To the Graduate Council:

I am submitting herewith a thesis written by Hua Song entitled “FIBER SPLITTING OF BICOMPONENT MELT BLOWN MICROFIBER NONWOVENs BY CHEMICAL AND WATER TREATMENT”. I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Textiles, Retailing and Consumer Sciences.

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(Original signatures are on file with official student records.)
FIBER SPLITTING OF BICOMPONENT MELT BLOWN MICROFIBER NONWOVENS BY CHEMICAL AND WATER TREATMENT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Hua Song
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ABSTRACT

The melt blowing process is unique because it is used almost exclusively to produce microfibers rather than fibers the size of normal textile fibers. With bicomponent meltblown bicomponent fabrics, PLA/PP and PLA/PTT, an alkaline treatment was applied to the fabrics, causing the dissolvable part (PLA) removed from the bicomponent fibers.

Alternatively, water treatment is preferred compared to alkaline treatment. Water dispersive Eastman AQ polymers were introduced to melt blown processing for the first time. After the water dispersive AQ polymer was determined to be able to be processed into a nonwoven fabric using the melt blowing processing line, the feasibility of processing bicomponent nonwoven with that polymer was proved. Then, AQ/PP bicomponent melt blown fabrics were produced with TANDEC Reicofil® Bicomponent Meltblown Line successfully. Water treatment was performed on the bicomponent webs, causing the dispersive part, AQ polymer, dispersed in soft water.

The effects of alkaline and water treatment on the properties of bicomponent melt blown webs were studied. After both treatments, bicomponent melt blown fabrics tended to decrease in fiber size, basis weight, thickness, tenacity and stiffness. Air permeability appeared to decrease for high PLA or AQ composition samples, and hydrostatic pressure as well as derived filtration efficiency increased for those samples. Elongation increased notably for most samples with different bicomponent ratios after water treatment.

The relationship between polymer ratio in a bicomponent fiber and the fiber cross-section geometry was mathematically investigated, as well as specific surface area change of a fiber after fiber size reduction treatments.

A preliminary experimental study was done to give some general optimized water treatment conditions for AQ/PP bicomponent melt blown fabrics. Also, an empirical rule was summarized about the treatment time of complete AQ polymer dispersion. Some DSC scans of AQ resins and AQ polymer nonwoven products indicated the possibility of recycling AQ polymer after the water treatment.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Background and Literature Review</td>
<td>1</td>
</tr>
<tr>
<td>Melt Blown Nonwovens</td>
<td>1</td>
</tr>
<tr>
<td>Bicomponent Fibers</td>
<td>2</td>
</tr>
<tr>
<td>Microfiber Processing</td>
<td>4</td>
</tr>
<tr>
<td>Biodegradable and Water Soluble Polymers</td>
<td>5</td>
</tr>
<tr>
<td>Objective of This Research</td>
<td>7</td>
</tr>
<tr>
<td>II. EXPERIMENTS</td>
<td>9</td>
</tr>
<tr>
<td>Alkaline Solution Treatment</td>
<td>9</td>
</tr>
<tr>
<td>Polymer Materials</td>
<td>9</td>
</tr>
<tr>
<td>Chemicals</td>
<td>9</td>
</tr>
<tr>
<td>Chemical Treatment</td>
<td>9</td>
</tr>
<tr>
<td>Testing</td>
<td>9</td>
</tr>
<tr>
<td>Preliminary Study Eastman AQ Polymer</td>
<td>10</td>
</tr>
<tr>
<td>Eastman AQ Resin</td>
<td>10</td>
</tr>
<tr>
<td>Eastman AQ Polymers Melt Blown Nonwoven fabrics Testing</td>
<td>10</td>
</tr>
<tr>
<td>Water Treatment</td>
<td>11</td>
</tr>
<tr>
<td>Polymer Materials</td>
<td>11</td>
</tr>
<tr>
<td>Processing</td>
<td>11</td>
</tr>
<tr>
<td>Water Treatment</td>
<td>11</td>
</tr>
<tr>
<td>III. RESULTS AND ANALYSIS</td>
<td>16</td>
</tr>
<tr>
<td>Chemical Treatment</td>
<td>16</td>
</tr>
<tr>
<td>Eastman AQ Polymer Preliminary Study</td>
<td>18</td>
</tr>
<tr>
<td>Eastman AQ resins</td>
<td>18</td>
</tr>
<tr>
<td>Eastman AQ polymers melt blown fabrics</td>
<td>18</td>
</tr>
<tr>
<td>Water Treatment</td>
<td>19</td>
</tr>
<tr>
<td>AQ Polymer Solution Process</td>
<td>19</td>
</tr>
<tr>
<td>Incomplete Dispersion of AQ/PP Bicomponent Nonwoven Web</td>
<td>19</td>
</tr>
<tr>
<td>Complete Dispersion of AQ/PP Bicomponent Nonwoven Web</td>
<td>20</td>
</tr>
<tr>
<td>SEM images analysis</td>
<td>20</td>
</tr>
<tr>
<td>Physical Properties Analysis</td>
<td>23</td>
</tr>
<tr>
<td>Differential Scanning Calorimetry Analysis</td>
<td>40</td>
</tr>
<tr>
<td>AQ Bico Distilled Water Treatment Optimization</td>
<td>46</td>
</tr>
<tr>
<td>IV. CONCLUSION AND RECOMMENDATION</td>
<td>49</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>51</td>
</tr>
<tr>
<td>VITA</td>
<td>54</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Figure 1. Schematic of a melt blowing process</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2. Cross sections of bicomponent fibers</td>
<td>3</td>
</tr>
<tr>
<td>Figure 3. Branched Water Dispersible Polyester Structure</td>
<td>8</td>
</tr>
<tr>
<td>Figure 4. Sodiosulfoisophthalic Acid</td>
<td>8</td>
</tr>
<tr>
<td>Figure 5. SEM microphotographs of bicomponent melt blown web (PLA/PP 75/25)</td>
<td>17</td>
</tr>
<tr>
<td>Figure 6. SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven before water treatment</td>
<td>21</td>
</tr>
<tr>
<td>Figure 7. SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven after water treatment</td>
<td>21</td>
</tr>
<tr>
<td>Figure 8. Cross section SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven after water treatment</td>
<td>22</td>
</tr>
<tr>
<td>Figure 9. Cross section SEM microphotograph of #9, 50/50 AQ/PP melt blown nonwoven after water treatment</td>
<td>22</td>
</tr>
<tr>
<td>Figure 10. More cross section SEM microphotograph of #9, 50/50 AQ/PP melt blown nonwoven after water treatment</td>
<td>23</td>
</tr>
<tr>
<td>Figure 11. Physical tests on AQ/PP bicomponent nonwoven webs</td>
<td>25</td>
</tr>
<tr>
<td>Figure 12. Fiber diameter distribution of #7 (25/75 AQ/PP) melt blown webs before and after water treatment, determined from OM and SEM images</td>
<td>29</td>
</tr>
<tr>
<td>Figure 13. Fiber diameter distribution of #10 (75/25 AQ/PP) melt blown webs before and after water treatment, determined from images</td>
<td>30</td>
</tr>
<tr>
<td>Figure 14. Ideal cross section diagram of a side-by-side bicomponent fiber</td>
<td>31</td>
</tr>
<tr>
<td>Figure 15. Fiber diameter distribution of #9 (50/50 AQ/PP) melt blown webs before and after water treatment, determined from images</td>
<td>32</td>
</tr>
<tr>
<td>Figure 16. AQ polymer weight percentage in a bicomponent fiber verses its relative position in the fiber’s cross-section</td>
<td>35</td>
</tr>
<tr>
<td>Figure 17. Polymer components’ arrangement in a bicomponent fiber (cross section)</td>
<td>37</td>
</tr>
<tr>
<td>Figure 18. Specific area S/V verses height of the left part in a bicomponent fiber after treatment</td>
<td>37</td>
</tr>
<tr>
<td>Figure 19. DSC scans of Eastman AQ35S and AQ55S pellets</td>
<td>39</td>
</tr>
<tr>
<td>Figure 20. DSC scans of Eastman AQ35S and AQ55S melt blown nonwoven webs</td>
<td>41</td>
</tr>
<tr>
<td>Figure 21. More DSC scans of Eastman AQ35S and AQ55S melt blown nonwoven webs</td>
<td>41</td>
</tr>
<tr>
<td>Figure 22. DSC scans of Eastman AQ35S/PP bicomponent melt blown nonwoven webs: #7, 25/75 AQ/PP; #9, 50/50 AQ/PP; #10, 75/25 AQ/PP</td>
<td>42</td>
</tr>
<tr>
<td>Figure 23. DSC scans of Eastman AQ35S/PP bicomponent melt blown nonwoven webs after complete water treatment: #10, 75/25 AQ/PP; #9, 50/50 AQ/PP; #7, 25/75 AQ/PP</td>
<td>43</td>
</tr>
<tr>
<td>Figure 24. Two DSC scans of film extracted from #7 25/75 AQ35S/PP water treatment solution by natural evaporation</td>
<td>45</td>
</tr>
<tr>
<td>Figure 25. DSC scans of solution extractants from #10, 75/25 AQ35S/PP nonwoven web and Eastman AQ35S pellets by heating up solution</td>
<td>45</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1. Typical Properties of Eastman AQ35S and AQ55S polymers</td>
<td>8</td>
</tr>
<tr>
<td>Table 2. Eastman AQ melt blown nonwovens production conditions</td>
<td>11</td>
</tr>
<tr>
<td>Table 3. Samples for water treatment</td>
<td>12</td>
</tr>
<tr>
<td>Table 4. Melting flow rate testing results</td>
<td>18</td>
</tr>
<tr>
<td>Table 5. AQ content in AQ/PP bicomponent fibers and corresponding geometrical features. R is the radius of the fiber; S stands for the surface area of a whole fiber, and V is its volume, S/V gives the specific area of a fiber.</td>
<td>36</td>
</tr>
<tr>
<td>Table 6. Normalized heat of flow of PP melt peak in bicomponent melt blown webs before and after water treatment.</td>
<td>43</td>
</tr>
<tr>
<td>Table 7. Basis weight percent change at different treatment time and temperature</td>
<td>48</td>
</tr>
<tr>
<td>Table 8. Recommended treatment conditions at 0.05% solids concentration:</td>
<td>48</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

Background and Literature Review

Melt Blown Nonwovens

The definitions of the nonwovens most commonly used nowadays are those by the Association of the Nonwovens Fabrics Industry (INDA) and the European Disposables and Nonwoven Association (EDANA).

