaugh (1990) studied the effect of die design on the mean fiber diameter. They found when the capillary diameter (d_1), that carries the polymer flow, was increased, the fiber diameter decreased slightly. They explain this unexpected result is due to the deceasing area available for air flow which results in an increase in air velocity. Increase in velocity increases attenuation until air flow is too violent and causes fiber break. The study also showed that a decrease in the annulus orifice diameter (d_2), through which the air flows, decreased fiber diameter. However, just as with the capillary diameter, if the area for air flow is reduced too much, the air velocity will become too violent and cause broken fibers. These two diameters can be seen in Figure 10. Kayser and Shambaugh also found a decrease in nozzle dimensions (A_a/A_p, where A_a is area for air flow and A_p is area for polymer flow) decreases fiber diameter. There is, however, a limit to decreasing dimension size as a drop in pressure can occur. Tyagi and Shambaugh (1995) studied the effect of oscillating air on fiber diameter and Milligan et al. (1992) studied the effect of crossflow air on fiber diameter. Both studies indicated the use of these air flows, in comparison to the traditional continuous air flow, resulted in smaller mean fiber diameter.

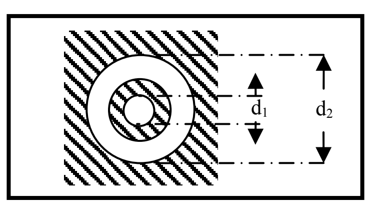

Figure 10. A cross-section bottom view of a concentric die design. Adapted from "The Manufacture of Continuous Polymeric Filaments by the Melt-Blowing Process," by J. C. Kayser and R. L. Shambaugh, 1990, *Polymer Engineering and Science*, 30(19), p. 1237.

3.3.2 Effect of Various Process Variables

Table 11 displays various studies on the effect of meltblown process variables on other variables. Two key independent variables studied were DCD and air flow. Other independent variables studied were polymer flow rate, die temperature, air temperature, air pressure, melt temperature, and the use of crossflow air.

Bresee and Qureshi (2004) and Lee and Wadsworth (2000) studied the effect of DCD on fiber entanglement and found there is an indirect relationship between the two variables. Researchers also studied the effect of DCD on pore structure, or pore cover, mean pore size, air permeability, fiber orientation, fiber and gas (air) velocity, Young's modulus, and bending rigidity (web stiffness). Bresee and Qureshi found that an increase in DCD, increased pore structure and decreased fiber orientation. Uyttendaele and Shambaugh (1990) found that an increase in DCD, increased fiber velocity and decreased gas velocity. However, in 1992, Wu and Shambaugh revised the 1990 research to show that an increase in DCD, decreased fiber velocity. Choi et al. (1988) found that an increase in DCD, decreased tenacity, Young's modulus, and bending rigidity and increased elongation at break. Lee and Wadsworth found that a decrease in DCD decreased mean pore size and air permeability.

Table 10

Process Variables Effect on Mean Fiber Diameter

Principle Investigator	Researchers	Dependent Variable	Independent Variables									
		Mean Fiber Diameter	Polymer Throughput	Polymer Temp.	MFI	Air Flow Rate	Air Velocity	Air Pressure	Air Temp.	Die Temp.	DCD	Others
	Chen, Li, & Huang (2005a)	↓	↓	-	-	-	↑	-	-	-	↑	-
	Chen, Wang, & Huang (2005)	↓	↓	↑	↑*	-	↑	-	n/a*	-	-	-
Bresee	Bresee & Qureshi (2006)	↓⇧	⇧	-	-	↑	-	-	-	↑	↑	Collector speed n/a
Shambaugh	Kayser & Shambaugh (1990)	↑⇩	↑	-	-	-	-	-	-	-	-	Capillary diameter (d_1) ⇧ Annulus orifice diameter (d_2) ⇩ Nozzle dimensions (A_a/A_p) ⇩
Shambaugh	Uyttendaele & Shambaugh (1990)	↓	-	-	-	-	-	-	-	-	↑	-
Shambaugh	Rao & Shambaugh (1993)	↓	↓	↑	-	-	↑	-	↑	-	-	-
Shambaugh	Tyagi & Shambaugh (1995)	↑⇩	↑	⇧	-	⇧	-	-	⇧	-	-	⇩ Fiber diameter with use of oscillating air
Shambaugh	Moore et al. (2004)	↑⇩	↑	-	-	⇧	-	-	-	-	-	-
	Straeffer & Goswami (1992)	↑⇩	↑	-	n/a*	-	⇧	-	-	-	-	-
Wadsworth	Choi et al. (1988)	↓	-	-	-	-	-	↑	-	↑	-	-
Wadsworth	Lee & Wadsworth (1990)	↓	-	-	-	↑	-	-	↑	↑	n/a after 30cm*	-
Wadsworth	Milligan et al. (1992)	↓	-	↑	-	-	↑	-	-	-	-	↓ Fiber diameter with use of crossflow air
	Wente et al. (1954)	↑⇩	↑	-	-	-	-	⇧	⇧	⇧	-	-
	Zhang et al. (2002)	↓⇧	⇧	↑	-	↑	-	-	↑	-	-	-

Note. The * indicates a disagreement among researchers.