EDANA definition: *Nonwovens are a manufactured sheet, web or batt of directionally or randomly oriented fibers, bonded by friction, and/or cohesion and/or adhesion, excluding paper or products which are woven, knitted, tufted stitchbonded incorporating binding yarns or filaments, or felted by wetmilling, whether or not additionally needed. The fibers may be of natural or man-made origin. They may be staple or continuous or be formed in situ* [EDANA, 1988].

Melt blowing is one of the most popular processes to make super fine fibers on the micron or sub-micron scale. It is a “one-step process in which high velocity fluid, normally air blows molten thermoplastic resin from an extruder die tip to a conveyor, or take-up screen, or substrate to form a fine fibered, self-bonded web” [Staff report, 1989]. The melt blown process converts resins to nonwoven fabrics in a single integrated process. The schematic of the melt blowing process is shown in Figure 1. A typical melt blowing process consists of the following elements: extruder, metering pumps, die assembly, web formation, and winding.

The concept of melt blowing thermoplastics was first introduced to the public in 1954 through a Naval Research Laboratory project initiated by Wente [Haynee, 1991]. Since then, the melt blowing process and a variety of melt blown products have been recognized, developed, and commercialized. Over 320 US patents have been granted to the technologies and products related to melt blowing in the past 50 years. It is clear that the melt blown technology is finding its application in more and more fields.

This melt blown process is unique because it is used almost exclusively to produce microfibers rather than fibers the size of normal textile fibers, generating fine fibers not available to the other nonwoven processes. Melt blown microfibers generally have diameters in the range of 2 to 5 µm, although they may be as small as 0.1µm and as large as 10 to 15 µm. Differences between melt-blown nonwoven fabrics and other nonwoven fabrics, such as degree of softness, cover or opacity and porosity can generally be traced to differences in filament size. The average fiber diameter can be controlled by the specific resin employed and the processing conditions selected. With such fiber fineness,
the number of fibers per unit weight is greatly increased. Further, the amount of fiber surface exposed is also substantially greater than that exposed in conventional webs. As a consequence, these characteristics can have a significant impact in a variety of product applications. At the present time, filtration media, medical fabrics, sanitary products, oil adsorbents, apparel, hot-melt adhesives, electronic specialties and other miscellaneous applications, such as the tents and elastomeric nonwoven fabrics are successfully served by melt-blown products.

**Bicomponent Fibers**

Bicomponent fibers are not new. Thus, wool is a naturally occurring bicomponent fiber, and glass bicomponent fibers were produced in the latter part of the nineteenth century. Bicomponent, side-by-side viscose fibers were patented in 1937 [Porter, 1984]. In the 1960s, bicomponent nylon fibers were introduced for use in hosiery and in nonwoven products.

One of the first producers of bicomponent fibers was the Du Pont Company, with its self-crimping Cantrece, a bicomponent nylon monofilament used in hosiery [Davies, 1991]. In recent years, the Japanese have developed the market for the sheath/core bicomponent fiber, which is mainly used in nonwoven fabrics. In these fibers, the sheath is the lower melting component used to thermally bond fiber to fiber in nonwoven fabrics.

Bicomponent fibers may be classified as sheath/core, side-by-side, eccentric, islands-in-the-sea, and citrus, as shown by the cross sections of these fibers given in
Figure 2. Cross sections of bicomponent fibers

Figure 2. The islands-in-the-sea and citrus bicomponent fibers are used chiefly to make microfibers; microfibers have no universally accepted definition but are usually considered to be those with a denier per filament of less than 1. With bicomponent fibers, one of the fiber components is removed by the use of heat, a solvent, or a chemical or the two component fibers can be physically split apart. The Japanese have produced microfibers from PET and other polymers that imitate silk in some properties. Today, many companies, especially in Europe and the United States, have learned how to control the spinning of microfibers directly without making precursor bicomponent fibers. These microfibers have grown rapidly in volume.

Side-by-side bicomponent fibers are produced, as the name implies, by spinning two fiber components together so that they are joined longitudinally. One of reasons for manufacturing these fibers is to provide helical crimp, caused by differences in the expansion or shrinkage of the two components of the fibers. The two components may differ in chemical composition or differ in some property such as molecular weight or degree of crystallization, which provides differential expansion or shrinkage. Sometimes the polymer components may differ in degree of hydrophilicity; for example, both polymers may be copolymers of polyacrylonitrile but contain different amounts of sulfonic acid groups. Bicomponent side-by-side inorganic fibers with crimp have also been produced.

Side-by-side bicomponent fabrics made with side-by-side bicomponent fibers have high bulk and resiliency. However, they may not have the strength of nonwoven fabrics made with sheath/core bicomponent fibers. Bouchillon [1992] points out that with these side-by-side fibers, “the bulk, resiliency, and stretch/recovery properties are desirable for many nonwoven applications, including: shoe components, apparel, toys, sleeping bags, pillows, furniture, and automotive.” Additives can also be used to impart various properties to fabrics made from side-by-side fibers.
Microfiber Processing

As mentioned above, microfibers have no universally accepted definition but are usually considered to be those with a decitex per filament of less than 1.

Most microfiber is made of polyester; however, other polymers are used, including nylon, polyacrylonitrile, polypropylene, cellulose acetate, and rayon. Mixtures of polymers such as polyester-nylon and polyester-polypropylene are also used. Microfibers are manufactured in both staple and filament forms. Microfibers are chiefly made in three different ways: (1) chemical dissolution of one of the components in a bicomponent fiber, (2) physical splitting of a bicomponent fiber, and (3) direct spinning of the microfiber. Methods 1 and 2 can be accomplished in the fabric finishing process.

The production of polyester microfibers started in Japan in the 1970s by size reduction of the fibers in polyester fabrics, using hot alkaline treatment to dissolve their surface polymer. Polyester fabric was subjected to hot alkaline treatment to remove up to 40-50%, usually 20-30%, of the fabric weight. The treatment resulted in smaller diameter fibers and a fabric “with an increased liveliness, drape, and covering power, plus a warm, dry, silk-like hand with increased scoop”. In the United States similar treatment of polyester fabric is carried out with lower weight loss, typically 8-15% (Goldstein, 1993). Rame [1992] has studies the loss in weight of polyester fibers in alkali and found that it is linear from 15 to 95°C at 10% concentration of alkali. He found that silk like properties can be imparted to polyester with a weight reduction of 8 to 12%.

Microfiber can be produced from a bicomponent fiber by dissolving one component. The bicomponent fiber may be splittable, resulting in microfibers that are a mixture of both components. Microfibers can be made from bicomponent fibers of various configurations, including islands-in-the-sea and citrus structures. The microfiber made by Kanebo in Japan [Murata, 1993] is split by a chemical treatment. Fabrics made from a resulting polyester/nylon microfiber have a hand similar to silk.

A 1992 U.S. patent to Chisso Corp. in Japan describes the preparation of microfibers from islands-in-the-sea or side-by-side multicomponent fibers [Kawano, 1992]. For the islands-in-the-sea fibers, the sea component is dissolved, leaving the island component as a very small microfiber less than 0.1 dtex in size. An example of a side-by-side fiber is given in which one side of the fiber is an islands-in-the-sea with a sea component of saponifiable polyvinyl alcohol and an island component of polypropylene. The other side of the fiber is polyethylene. The polyvinyl alcohol is extracted with water or an alkaline solution. What remains are very fine microfibers (less than 0.1 denier) of polypropylene mixed with larger (5.5 denier) polyethylene fibers. An example is also given of a sheath/core fiber in which the sheath component contains saponified polyvinyl alcohol as the sea component and polypropylene as the island component. The core component is polyethylene. After extraction of the saponified polyvinyl alcohol with water or alkaline solution, the very fine microfibers are polypropylene of less than 0.1 denier and the core
component contains large (2.4 denier) polyethylene fibers. The patent also describes nonwoven fabrics made from a mixture of very fine polypropylene fibers and the larger polyethylene fibers. The polyethylene fiber becomes the binder fiber in the nonwoven fabric. The water or alkaline solution extraction may be carried out after the fabric is prepared.

Microfibers’ small diameter and high surface area should enable them to produce superior fabrics for many uses, such as nonwoven fabrics made with microfibers and thermally bonded have been used in interfacing [Bolliand, 1992]. Microfibers will no doubt find new uses in the future.

Biodegradable and Water Soluble Polymers

*Polylactide (PLA)*

Polylactide (PLA) is an exciting new polymer made from renewable resources such as corn, leading to less use of fossil fuel and lower carbon dioxide emissions than traditional hydrocarbon based polymers. PLA polymers can be safely disposed of in typical solid waste disposal routes. PLA represents one of the most important biodegradable polymers [Fambri, 1996].

PLA derives from the polymerization of the lactide or lactic acid. Two enantiomorphous stereoisomers of lactic acid exist, referred to as L and D type isomers. Polymers containing large amount of both L and D isomers do not possess the stereoregularity to crystallize. Since the glass transition occurs at a relatively low temperature (=58°C), such polymers do not find many applications. The polymers that are most useful for fiber and Nonwovens applications contain a preponderance of a single isomer, which in the present case is the L isomer. However, the amount of D isomer is the polymer is an important variable that influences the properties of the polymer. The primary mechanism of degradation of PLA is via hydrolysis. Water attacks the chain backbone at the ester linkage. This ultimately results in chain scission and polymer breakdown [Spruiell, 1997].

PLA Polymers has been shown to biodegrade similarly to paper under simulated composting conditions (ASTM D5338 at 58°C [135°F]).

*Polyvinyl Alcohol (PVOH)*

Polyvinyl alcohol (PVOH) is a biodegradable plastic material which has been the subject of extensive technological advances over the past few years. It was first synthesized in 1924 by Herman and Haehnel [Consortium Pat, 1924 and 1926], by the
hydrolysis of polyvinyl acetate and its major initial use was for textile sizing. Low hydrolysis grades (i.e., < 90% hydrolysis) will exhibit good cold water solubility and allow a PVOH product to fall apart rapidly in a sewage or septic environment. Fully hydrolyzed grades (i.e., > 98% hydrolysis) would impart good strength in cold water but would not fall apart upon disposal.

Thermal degradation characteristics of PVOH have traditionally limited its applicability as a thermoplastic. Unplasticized PVOH thermally degrades above about 180°C (356 °F), with the release of water and the formation of conjugated double bonds. Further degradation can then lead to discoloration and crosslinking, depending on the amount of oxygen present. Because the crystalline melting point of PVOH ranges from about 180°C (356°F) to 240°C (464°F), its use as a thermoplastic which can be processed on conventional melt-processing equipment have hitherto been extremely restricted. Cooper [2002] summarized some attempts that have been made to improve this property.

Dever and etc. (1993) successfully processed a commercially available, water soluble, biodegradable 88% hydrolyzed PHOH Vinex 2019™ resin into melt blown nonwovens. The rate of cold water solubility of the pure PVOH melt blown material was reduced using chemical treatments. But it is not commercially available now.

A soft-flow, extrusion grade cellulose acetate resin and a polyvinyl alcohol (26-30 melt index) resin were successfully melt blown on a 6-inch wide pilot melt blowing line (Khan, 1993).

Partially hydrolyzed polyvinyl alcohol from Du Pont EIVANOL® was tried at the beginning of the study. But the large viscosity and degradation at around 250°C happened in the trial led to the failure of its application in this research.

**Eastman AQ Polymer**

The new product of Eastman Chemical Company, a branched polyester introduced and commercialized in the fall of 1995, can be used to formulate hot-melt adhesives that disperse easily in water. Hot-melt adhesives based on the new raw material can be used in a variety of applications including nonwoven products such as disposable diapers, packaging, bookbinding and labels. Products containing the water-dispersible adhesive can then be more easily repulped or recycled. Eastman AQ polymer is one of a new family of polymers offering the hot-melt adhesives market the advantage of being readily dispersible in water, while being nondispensible in saline (i.e., body) fluids. This controlled dispersibility can be exploited as a method of recovery.

The water-dispersible polyesters are branched, amorphous materials comprised of difunctional acids and various glycols. Their water-dispersibility is due to the presence of pendent sodiosulfo groups randomly distributed along the polymer backbone, as shown in
Figure 3. Incorporation of the ionic moieties is readily accomplished by the copolymerization of 5-sodiosulfo-isophthalic acid (Figure 4) into the polymer backbone [Eastman Chemical Company].

The unique properties of the new polyester are derived from a branched architecture and a specific combination of monomers resulting in a low Tg and enhanced compatibility with other resins. The low Tg provides, in part, the means by which water-dispersibility is readily obtained at or below room temperature. The branched structure of the polyester, results in low melt viscosity profiles that are required for hot-melt adhesive formulations. These water-dispersible polymers are available in melt viscosities ranging from 4500 cps to 400,000 cps.

Eastman AQ polymers are thermoplastic and amorphous polyesters that disperse directly in water without the assistance of organic cosolvents, surfactants, or amines. Most of the end groups of Eastman AQ polymer chains are hydroxyl groups. Although hydroxyl numbers are fairly low, typically less than 10, the potential for cross-linking reactions still exists, such as reaction with melamine/formaldehyde resins, and for chain extension with, for example, dissocyanates. The carboxyl (-COOH) content of the Eastman AQ polymers is low but detectable; acid numbers are typically less than two. Typical characteristics of two types of AQ polymer, AQ35S and AQ55S are listed in Table 1. Tests conducted at an independent laboratory indicated that these polymers are not readily biodegradable.

Objective of This Research

A lot of effort has been made on microfiber production by alkaline treatment, but none of them were on bicomponent melt blown nonwovens. Melt blown process is used almost exclusively to produce microfibers rather than fibers the size of normal textile fibers. With the microfiber melt blown bicomponent nonwovens, alkaline treatment is expected to get even finer fibers.

The alkaline treatment process requires safe precaution, and involves environmental problems. The most available and easiest solution is water. Besides, water treatment can greatly simplify application of microfiber reduction treatment by eliminating the cost, time, and need for alkaline treatment if it has the same effect on microfiber production. Therefore, a suitable water soluble polymer or water dispersive polymer is sought to satisfy this requirement. The other objective of this study was to determine whether a water soluble polymer could be processed into a nonwoven fabric using available melt blowing processing conditions. If this was feasible, the second objective of the study was to study the feasibility of processing bicomponent nonwoven with that polymer.

Lastly and mostly important, the effect of alkaline and water treatment on the bicomponent melt blown webs was to be determined.
Figure 3. Branched Water Dispersible Polyester Structure

Figure 4. Sodiosulfoisophthalic Acid

Table 1. Typical Properties of Eastman AQ35S and AQ55S Polymers

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Solid Polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent solid</td>
<td>AQ35S</td>
</tr>
<tr>
<td>Physical form</td>
<td>100</td>
</tr>
<tr>
<td>Approximate molecular weight, Mn b</td>
<td>Pellet</td>
</tr>
<tr>
<td>Hydroxyl number</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Acid number</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Tg, C</td>
<td>35</td>
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<tr>
<td>Color</td>
<td>Clear, light amber</td>
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CHAPTER II
EXPERIMENTS

Two different treatments were evolved in the investigation of microfiber bicomponent nonwoven webs. They are alkaline solution treatment and water treatment, and especially the water treatment study was given the greatest emphasis.

Alkaline Solution Treatment

Polymer Materials

White bicomponent nonwoven fabrics
Group 1: (PLA/PP)% 75/25 50/50 25/75
Group 2: (PLA/PTT)% 50/50 25/75

Chemicals

36% (solid percentage) sodium hydroxide (Fish ChemAlert® Guide NaOH pellet, Fisher Scientific, NF/FCC) solution was prepared by dissolving NaOH particles in distilled water.

Chemical Treatment

The prepared bicomponent nonwoven fabrics samples were weighed accurately. Then, the treatment was carried out in a container under standard room temperature and humidity. After treatments, the samples were washed with excess water, carefully collected to a net, and dried in air for sufficient time to complete the drying.

Testing

Eight tests including fabric Basis Weight (IST 130.2 (98)), Thickness (IST 120.1 (ASTM D 5729-97), Air Permeability (IST 70.1 (ASTM D 737-96)), Hydrohead (IST 80.6 (98)), Tensile (IST 110.4 (ASTM 5035-95), Flexual Rigidity (IST 90.1 (ASTM D 5732-95)), Filtration Efficiency and Fiber Diameter, were performed before and after chemical treatment, respectively.
Preliminary Study Eastman AQ Polymer

Eastman AQ Resin

The following testings were performed on Eastman AQ35S and AQ55S resins:

*Differential Scanning Calorimetry (DSC):* Summarized in Water Treatment part.

*Melt Flow Index:* According to ASTM D1238-89, a melt flow indexer was used to test melt flow rate (MFR) of polymers at the recommended operation temperature: 275°C and 300°C.

*Dispersion Pellets of Eastman AQ polymers in Water:* 30% (57g pellet, 277ml water) solid pellets of Eastman AQ 35S polymers were slowly sifted into distilled water at 76°C. Moderate agitation by magnetic stirrer was provided.

Eastman AQ Polymers Melt Blown Nonwoven fabrics Testing

The following tests were performed on melt blown nonwoven fabrics of Eastman AQ polymers:

*Regular Nonwoven Fabric testing:* Eastman AQ35S and AQ55S were utilized to produce monocomponent nonwoven fabrics on the 6-inch wide melt blowing (MB) pilot line at UTK. Production conditions are listed in Table 2. Six regular nonwoven fabric tests were performed with the same standards as above: Basis Weight, Thickness, Fiber Diameter, Air Permeability, Tensile and Stiffness.

*DSC:* Summarized in Water Treatment part

*Dispersion Nonwovens of Eastman AQ polymers in Water:*
1. Cold tap water treatment: Two samples from each nonwovens were collected and put in regular tap water (20°C) for about 20 hours, taken out, dried naturally.
2. Hot distilled water treatment: Distilled water was heated up to recommended temperature (72-77°C for AQ35S, 85-90°C for AQ55S) by Eastman Chemical Company. Weighted nonwovens were put in and moderate agitation by magnetic stirrer was provided.

*Imaging:* Olympus optical microscopy was used to catch microphotographs for #2 AQ 35S nonwoven. These images were all taken with 50X objective. The images were digitally transferred to a computer screen by digital camera (MTI CCD 72S) attached to the optical microscopy and analyzed by Scion Image (an image analysis software).
Table 2. Eastman AQ melt blown nonwovens production conditions

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Polymer</th>
<th>Melt Polymer Temp (°F/°C)</th>
<th>Throughput (g/h/min)</th>
<th>Air Temp (°F/°C)</th>
<th>Pressure (Psi)</th>
<th>DCD (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>AQ55</td>
<td>530 /257</td>
<td>0.4</td>
<td>560/287</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>#2</td>
<td>AQ35</td>
<td>510 /237</td>
<td>0.3</td>
<td>510/237</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>#3</td>
<td>AQ35</td>
<td>510/237</td>
<td>0.3</td>
<td>510/237</td>
<td>3</td>
<td>24</td>
</tr>
</tbody>
</table>

**Water Treatment**

**Polymer Materials**

1. Eastman AQ 35S, clear, light amber pellets, amorphous polyester, MFR = 319g/10min at 300°C, Tg = 35°C, density $\rho = 1.2 \text{ g/cm}^3$
2. Eastman AQ 55S, clear, light amber pellets, amorphous polyester, MFR = 139g/10min at 300°C, Tg = 55°C, density $\rho = 1.2 \text{ g/cm}^3$
3. Exxon PP 3546G, white pellets, MFR = 1200g/10min at 230°C, Tm = 165°C, Tg = -17°C, density $\rho = 0.9\text{ g/cm}^3$,
4. Basell PP, white pellets, MFR = 800g/10min at 230°C, Tm = 165°C, Tg = -17°C, density $\rho = 0.9\text{ g/cm}^3$,

**Processing**

The first objective of this study was to determine whether Eastman AQ polymer could be processed into a nonwoven fabric using melt blowing processing. This work includes results obtained from trial runs on the 6-inch wide melt blowing (MB) pilot line at the University of Tennessee, Knoxville (UTK). After it was proved to be feasible, Eastman AQ 35S polymer and polypropylene were processed into a bicomponent nonwoven utilizing 24-inch Recofil® bicomponent MB pilot line at UTK.