Bresee et al. (2005) and Lee and Wadsworth (2000) studied the effect of air flow rate on fiber entanglement. Bresee et al. claims an indirect relationship but Lee and Wadsworth found a direct relationship between the variables. This difference in findings may be due to the fact that Bresee et al. tested a higher air flow range of 370 – 630 ft^3/min than Lee and Wadsworth who tested an air flow range of 160 – 370 ft^3/min. Straeffer and Goswami (1992) and Zhang et al. (2002) both studied the effect of air flow rate on tenacity. They found there is a direct relationship between the two variables. Researchers also studied the effect of air flow rate on pore structure, or pore cover, mean pore size, air permeability, fiber orientation, and elongation at break. Bresee et al. found an increase in air flow rate decreased pore structure and increased fiber orientation. Straeffer and Goswami also found an increase in air flow rate, decreased elongation at break but increased yield stress and initial modulus. Lee and Wadsworth found an increase in air flow rate decreased mean pore size and air permeability.

Besides air flow rate, Straeffer and Goswami also studied the effect of polymer flow rate on tenacity, elongation at break, yield stress, and initial modulus. They found that a decrease in polymer flow rate, increased tenacity, yield stress, and initial modulus, and decreased elongation at break. Zhang et al. also studied the effect of polymer flow rate. They found that increasing throughput decreased hydrostatic head and bulk density.

Choi et al. (1988) studied the effect of die temperature on tenacity, elongation at break, Young's modulus, and bending rigidity, and found that an increase in die temperature decreased all four variables. Lee and Wadsworth (1990) also studied the effect of die temperature and air temperature (together known as the processing temperature) and found an increase in processing temperature increased fiber entanglement and decreased mean pore size and air permeability. Zhang et al. (2002) found an increase in air temperature increased tenacity. Choi et al. found an increase in air pressure decreased tenacity, elongation at break, Young's modulus, and bending rigidity. Zhang et al. studied the influence of melt temperature, or polymer temperature, on air permeability, tenacity, elongation at break, and hydrostatic head. They found an increase in melt temperature decreased air permeability, elongation at break, and hydrostatic head and increased tenacity. Milligan et al. (1993), in their study of crossflow air, found that the use of crossflow air, in comparison to continuous air jets, increased fiber entanglement, air permeability, tenacity, elongation at break, and bursting strength.

Table 11
Effect of Various Process Parameters

Principle Investigator	Researchers	Independent Variables	Dependent Variables						
			Fiber Entanglement	Pore Structure (cover)	Mean Pore Size	Air Permeability	Tenacity	Elongation at Break	Other
Bresee	Bresee & Qureshi (2004)	↑ DCD	↓	↑	-	-	-	-	↓ Fiber orientation
Bresee	Bresee et al. (2005)	↑ Air flow rate	↓*	↓	-	-	-	-	↑ Fiber orientation
Shambaugh	Uyttendaele & Shambaugh (1990)	↑ DCD	-	-	-	-	-	-	↑ Fiber velocity ↓ Gas velocity
Shambaugh	Wu & Shambaugh (1992)	↑ DCD	-	-	-	-	-	-	↓ Fiber velocity (revised from 1990)
	Straeffer & Goswami (1992)	↑ Air flow rate	-	-	-	-	↑	↓	↑ Yield stress ↑ Initial modulus
		↓ Polymer flow rate	-	-	-	-	↑	↓	↑ Yield stress ↑ Initial modulus
	Choi et al. (1988)	↑ Die temperature	-	-	-	-	↓	↓	↓ Young's modulus ↓ Bending rigidity
		↑ Air pressure	-	-	-	-	↓	↓	↓ Young's modulus ↓ Bending rigidity
		↑ DCD	-	-	-	-	↓	↑	↓ Young's modulus ↓ Bending rigidity
Wadsworth	Lee & Wadsworth (1990)	↑ Processing temp. (die temp. & air temp.)	↑	-	↓	↓	-	-	-
		↑ Air flow rate	↑*	-	↓	↓	-	-	-
		↓ DCD	↑	-	↓	↓	-	-	-
	Milligan et al. (1993)	Use of crossflow air	↑	-	-	↑	↑	↑	↑Bursting strength
	Zhang et al. (2002)	↑ Melt temperature	-	-	-	↓	↑	↓	↓ Hydrostatic head
		↑ Polymer flow rate	-	-	-	-	-	-	↓ Hydrostatic head ↓ Bulk density
		↑ Air temperature	-	-	-	-	↑	-	-
		↑ Air flow rate	-	-	-	-	↑	-	-

Note. The * indicates a disagreement among researchers.

4. Conclusion

The meltblown process is, in many ways, a phenomenon. The variables of the meltblown process are complex because of the many parameters and interrelationships between variables. The quality of the equipment, the selection of the polymer, and the parameter settings all contribute to the quality of the end product. This paper discusses a general trending of these variables. The trends were found to be nonlinear with the exception of two, Bresee and Qureshi (2004) and Lee and Wadsworth (1990). Bresee and Qureshi stated the effect of DCD on pore structure was linear and Lee and Wadsworth stated the effect of DCD on air permeability was also linear. While there has been considerable research conducted on the meltblown process, there are several variables which should be studied further. Table 10 shows research conducted on variables which influence mean fiber diameter. However, research is lacking on the relationship between air pressure and mean fiber diameter as well as MFI and mean fiber diameter. Table 11 also shows extensive research has been conducted on the interaction of numerous variables. Further studies, however, could be conducted to verify previous research on variables such as the influence of DCD as well as air flow on other variables. The significance of the parameters on others variables, and fiber and web characteristics, vary depending on data collection methods, process parameter settings, and polymer(s) used. An understanding of these factors is important to those individuals managing a meltblown line and to the researchers studying the process.

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