**Water Treatment**

Eastman AQ35 water dispersive polymer was applied with polypropylene to produce bicomponent meltblown fabrics. Polypropylene is the most commonly used polymer for melt blown nonwoven products, because it produces the best web among the low cost resins (Choi, 1988).
Three kinds of water treatment were performed on bicomponent meltblown fabrics:
1. soaked in tap water (hard water)
2. soaked in distilled water for seconds
3. soaked in distilled water for hours

In the trial experiment applying the first treatment, the bicomponent specimen did not lose any weight, which indicates no AQ35 was dispersed in the tap water because of hard water ions (Ca$^{+2}$, Mg$^{+2}$, Fe$^{+3}$, etc.) it contains, which retard the dispersion rate of the AQ polymers in water; in the second treatment, specimens were soaked in distilled water only for seconds. No weight loss is expected within such a short time, but the water came in contact with AQ polymer and the subsequent dispersion reaction is presumed to happen; in the third treatment, specimens were soaked in distilled water for about 20 hours. Complete weight loss from AQ polymer is expected.

According to the above description and explanation, tap water treatment was not adopted in the further research.

**Sampling**

Table 3 lists samples processed for water treatment. 13” by 17” pieces were cut from #7 and #9 samples, and 7” by 13” pieces were cut from the other samples due to the limitation of treatment containers’ size, and the consideration of required specimen size for later testing. Specimens were weighed before any treatment

In the short time water treatment, specimens were soaked into plastic containers with sufficient distilled water for no more than 10 seconds, and taken out when the specimens looked thoroughly wet.

**Table 3. Samples for water treatment**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Description (Weight ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Pure PP$_{Exxon}$</td>
</tr>
<tr>
<td>#4</td>
<td>Pure AQ35</td>
</tr>
<tr>
<td>#7</td>
<td>25/75 AQ/PP$_{Exxon}$</td>
</tr>
<tr>
<td>#8</td>
<td>25/75 AQ/PP$_{Basell}$</td>
</tr>
<tr>
<td>#6</td>
<td>50/50 AQ/PP$_{Exxon}$</td>
</tr>
<tr>
<td>#9</td>
<td>50/50 AQ/PP$_{Basell}$</td>
</tr>
<tr>
<td>#10</td>
<td>75/25 AQ/PP$_{Basell}$</td>
</tr>
</tbody>
</table>
In the long time complete dispersion water treatment, #7 and #9 specimens were put into plastic container with 1500 ml room temperature (about 20°C) distilled water, and other specimens into a smaller container with 1000 ml the same kind of distilled water. After sufficient time, when the specimens didn’t feel slippery resulting from the still attached AQ polymer, then taken out.

All the treated wet specimens were dried naturally, and weigh up their weight again.

**Conditioning**

All the specimens were conditioned in the standard atmosphere for testing, which is 21 ± 1°C (70 ± 2°F) and 65 ± 2% humidity. But due to the mechanical problem the conditioner faced during the testing period, the humidity was only around 50 % at testing.

**Testing**

**Basis weight and Thickness**

Ten measurements were made on 10 random places on each specimen. The average values were reported according to INDA Standard Test Methods: IST 130.1 and IST 120.1 (ASTM D5729-97).

**Air Permeability**

The rate of air flow passing perpendicularly through a known area under a prescribed air pressure differential between the two surfaces of a material. According to ASTM D737-96, ten specimens were taken randomly for each sampling unit. FX 3300 Air Permeability Tester provides a pressure drop of 125 Pa (12.7 mm or 0.5 in. of water) across the specimen. The average values and standard deviation were reported.

**Water Resistance (Hydrostatic Pressure Test)**

According to IST 80.6 (98), three random specimens were tested for each material. The FX 3000 Hydro Static Head Tester provides a pressure gradient of 60 mbar of water per minute. A supporting nylon net was attached under each specimen.

**Fiber Diameter**

Fiber diameter was determined from images of a scanning electron microscope and an Olympus optical microscope, with the application of Scion Image software.
Two randomly selected specimens were mounted on a sample stub for each sample.

Polymers in nonwoven fabrics are non-conductive or poorly conductive materials, and charge will be implanted deep beneath the specimen surface. If this is allowed to occur then suitable imaging may never be achieved. Coating was adopted to avoid charging here.

The mounted sample was coated with gold blend by low vacuum plasma sputtering instrumentation. Low vacuum plasma sputtering characterized by a luminescence known as the glow discharge, a dazzling lavender glow for air and argon [Postek, 1980]. Electrons produced by ionization bombarding the anode may produce heat in a specimen resting on the anode surface, and may damage it, therefore the coating time cannot be too long. Each specimen was coated 15 seconds for three times with 10 seconds interval between them to release heat.

To achieve a fabric cross-section image, a sharp razor was used to cut a cross section for each sample. When taking images, the cross section side faces up toward the electron gun inside SEM. Microscopy data were gathered using the Cambridge 360 Scanning Electron Microscope in Materials Science Department Microscope lab at University of Tennessee, Knoxville. About 150 fiber diameter measurements were made on each sample.

**Optical Microscope**

In the optical microscope measurement, a video camera was attached to the microscope, and measurement was performed on the images displayed on the computer monitor with 50X objective. All fibers with sharply shown edges in the image were measured. The scale setting applied in Scion software was 3.45 pixels / micrometer. About 100 fiber diameter measurements were made for each sample.

**Stiffness**

Due to limited amount of treated samples, three or four specimens were taken only in machine direction if no large variation was noticed. Following ASTM D5732 – 95, FRL Cantilever Bending Tester was used to get the bending length and flexural rigidity.

**Tensile strength, Elongation and Tenacity**

Following ASTM standard D5035 –95, peak force and elongation were measured on an Instron tensile tester (constant rate of extension) with a loading cell of 10 lb capacity and a gauge length of 3 inches. Fiber random specimens were measured for each sample.
Differential scanning calorimetry (DSC) was used to characterize the thermal behavior of the melt blown webs. DSC scans of the materials and the melt blow webs were done using the Mettler Toledo DSC 821e. The samples were scanned from 25°C to 300°C at a heating rate of 15°C/min. Nitrogen purging was maintained throughout the scanning.

Three AQ polymer products were scanned for thermal analysis: Eastman AQ pellets, pure Eastman AQ melt blown nonwoven webs, Eastman AQ35S / PP bicomponent melt blown nonwoven webs, and miscellaneous AQ polymer products.

Eastman AQ pellets were heated up from 25°C to 400°C; other samples were heated up from 40°C to 300°C followed by cooling at about 50°C/min to 40°C to allow recrystallisation. A second heating cycle was then implemented. All samples used weighed between 3-6 mg and an effort was made to prepare the pieces constituting the 3-6 mg of similar dimensions since a slight dependence on sample dimensions was noticed.
CHAPTER III
RESULTS AND ANALYSIS

Chemical Treatment

In the alkali solution, PLA, one component of the bicomponent fiber, is known to decompose via hydrolysis mechanism in alkali solution, and the other component, polypropylene (PP) will not be affected. After treatment, those bicomponent nonwoven fabrics are expected to have different levels of properties change based on the different components and bicomponent ratios.

Eight properties of the bicomponent nonwoven fabrics before and after treatment were compared. Samples containing more polyester are supposed to decompose more in alkali solution, which is shown by the greater decrease in basis weight and thickness of sample 1-1 (75/25 PLA/PP) than any other samples with lower PE composition. The fabric structure is more sparse than before treatment, which may lead to the decrease in hydrohead, and increase in air permeability. According to the summarized data and SEM images (Figure 5), chemical treatment tends to decrease basic weight, thickness, diameter, hydrohead, stiffness and tenacity of the meltblown fabrics, but increase filtration efficiency assuming the same bulk density. Air permeability tended to keep about the same values as before treatment for all samples. Elongation at peak increased for 75/25 PLA/PP and 50/50 PLA/PP, but decreased for other samples. The well-treated fabric looks semitransparent, and feels very soft. Therefore, it is suggested that chemical treatment on meltblown fabrics can produce microfiber fabrics conveniently and improve filtration efficiency.

Meltblown fibrous materials are broadly used for filter media because of their high filtration efficiency (FE), low pressure drop and long service life. These properties are affected by the fibrous structure and defects in the nonwoven materials. In addition to fiber diameter and packing density, the non-uniformity of fiber size and basis weight, and pinholes in nonwoven materials are considered to be defects that affect FE, pressure drop and service life of filters. In our experiment, the physical diameter and the effective diameter both tend to decrease, but the effective diameter may be more reasonable here because of the irregular fiber shape (ribbon like) after treatment. Media having finer fibers provide higher FE but also higher pressure drop across the webs while coarser diameter presents lower pressure drop but lower FE. This tendency indicates possible microfiber production or other potential filtration applications.
Figure 5. SEM microphotographs of bicomponent melt blown web (PLA/PP 75/25).
Eastman AQ Polymer Preliminary Study

The primary objective of this study was to determine whether Eastman AQ polymer could be melt blown. This work included results from experiments on AQ resins and trial runs on the 6-inch wide melt blowing (MB) pilot line facility at UTK.

Eastman AQ resins

*Melt Flow Index Testing:* From the observation, both polymers were melted immediately at two temperatures and flew smoothly in melt flow indexer. Results in Table 4 are only expected to provide a general idea of the spinning possibility and proper setting temperature.

*Dispersion of Eastman AQ pellets in Water:* Complete dispersion for 30% solid pellets of Eastman AQ 35S was achieved in 20 to 30 minutes in distilled water at 76°C

Eastman AQ polymers melt blown fabrics

*Regular physical testing:* From regular nonwoven webs testing, the samples all have very poor tenacity and elongation. However, it is not the point of our interest, because it is supposed to be dispersed into water completely in later work, and its physical properties will not play any role in the final products.

*Dispersion of Eastman AQ melt blown nonwoven web in Water:*
1. Cold tap water treatment: After 20 hours soaking in tap water at 20°C, the samples all shrank remarkably, almost half in size, both in machine direction and cross machine direction. Furthermore, all the samples after treatment became extremely brittle, more like films than nonwovens, but fiber distribution still can be observed on the sample. Expected weight loss was only around 3% in the cold tap water treatment.

2. Hot distilled water treatment: All the samples shrank immediately on contacting the hot water. Clear distilled water became turbid gradually. Almost complete dispersion was observed in 90 minutes, except a little amount of web left suspected as impurity.

<table>
<thead>
<tr>
<th>Table 4. Melting flow rate testing results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>AQ35S</td>
</tr>
<tr>
<td>AQ35S</td>
</tr>
<tr>
<td>AQ55S</td>
</tr>
<tr>
<td>AQ55S</td>
</tr>
</tbody>
</table>
Water Treatment

AQ Polymer Solution Process

Eastman AQ polymers are thermoplastic and amorphous polyesters that disperse directly in water without the assistance of organic cosolvents, surfactants, or amines. An Eastman AQ polymer was considered “soluble” if one gram of polymer pellets was taken up in nine grams of solvent (agitated) within one week at room temperature (~22°C(75°F)). Note that the solubility may increase at higher temperature or longer time periods. Forty percent solids is near the maximum level that can be achieved for Eastman AQ 55 polymer before turning into gel. Eastman AQ 35 behaves similarly [Eastman Chemical Company].

Dissolving a polymer is a slow process that occurs in two stages. First, solvent molecules slowly diffuse into the polymer to produce a swollen gel, and then the second stage of solution can take place if the polymer-polymer intermolecular forces can be overcome by the introduction of strong polymer-solvent interactions. Here the gel gradually disintegrates into a true solution [Billmeyer, 1984].

Incomplete Dispersion of AQ/PP Bicomponent Nonwoven Web

To investigate the effect of time on the solubility of AQ35S bicomponent nonwoven web, first some specimens were soaked in distilled water just for seconds. Specimens after become brittle and stiff. Air permeability changed essentially at some places on the treated web. For example, on the 75/25 AQ/PP treated fabric, air permeability dropped by nearly one fourth at some places, but remained almost the same as before treatment at some other places. Within these several seconds, what probably happened was water molecules diffused into the web and reacted with AQ polymer to produce a swollen gel left in the web. The swollen gel covered some open space, and therefore greatly decreased air permeability at those places. This assumption was confirmed by SEM images taken from those treated fabrics. In image 10TS1 and 10TS2, AQ dispersive polymer are shown to be swollen gel and spread out in the web, covering some spaces, also leaving several spaces open.

Another batch of specimens were soaked in distilled water for longer time of 2.5 hours within 0.2 to 0.4% weight solution concentration. On contacting with water, AQ dispersive polymer in every bicomponent fiber swells firstly, and then dispersed into water gradually. When taken out from water after 2.5 hours, specimen’s surface except #7 felt quite slippery indicating that 2.5 hours is not sufficient for swollen AQ polymer gel to disintegrate into water completely and some were still left on the specimens. For #7 (25/75 AQ/PP) specimens, air permeability increased by about 4% after this treatment; for #9 (50/50) and #10 (75/PP AQ/PP) specimens, air permeability decreased by
approximately 5.5% and 87.7%, respectively. It can be readily understood because #7 contains less AQ polymer than #9 and #10, and those AQ polymer all dispersed into water in 2.5 hours and left the web sparser, while the extra AQ polymer contained in #9, especially #10 with higher thickness, were partly left in the web, covered some open spaces and, therefore, decreased air permeability in different degrees.

**Complete Dispersion of AQ/PP Bicomponent Nonwoven Web**

Most work was done on the completely dispersed AQ/PP bicomponent nonwoven webs. Specimens after 20 hours water treatment were softer, lighter and appeared to contain strong static charges.

**SEM images analysis**

All the images were taken with 20KV accelerating voltage, 12 mm working distance, and 500X magnification except some images, which will be mentioned later. 75/25 AQ/PP (#10) fibers’ shape changed most after water treatment among three composition groups: 75/25, 50/50, 25/75 AQ/PP.

75/25 AQ/PP treated fabric (#10): fibers shape changed from the original cylindraceous shape before treatment (Figure 6), and now in prominent ribbon shape (Figure 7). Some fibers even look transparent in the images. Besides, a “spider web” formed by some super fine fibers can be observed in some of the images. The very thin ribbon shape of fibers is more clearly displayed from cross section photos. Fibers with half side lost can be observed in image (Figure 8), where several fibers’ ends face out of the paper and show off their half round cross section.

50/50 AQ/PP treated fabric (#9): fibers seem to be finer than those before treatment, but not in very obvious ribbon shape like in 75/25 AQ/PP fabrics. Therefore it is hard to determine only from the top view of fabrics if half whether the fibers were washed off as supposed or not. However, in the cross section images Figure 9 and Figure 10, nearly every single fiber was clearly shown to have lost half of the body, which illustrates the treatment efficiency.

25/75 AQ/PP treated fabric (#7): fibers also seemed to be finer than those before treatment. Ribbon like fibers were not obvious in the images. No cross section images were taken for this specimen, but as indicated by #9 images, partly lost fibers should be observed in the cross section image if any was taken. More than 25% basis weight loss also suggests this conjecture.
Figure 6. SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven before water treatment.

Figure 7. SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven after water treatment.
Figure 8. Cross section SEM microphotograph of #10, 75/25 AQ/PP melt blown nonwoven after water treatment.

Figure 9. Cross section SEM microphotograph of #9, 50/50 AQ/PP melt blown nonwoven after water treatment.
Physical Properties Analysis

*Basis weight*

PP is hydrophobic, and it will not be affected by water treatment. AQ dispersive polymer will be dispersed in soft water under proper conditions, therefore, pure AQ nonwoven webs will be completely dispersed in water. Basis weight loss after water treatment is expected to agree with bicomponent ratio (Figure 11-A). For example, 25/75 AQ/PP is expected to lose 25% weight after treatment. In the experiments, all specimens lost more weight than expected. They were 34.3% weight loss for #7 (25/75 AQ/PP), 62.6% for #9 (50/50 AQ/PP), and 79.6% for #10 (75/25 AQ/PP). One of the reasons for the extra weight loss is some floating or unfirmly bonded fibers fell off during the long time soaking in water. The fragmentary fibers found in the container later are evidence for this presumption. The other possibility is that the real bicomponent ratios of the bicomponent webs were not exactly equal to the naming (designed) because some factors in production, such as polymer distribution cross the die. This phenomenon may imply an efficient method to verify the real bicomponent ratios for bicomponent nonwoven webs, and further examine production parameter designs and equipment working conditions.
The other possible reason considered was the dispersion of the hydrophobic polypropylene, not just the AQ polymer, because Eastman AQ polymers have the capacity to disperse many water-insoluble, hydrophobic materials in water. But later experiment proved it was wrong. Pure PP web did not lose any weight even after a week’s soaking in AQ dispersion solution.

**Thickness, Flexural rigidity and Bulk density**

All specimens decreased sharply in thickness (Figure 11-B) and flexural rigidity or stiffness (Figure 11-C), especially #10 with 75% AQ decreased most, 67% thinner in thickness and 98% in stiffness. Specimens became evidently lighter and softer. The bulk density (Basis Weight divided by Thickness) shows the same decreasing trend.

**Tensile**

Generally the melt blown nonwoven web is considered to be soft and bouncy, and a method that does not require a direct measurement of web thickness to obtain tenacity is suggested [Choi, 1988], to avoid the difficulty of measuring the actual web thickness or maintaining the same thickness under different conditions. Choi’s application was on pure propylene webs, where PP’s density was applied directly in the calculation. For bicomponent webs, the overall polymer density still can be obtained according to each polymer’s component ratio in the bicomponent fibers with the knowledge of each polymer’s density. However, the accuracy of that is not known for certain. Two problems need to considered at the same time: one is the real component ratio may not be the same as the naming (designed) ratio; the other one is that there are some big bundles and bonding points contained in the web, whose polymer composition may not be the same as the rest regular fibers. Besides, the specimens tested in this study were not particularly bouncy. As a result, another simple method based on original definition for tenacity is suggested here, which should be closer to the true value.

Tenacity in Pascals (N/m²)

\[ \text{Tenacity} = \frac{\text{Load (Kg)} \times 9.8 \ (\text{m/sec}^2)}{[\text{Width of Specimen (m)} \times \text{Thickness of Specimen (m)}]} \]

From Figure 11- D, Peak load all decreased except #9 increased a little, which might be induced by the non-uniformity of the web. Peak tenacity in Figure 11-E decreased for 25% AQ, and increased for #10 with 75% AQ, but two 50% AQ specimen #6 and #9 behaved oppositely, the former decreased and the latter increased. #6 has higher basis weight and thickness. The trend of elongation change (Figure 11-F) is certainly interesting; all increased to some extent. Water molecule’s movement during the treatment perhaps helped fiber orientation in the web and account for the greater elongation.
Figure 11. Physical tests on AQ/PP bicomponent nonwoven webs
Figure 11. Continued
(I) Hydrostatic Pressure

(J) Relative Hydrostatic Pressure

(K) Air Permeability

(L) Relative Air Resistance

Figure 11. Continued
Fiber Diameter

Fiber diameter images were obtained by means of both optical microscopy (OM) and scanning electron microscope (SEM). Reasons for that are the characteristics of each instrument: OM has large field of vision, but smaller magnification and resolution; on the other hand, SEM has a very small field of vision, but large magnification and resolution. Fiber diameters in melt blown webs are in micrometer scale, which is on the limit of regular OM resolution, but readily available for SEM whose resolution is of the order of 0.002 – 0.1 nm. When taking OM images, one’s OM operation technique is important to get fiber diameter as accurate as possible; on the other hand, generally there are about 20 fibers on the surface layer in each SEM image with 500 magnification, which are obviously not sufficient to be the representatives of millions of fibers in a web, besides the melt blown web is not quite uniform in fiber size in the first place. As a result, the accuracy of SEM image measurement for fiber diameter will be limited.

It can be seen in Figure 11-G, the comparison of the OM determined fiber diameter between water treated and control specimens, most fiber diameters tended to decrease after water treatment as expected. However, two specimens’ fiber diameters “increased” surprisingly. They are #7 and #6 with 25% and 50% AQ, respectively. Theoretically, it is not likely to happen because of the prominent weight loss of the specimen. It should result from measurement error. The polypropylene component of #7 and #6 specimens is from Exxon Company with melt index (MI) of 1200, while for other specimens, PP is from Basell company with MI of 800, which is closer to the MI of Eastman AQ35S polymer. Besides, #7 and #6 samples are quite non-uniform, having stripes along the machine direction and large thickness variation along cross direction. One conjecture about OM measurement is, the water treated specimen measured happened to be picked up from sample area with higher thickness or area with coarser fibers distributed mainly. In the first case, the transmission of light is less than that of thinner specimen area, and fewer fibers could be observed except some big size fibers.

With SEM images, about 150 fiber diameter measurements on four or five images were made for each specimen to make up the small field of view of SEM. In Figure 11-H, all three compositions specimens decreased in fiber diameter, including #7, the same sample showed the opposite result with OM measurements, which accents the necessity of applying two methods on the fiber diameter measurements.

During diameter measurements, particularly large fibers and bundles of fibers were frequently observed, but are still measured as regular single fibers, which raised the average value up to some extent. Fiber diameters exhibited a broad distribution. To get comprehensive impression of fiber’ diameter distribution in the web, and to compare OM and SEM image measurements overall, the fibers’ diameter distribution is plotted. In Figure 12 and Figure 13, where #7 and #10 specimens fiber diameter distribution is
Figure 12. Fiber diameter distribution of #7 (25/75 AQ/PP) melt blown webs before and after water treatment, determined from OM and SEM images.
Figure 13. Fiber diameter distribution of #10 (75/25AQ/PP) melt blown webs before and after water treatment, determined from images.
plotted against frequency percentage, the OM and SEM image measurements don’t match each other very well, but in Figure 15, the two measurements are surprisingly similar for #9 specimen’s fiber diameter distribution. Besides, from the distribution, it can be seen even fiber after water treatment, part of the fiber is washed off, big fibers whose diameter are greater than 10 micrometer still exist.

Fiber geometry analysis

When we look at the SEM images, especially #10 specimen, the fibers look just like ribbons. That change should resulted from the dispersion of AQ polymer into water and corresponding geometrical change with different composition ratio. A detailed analysis on the relationship between composition (weight ratio) and two components’ position in bicomponent fibers is performed in the following paragraphs. It would be helpful to understand how the fiber shape came along in water treated specimens.

The bicomponent fiber composition ratio is the weight ratio of two component polymers in every fiber. Figure 14 is the diagram of a side by side bicomponent fiber cross section. The fibers are approximated by circular cylinders. Two components in the fiber distributes side by side, with one component side shaded to differentiate from the other component side. $S_1$ stands for the surface area of one component in the cross section, in the study here which is AQ35S polymer; $S_2$ is the surface area of the other component in the cross section, here is polypropylene; R is the radius of the circle; r stands for half of the base of AQ polymer part in the circle; h is the height of AQ polymer part along diameter, in the range of 0 (100% PP) to 2R (100%AQ). The interface between the two components is simplified as a straight line. Actually, the differences between each polymer’s reology property and density, etc. might lead to a curved interface. But it will not affect the intension of this discussion here.

![Figure 14. Ideal cross section diagram of a side-by-side bicomponent fiber.](image)
Figure 15. Fiber diameter distribution of #9 (50/50 AQ/PP) melt blown webs before and after water treatment, determined from images.
The weight ratio is calculated first,

\[
\frac{m_1}{m_2} = \frac{\rho_1 V_1}{\rho_2 V_2} = \frac{\rho_1 S_1}{\rho_2 S_2} = \frac{\rho_1 S_1}{\rho_2 S_2} \tag{Equation 1}
\]

where \(m_1, \rho_1, V_1\) and \(S_1\) are the weight, density, volume of a fiber and cross section area of the fiber separately for polymer component 1, and \(m_2, \rho_2, V_2\) and \(S_2\) are for polymer component 2.

Derived from Equation 1, we get

\[
S_1 = \frac{m_1}{m_2} \frac{\rho_2}{\rho_1} S_2 \tag{Equation 2}
\]

together with equation 3, which is

\[
S_1 + S_2 = \pi R^2 \tag{Equation 3}
\]

the cross section area of each component can be derived, which is

\[
S_1 = \frac{m_1 \rho_2}{m_2 \rho_1 + m_1 \rho_2} \times \pi R^2 \tag{Equation 4}
\]

let \(y = \frac{m_2 \rho_1}{m_1 \rho_2} \),

\[
y = \frac{m_2 \rho_1}{m_1 \rho_2} \tag{Equation 5}
\]

so \(S_1 = y \pi R^2\)

In the meantime, \(S_1\) can be expressed geometrically according to Figure 5,

\[
S_1 = \frac{2 \arccos \left( \frac{R - h}{R} \right) \pi R^2}{2\pi} - \frac{2 \sqrt{R^2 - (R - h)^2} \times (R - h)}{2} \tag{Equation 6}
\]

let \(z = \frac{h}{R}, \quad z \in [0,2]\)

then, combined with equation 5, we get,

\[
y = \frac{\arccos(1 - z)}{\pi} - \frac{\sqrt{1 - (1 - z)^2} \times (1 - z)}{\pi} = \frac{m_1 \rho_2}{m_2 \rho_1} \frac{1 + m_1 \rho_2}{m_2 \rho_1} \tag{Equation 7}
\]
\[
\frac{m_1}{m_2} = \frac{y \rho_1}{1 - y \rho_2}
\]

based on the above relationship, the weight percentage of each polymer can be obtained,

\[
\% \text{Polymer}_1 = \frac{m_1}{m_1 + m_2} \times 100 = \frac{m_1}{m_2 + 1} \times 100 = \frac{y \rho_1}{1 - y \rho_2} \times 100
\]

to be specific in the study here, density of AQ polymer \(\rho_{AQ}\) is about 1.2 g/cm\(^3\), and \(\rho_{PP}\) is 0.9 g/cm\(^3\)

\[
\% \text{AQ} = \frac{m_{AQ}}{m_{AQ} + m_{PP}} \times 100 = \frac{y \rho_{AQ}}{1 - y \rho_{PP}} + 1 \times 100 = \frac{y 4}{1 - y 3} + 1 \times 100
\]

where still

\[
y = \arccos(1 - z) - \frac{\sqrt{1 - (1 - z)^2 \times (1 - z)}}{\pi} = \frac{m_1 \rho_2}{m_2 \rho_1} + 1 + \frac{m_1 \rho_2}{m_2 \rho_1}
\]

The relationship between AQ polymer weight percentage in a bicomponent fiber and the relative position it covers in the fiber’s cross section is plotted in Figure 16.

With the relationship in mind, the AQ/PP sample’s composition ratios, corresponding positions in fiber’s cross-section, and diagrams of fiber’s cross-section are summarized in Table 5. It is clear that \(h\) increases with AQ content, but \(r\) varies differently. When AQ polymer takes up 50%, its \(r\) is closest to the fiber’s \(R\) among three compositions, which is 0.99R. It indicates that when the AQ polymer part is dispersed into water during treatment and only PP is left, the fiber diameter measurement should get very similar results as control sample measurement, assuming fiber’s axes all lie in planes perpendicular to the paper, in another word, the fiber cross-section end in the diagrams going through the paper, and we observe the longitudinal fibers from top. Conversely, 25% AQ fibers who have the largest difference between \(r\) and \(R\), where \(r = 0.87R\), are expected to have largest fiber diameter decline after treatment among the three composition samples. Experiments results from SEM measurement are: #7 decreased 2%, #9 declined by 21%, and #10 14%. Obviously, experiment and theory don’t match very well. It implies other factors may exist during real measurement.
Figure 16. AQ polymer weight percentage in a bicomponent fiber verses its relative position in the fiber’s cross-section.
Table 5. AQ content in AQ/PP bicomponent fibers and corresponding geometrical features. R is the radius of the fiber; S stands for the surface area of a whole fiber, and V is its volume, S/V gives the specific area of a fiber.

<table>
<thead>
<tr>
<th>AQ percentage (%)</th>
<th>h/R</th>
<th>r/R</th>
<th>S/V  (R = 1)</th>
<th>Cross section diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.51</td>
<td>0.87</td>
<td>1.5</td>
<td><img src="image1" alt="Cross section diagram" /></td>
</tr>
<tr>
<td>50</td>
<td>0.89</td>
<td>0.99</td>
<td>2.3</td>
<td><img src="image2" alt="Cross section diagram" /></td>
</tr>
<tr>
<td>75</td>
<td>1.31</td>
<td>0.95</td>
<td>4.4</td>
<td><img src="image3" alt="Cross section diagram" /></td>
</tr>
</tbody>
</table>
Figure 17 displays four possibilities of fiber arrangement in a web, with fiber axes all lying in planes perpendicular to the paper. The main difference between them is the relative position of two components. It will make difference in fiber diameter measurements and related properties when one of the components is removed by some treatment, e.g. AQ polymer dispersed into water and only PP is left. Suppose the shaded part is removed and we look at the fibers from top to measure fiber diameter, which is represented by “D” in the figure. In Figure 17-A, the diameter measured is either the original diameter D or the diameter D’ of the new interface generated by the removed part. Which value predominates is mostly determined by personal tendency and image quality. In Figure 17-B, the removed part is underneath, so it will not be displayed in images, either will the diameter measurement be affected. In Figure 17-C, the fiber diameter is clearly only part of the original length. In Figure 17-D, similar situation to case A, two possible measurements could be made on the same fiber. However, either one will still be less than the original diameter of the fiber.

Now the four possibilities are employed to explain the unmatched results between theory and measurements mentioned previously. #7 specimen was supposed to have largest diameter decline among three composition specimens, but it was not true in measurement. From SEM image analysis, it appeared most fibers tend to align themselves in the way displayed in Figure 17-(A), e.g. one component in the bicomponent fiber predominated in one side of the web, and the other component predominated the other side of the web. If this statement holds true, D’ measurement actually dominated in #7 specimen. The large diameter decline in #9 and #10 specimens may result from actually more weight loss than the naming weight ratio.

In conclusion, for bicomponent fibers after treatment where one of the component is removed, fiber diameter measurement from images is affected by several factors: web uniformity, image quality, operator’s personal tendency, fiber orientation in the web and component alignment in each fiber.

![Figure 17. Polymer components’ arrangement in a bicomponent fiber (cross section).](image-url)
**Hydrostatic head, Relative hydrostatic head**

The hydrostatic pressure test measures the resistance of nonwoven fabrics to the penetration of water under hydrostatic pressure. All specimens experienced decline in hydrostatic pressure to some extent (Figure 11-I): 25% AQ polymer specimens #7 and #8 decreased less than #9 and #10 with 50% and 75% AQ polymer component separately. Conversely, when converted to relative hydrostatic head pressure (divided by corresponding basis weight) showed in Figure 11-J, the hydrohead values increased dramatically, which indicates that base on the same basis weight, the resistance to water penetration increased after water treatment.

**Air permeability, Relative air permeability**

Air permeability values (Figure 11-K) were higher than control samples for treated samples of #7, #8, and #6. This was expected, considering evidenced weight loss and thickness decline resulted from water treatment. However, #9 and #10 treated samples decreased in the air permeability value. Again, #6 and #9 have the same bicomponent composition ratio, but gave the opposite result. Higher thickness of #6 sample than #9 may account for it. The non-uniformity of the webs may also contribute to it. To confirm regular PP nonwoven webs are not affected by water treatment, a piece of pure PP nonwoven web was soaked into water for 20 hours, and the air permeability of it was compared with that of control sample. As expected, no changes are observed.

Considering the evidenced thickness and basis weight decline in the treated sample, relative air resistance value is more reasonable for property comparison. Higher air permeability value indicates less air resistance, which is directly related to filtration application. The inverse of air permeability value divided by corresponding basis weight for each sample was plotted in Figure 11-L. All the samples show greater air resistance after water treatment, moreover, #10 increased more than other samples, i.e. higher AQ component ratio larger increase in the air resistance.

Generally, the fine fibers of melt blown webs produce a high fiber surface area which is ideal for many filtration end uses. Based on previous assumption, the effect of the removal of one component in the fiber on fiber surface area is discussed in more detail here. Specific surface is defined by $S_0=S/V$, where $S$ is the total surface of the porous material and $V$ is the fiber volume. Surface energy increases with specific surface, so does the related filtration efficiency. In reference of Figure 15, the diagram of the ideal cross-section of a bicomponent fiber, the volume $V$ of a fiber would be

$$V = \left[\frac{2 \arccos\left(\frac{R-h'}{R}\right)}{2\pi} \times \pi R^2 - \frac{2(R-h')\sqrt{R^2-(R-h')^2}}{2}\right] \times l$$  \hspace{1cm} \text{Equation 8}
where $h'$ is the height of the left part after treatment, $h' = 2R - h$
and the surface area $S$ of a fiber is the following expression, Equation 9, where the
surface area of two ends of a fiber is omitted due to the large difference between the
length and diameter of a fiber.

$$
S = \left[ \frac{2 \arccos \left( \frac{R - h'}{R} \right)}{2\pi} \times 2\pi R + 2\sqrt{R^2 - (R - h')^2} \right] \times l
$$

\textbf{Equation 9}

therefore, the surface to volume ratio, the specific area is

$$
\frac{S}{V} = \frac{2 \arccos \left( 1 - \frac{h'}{R} \right) + 2 \sqrt{1 - \left(1 - \frac{h'}{R}\right)^2}}{R \arccos \left( \frac{h'}{R} \right) - (R - h') \sqrt{1 - \left(1 - \frac{h'}{R}\right)^2}}
$$

\textbf{Equation 10}

the unit of $S/V$ is $1/R$. Suppose $R=1$, then the relationship between specific area $S/V$ and
the height $h'$ of the left part in a bicomponent fiber after treatment is plotted in Figure 18. Combined with the relationship between $h/R$ and bicomponent ratio in Table 5, the AQ
polymer compositions are positioned on the curve, and the corresponding $S/V$ values are
listed in Table 5, too. It is clear that specific area increases much faster when more AQ
polymer contained in the bicomponent fiber, i.e. more mass is removed and thinner the
fiber becomes.

\textbf{Figure 18. Specific area $S/V$ verses height of the left part in a bicomponent fiber after treatment}
Even the direct fiber diameter measurements do not show obvious decrease in fiber size, the specific area actually changes, so do related properties, such as air resistance and water resistance, or other filtration applications.

**Differential Scanning Calorimetry Analysis**

**DSC scans of Eastman AQ pellets**

Figure 19 shows DSC scans of Eastman AQ35S and AQ55S pellets, from 25°C to 400°C, 15°C/min. The peaks at around 50°C are possibly from moisture contained in the polymers, which can be confirmed by the disappearance of those peaks in the second run. After that, both polymers show no detectable crystal melting dips before 310°C, which is unanimous to the amorphous morphology statement about the AQ polymer. At around 380°C, possible degradation peaks appear for both polymers.

**DSC scans of pure Eastman AQ melt blown nonwoven webs**

A specific area of interest is whether the thermal behavior of the final product (AQ melt blown webs) and that of the starting materials (AQ resins) are the same. This requires study of the thermal stability of Eastman AQ polymer. Figure 20 is the DSC scan of AQ35S, and AQ55S melt blown nonwoven web. Compared with Figure 19, no distinct characteristic peaks or dips were found, which indicates that AQ polymer after melt blown processing still retain similar morphology as AQ pellets, being amorphous, even though the overall thermal behaviors are still different. At the same time, crystalline melt peaks were found in the repeated DSC scans (Figure 21), which suggests that crystallization might happen in some places on the web during the melt blown processing.

**DSC scans of Eastman AQ35S/PP bicomponent melt blown nonwoven webs**

Figure 22 illustrates the thermographs of bicomponent melt blown webs of Eastman AQ35S/PP polymers, and Figure 23 presents that of the same webs but after complete water treatment. In Figure 22, three composition webs showed similar thermal characteristics, all had PP melt peaks occurring at around 160°C, but with different integrated peak area, which determines the endothermic enthalpy transitions. Being amorphous, AQ polymer did not show any melt peak in spite of its existence. After complete water treatment, no AQ polymer is supposed to be left in the web, so only PP contributed to the thermographs in Figure 23. To quantify the enthalpy change, and to associate it with polymer composition in the webs, the normalized heat of flow of the PP melt peak was summarized in Table 6 for each sample with different polymer ratio.
Figure 19. DSC scans of Eastman AQ35S and AQ55S pellets.

Figure 20. DSC scans of Eastman AQ35S and AQ55S melt blown nonwoven webs.
Figure 21. More DSC scans of Eastman AQ35S and AQ55S melt blown nonwoven webs

Figure 22. DSC scans of Eastman AQ35S/PP bicomponent melt blown nonwoven webs: #7, 25/75 AQ/PP; #9, 50/50 AQ/PP; #10, 75/25 AQ/PP.
Figure 23. DSC scans of Eastman AQ35S/PP bicomponent melt blown nonwoven webs after complete water treatment: #10, 75/25 AQ/PP; #9, 50/50 AQ/PP; #7, 25/75 AQ/PP.

Table 6. Normalized heat of flow of PP melt peak in bicomponent melt blown webs before and after water treatment.

<table>
<thead>
<tr>
<th>Normalized heat of flow (J/g)</th>
<th>Water Treated</th>
<th>Control</th>
<th>%change</th>
<th>Basis Weight %change</th>
</tr>
</thead>
<tbody>
<tr>
<td>#7 (25/75 AQ/PP)</td>
<td>99.46</td>
<td>71.08</td>
<td>28.5</td>
<td>34.3</td>
</tr>
<tr>
<td>#9 (50/50 AQ/PP)</td>
<td>99.32</td>
<td>36.44</td>
<td>63.3</td>
<td>62.6</td>
</tr>
<tr>
<td>#10 (75/25 AQ/PP)</td>
<td>90.65</td>
<td>13.41</td>
<td>85.2</td>
<td>79.6</td>
</tr>
</tbody>
</table>
Heat of flow of PP melt peak all increased for samples after complete water treatment in proportional to the PP composition in the bicomponent web. The percentage change of heat of flow is quite close to that of basis weight for each sample, which indicates DSC scans could be another method to verify the real AQ/PP weight ratios beside weight loss calculation.

**Miscellaneous DSC scans**

After water treatment, what is left in the solution should only be AQ polymer. To verify, the solution after treatment in a container was dried naturally, and the film left on the bottom of the container was collected for DSC analysis. Figure 24 shows two DSC scans of the film. The two scans look differently, which indicate the thermal property is not uniform in the film. Their shapes are closer to AQ pure nonwoven web thermograph than AQ pellets thermograph. Besides, no typical thermal characteristics were observed in the thermograph just like AQ resins; therefore, basically what have been washed off into the water is till AQ polymer with some changes. It suggests that the possibility of recycling of the AQ polymer.

The alternative way to study the leftover in the treatment solution is to provide heat to evaporate the solution quickly. Figure 25 shows the DSC scan of the polymer left in the treatment solution after evaporation under heating to 100°C. One notable endothermic peak at 154°C were suspected to come from PP, which may fall off from the web into water during soaking in water; However, in the second run, that peak disappeared, which should not happen if PP exist. This phenomenon is intriguing another idea: if the AQ resin will behave similarly. Some AQ resins were dispersed into water, and then experienced the same evaporation process. The DSC scan for the dried resin is shown in Figure 25 also, where an endothermic peak at 154°C (very close to 152°C) appears with smaller integrated area. Consequently, the peak appeared from either the polymer extracted from treatment solution or AQ resin extracted from dispersion solution is not from PP, but most likely the result of the heating process.

In conclusion, from DSC scans of AQ resin, AQ melt blown nonwovens, AQ/PP bicomponent melt blown nonwovens, and polymers extracted from AQ/PP nonwovens treatment solution, we get to know the thermal properties of AQ resin and AQ nonwoven products, and also related properties can be inferred from. First of all, AQ 35S and AQ55S are processable by melt blowing, and possible degradation could happen at around 380°C. Secondly, the thermal property of AQ melt blown webs are similar to AQ resins generally, being amorphous, in spite of some changes; besides crystallization may happen during production process. Thirdly, PP melting peak appeared in both AQ/PP bico web before and after treatment DSC thermal graphs, but had different thermal transition energy due to the treatment. The energy percentage change is consistent with
Figure 24. Two DSC scans of film extracted from #7 25/75 AQ35S/PP water treatment solution by natural evaporation.

Figure 25. DSC scans of solution extractants from #10, 75/25 AQ35S/PP nonwoven web and Eastman AQ35S pellets by heating up solution.
basis weight change percentage, which indicates another effective method to verify bicomponent ratio. Fourthly, polymer extracted from water treatment dispersion solution did not show much change with AQ resin in the DSC scans, which suggests the possibility of recycling.

**AQ Bico Distilled Water Treatment Optimization**

In the previous work, treatments were all performed at room temperature (about 20°C) distilled water without any heating for about 20 hours. From the large values of average basis weight percent change of different composition samples, which are 34.3% for #7 (25/75 AQ/PP), 32.9% for #8 (25/75 AQ/PP), 62.3% for #9 (50/50 AQ/PP), and 79.5% for #10 (75/25 AQ/PP), we can regard 20 hours as a sufficient treatment time for all the three composition fabrics at room temperature (about 20°C) to get complete AQ polymer dispersion. However, 20 hours is obviously not economical and efficient for industrial application. Attempts were made to find out what optimized treatment conditions, including treatment time, treatment temperature according to fabric composition, to be close as much as possible to shortest treatment time, acceptable temperature, and saturated dispersed solution concentration.

As Eastman chemical company mentioned in their AQ polymers brochure, the time needed to achieve complete dispersion will depend on the water temperature. For example, at 85°C, complete dispersion of Eastman AQ 55S polymer at 28% solids is usually achieved in 20 to 30 minutes. At 60°C, dispersion of Eastman AQ55S polymer at 28% solids takes about 90 minutes. The AQ polymer we used here is AQ 35S, whose dry glass transition temperature or softening point is 35°C. Based on the information, 50°C, 60°C and 85°C were selected as treatment temperatures in the optimization study.

**Experiment**

Cut 2” by 2” pieces from three different component fabrics and weigh each one; Prepare beakers to contain 500ml distilled water each, and put them on the heater; Plug in the heater and adjust to the preset temperature. Then, put pieces into the heated beakers with the preset temperature, provide slight stir with a glass stirrer. Take out the pieces at a scheduled time, put into drying over to dry up, and then weigh up the weight again.

**Analysis**

The weight concentrations were no more than 0.05% solids, so the saturation concentration of solution could be ignored and focus on treatment time and temperature optimization.
Table 7 summarizes the basis weight percent change at different treatment time and temperature. In 85°C distilled water, 15 minutes are sufficient for #7 and #8 specimens with 25% AQ polymer, because the basis weight percentage change before and after water treatment were equal or very close to 25%. In the same situation, #9 and #10 did not seem to disperse completely (44% and 72%), but already close to their AQ polymer composition, which are 50% and 75%, respectively. Another 15 minutes soaking didn’t improve much on their dispersion. When the water temperature is decreased to 60°C, #7 and #8 AQ part completely dispersed within 15 minutes. #9 still only got 41% weight loss, but #10 lost just about 75% weight. When the water temperature was decreased to 50°C, #7 and #8 completely dispersed in 30 minutes, while #9 and #10 weight loss were 20% less than their AQ polymer composition even in 2 hours. But #10 dispersive part seems to completely disperse in 2.5 hours at 50°C.

In conclusion, increase distilled water temperature can dramatically reduce treatment time at the cost of thermal energy. The shortest time to get complete or nearly complete dispersion for these three component specimens are 15 minutes or less at 85°C. Less AQ composition specimens seem to need less time or lower temperature to get complete dispersion than higher AQ composition ones, e.g. #7 and #8 with 25% AQ took 15 minutes at 60°C and 30 minutes at 50°C to lost 25% weight assuming the real AQ composition in the specimen is 25%, but #9 and #10 needed at least 1 hour at 60°C and 2.5 hours at 85°C to reach the expected weight loss. However, when compared to #9, #10, #10 tended to disperse completely and #9 not at the same time and temperature. Among the three composition specimens, #9 has the lightest basis weight, smallest thickness, fiber diameter and hydrohead, highest air permeability and most flexibility. Some recommended treatment conditions are listed in Table 8.
Table 7. Basis weight percent change at different treatment time and temperature

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Treatment Temp (±4°C)</th>
<th>15 min</th>
<th>30 min</th>
<th>45 min</th>
<th>1 h</th>
<th>1.5 h</th>
<th>2 h</th>
<th>2.5 h</th>
<th>20 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>#7</td>
<td>20°C</td>
<td>30.2</td>
<td>34.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>25°C</td>
<td></td>
<td></td>
<td>39.1</td>
<td>18.5</td>
<td>35.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60°C</td>
<td></td>
<td></td>
<td>25.4</td>
<td>24.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85°C</td>
<td></td>
<td></td>
<td>25.0</td>
<td>24.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td>20°C</td>
<td>32.9</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>25°C</td>
<td></td>
<td></td>
<td>37.6</td>
<td>31.1</td>
<td>35.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60°C</td>
<td></td>
<td></td>
<td>28.8</td>
<td>28.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85°C</td>
<td></td>
<td></td>
<td>33.3</td>
<td>33.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>#9</td>
<td>20°C</td>
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<td>55.0</td>
<td>62.3</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>50°C</td>
<td></td>
<td></td>
<td>20.7</td>
<td>23.5</td>
<td>21.9</td>
<td>25.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60°C</td>
<td></td>
<td></td>
<td>41.1</td>
<td>41.1</td>
<td>43.6</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>85°C</td>
<td></td>
<td></td>
<td>44.1</td>
<td>42.9</td>
<td></td>
<td></td>
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<tr>
<td>#10</td>
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<td>30.8</td>
<td>79.5</td>
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<td></td>
<td>75°C</td>
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<td>57.7</td>
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<td>56.4</td>
<td>75.9</td>
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<td></td>
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<td></td>
<td>76.6</td>
<td>75.0</td>
<td>74.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85°C</td>
<td></td>
<td></td>
<td>72.1</td>
<td>73.7</td>
<td></td>
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</table>

Table 8. Recommended treatment conditions at 0.05% solids concentration:

<table>
<thead>
<tr>
<th></th>
<th>85°C</th>
<th>60°C</th>
<th>50°C</th>
<th>20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>#7 &amp; #8 (25/75 AQ/PP)</td>
<td>15 minutes or less</td>
<td>15 minutes</td>
<td>30 minutes</td>
<td>2.5 hours</td>
</tr>
<tr>
<td>#9 (50/50 AQ/PP)</td>
<td>15 minutes</td>
<td>2 hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#10 (75/25 AQ/PP)</td>
<td>15 minutes</td>
<td>1 hour</td>
<td>2.5 hours</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER IV
CONCLUSION AND RECOMMENDATION

This chapter presents conclusions drawn from the experiments and analysis. It also includes some recommendations and suggestions for the future work.

A commercially available, water dispersive Eastman AQ polymer was successfully processed into bicomponent melt blown nonwovens with polypropylene. No processing problems were encountered when melt blowing the AQ polymer.

Alkali treatment was successfully applied on PET/PP bicomponent melt blown nonwovens, causing the dissolvable part dissolved in caustic solution. Water treatment applied on Eastman AQ/PP bicomponent melt blown nonwovens, caused the water dispersive part, Eastman AQ polymer, dispersed in distilled water.

The weight loss is dramatic in both situation, and in proportional to the samples bicomponent ratio, which suggests an effective method to verify the bicomponent ratio. Both treatments tend to decrease thickness, stiffness, and tenacity of bicomponent samples. For water treated samples, hydrostatic pressure, resistance to air increased for high AQ component samples, and elongation also increased notably. Increased specific area may contribute to those increases.

An ideal model of fiber cross section was used to investigate and quantify the relationship between bicomponent ratio and cross section of a bicomponent fiber when one component is removed by either treatment.

The water treatment greatly simplifies application of microfiber reduction treatment by eliminating the cost, time, and safety requirement of chemical treatment.

The diameter decreased to some degree after both treatments, super fine fibers are very promising. But the fibers’ shape changed from cylinder to ribbon. As a result, the regular fiber diameter measurement methods by optical microscopy (OM) and scanning electronic microscopy (SEM) are not suitable. Effective diameter derived from filtration test is a better option to express physical diameter. However, from large number of diameter measurements by OM and SEM, the trend of the change after treatment is still reliable. Furthermore, from the model mathematical calculation, the fiber shape after treatment can be derived; those “ribbon” fiber diameter measurements are affected by fiber alignment in the web;

The samples after both treatments are very soft, and have a silk-like hand.

DSC analysis was performed to study the thermal properties of Eastman AQ dispersive polymer, and corresponding nonwovens. The similarity between AQ resin and
polymer extracted from dispersion solution was found, which indicates the possibility of recycling of the AQ polymer after dispersion into water.

Finally, the water treatment conditions were investigated to find an optimized one for future work. An empirical rule was found:

\[ \frac{\text{Time needed for complete AQ dispersion}}{\text{BasisWeight} \times \text{Thickness} \times AQ \text{ Proportion}} \propto \frac{\text{Temperature} \times \text{WaterVolume}}{\text{Proportion}} \]

Future work is directed toward developing a high quality, consistent microfiber melt blown nonwoven material of water dispersible polymer.

More uniform samples are recommended for further future work.


VITA

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