Zheng, Huabing The Impact of Input Energy, Fiber Properties, and Forming wires on the Performance of Hydroentangled Fabrics. (Under the direction of Dr. Abdelfattah Seyam and Dr. Donald A. Shiffler.)

Extensive critical literature review of the development of hydroentangled technology and research regarding fabric performance in terms of fiber and process parameters was conducted. The review revealed that hydroentanglement is the fastest growing nonwoven bonding technology with an annual growth rate of about 20%. The review also indicated that the research in public domain regarding fabric performance as related to forming wire geometry and fiber properties is not thoroughly covered. The research areas in process and fabric geometry modeling have not been considered by previous researchers.

A model describing the force and energy required to form fabric aperture was derived by developing hydroentangled fabric geometry and calculating the energies required to achieve the geometry. Three energy components were considered, namely fiber bending, fiber-to-fiber friction, and fiber stress-strain. The model predicts the three energies in terms of fiber properties and forming wire geometry. Numerical examples illustrating the use of model to calculate the three energies for range of forming wires a fiber are given. The numerical solution shows that the calculated energies from the model that is required to form fabrics is extremely very small as compared to the water jet energy. This indicates that most of the energy is lost.
Experimental trials were conducted using different fibers with range of properties, forming wires, and water jet pressure. Fabric tensile strength is used as an indicator of degree of hydroentanglement to assess the fabric performance. The results show that the hydroentangled fabric tensile strength is significantly influenced by forming wire type, fiber properties, and jet pressure.

Three force mechanisms (flexural rigidity, friction force, and strain force) were analyzed to reveal which force is more significance in governing fabric strength.
THE IMPACT OF INPUT ENERGY, FIBER PROPERTIES, 
AND FORMING WIRES ON THE PERFORMANCE OF 
HYDROENTANGLED FABRICS

by

HUABING ZHENG

A dissertation submitted to 
the Graduate Faculty of North Carolina State University 
in partial fulfillment of the requirements for 
the Degree of Doctor of Philosophy

FIBER AND POLYMER SCIENCE

Raleigh
September 2003

Approved by

A. Seyam
Co-Chairman of Advisory Committee

Donald J. Kelly
Co-Chairman of Advisory Committee

B. Pound

[Signature]
BIOGRAPHY

Huabing Zheng was born on August 1, 1971 in Hubei, China, the son of Mr. Yunwen Zheng and Mrs. Yunying Zhu.

After graduating from First High School of Gongan, Hubei, China in 1988, he enrolled in Zhejiang University, Hangzhou, China, and received a Bachelor of Science degree in Polymer Science and Engineering in July, 1992. The author then worked as assistant chemical engineer and chemical engineer in Yizheng Chemical Fiber Co. Ltd, Jiangsu, China, until August, 1997. He then enrolled in the graduate program at Zhejiang University, Hangzhou, China, and earned a Master of Science degree in Polymer Science and Engineering in March, 2000. He came to the United States in July, 2000, and continued his education in the Fiber and Polymer Science program to pursue Ph. D degree at Nonwovens Cooperative Research Center (NCRC), College of Textiles, North Carolina State University.

The author was married in August 2001 to the former Miss Bing Huang in Hubei, China.
ACKNOWLEDGEMENTS

My sincere thanks go to the many people who supported and inspired me intellectually and mentally during my studying at the College of Textiles, North Carolina State University.

I would like to thank my advisors Dr. Abdelfattah M. Seyam and Dr. Donald A. Shiffler for their great patience and support throughout my research project. Dr. Seyam was always a great resource for me, and he was always available and ready to help me. Dr Shiffler has always been an inspiration for me with his smart curiosity and impressive intellect. I have learned for my life from his broad life and industrial work experience.

I also wish to thank the other faculty members of my committee, Dr. Behnam Pourdeyhimi, Dr. Andrey V. Kuznetsov, and Dr. Mohamed Bourham for their sincere help and valuable suggestions for this study.

The research would not have been possible without the financial support from the Nonwovens Cooperative Research Center at NCSU. I appreciate very much the research assistantship provided by the NCRC during my Ph. D studies, as well as the generous instrumental equipment available for my use and the intellectual and material support from industrial member companies, in particular Wellman, Shell, Albany International and Goulston Technologies, Inc..

Finally, I thank all my family, especially my wife, for all their love and support over these years.
# TABLE OF CONTENT

| LIST OF FIGURES ................................................................. | vii |
| LIST OF TABLES ................................................................. | ix |
| NOMENCLATURE ...................................................................... | x |
| 1 INTRODUCTION ..................................................................... | 1 |
| 2 LITERATURE REVIEW ....................................................... | 3 |
| 2.1 Development of Hydroentanglement Technology ................ | 3 |
| 2.1.1 Fiber Selection ...................................................... | 4 |
| 2.1.1.1 Fiber Flexural Rigidity ......................................... | 5 |
| 2.1.1.2 Fiber Length ...................................................... | 6 |
| 2.1.1.3 Fiber Crimp ....................................................... | 7 |
| 2.1.1.4 Fiber Wettability and Surface Friction Behavior ...... | 7 |
| 2.1.1.5 Fiber Types in Application .................................... | 7 |
| 2.1.2 Fiberweb Formation .................................................. | 8 |
| 2.1.2.1 Dry-laid ............................................................... | 9 |
| 2.1.2.2 Wet-laid ............................................................... | 9 |
| 2.1.2.3 Direct-laid ........................................................... | 10 |
| 2.1.3 Fiberweb Entanglement .............................................. | 11 |
| 2.1.3.1 Web Supporting Substrate ..................................... | 12 |
| 2.1.3.2 Water Jet Entangling ............................................ | 17 |
| 2.1.3.3 Water Extraction .................................................. | 24 |
| 2.1.3.4 Water Circulation and Filtration ........................... | 24 |
| 2.1.4 Drying and Finishing ................................................ | 25 |
| 2.1.5 Multi-Step Hydroentanglement Line ......................... | 26 |
| 2.2 Significance of Hydroentanglement Technology ............. | 27 |
| 2.2.1 Characteristics and Application of Spunlaced Fabrics .. | 27 |
| 2.2.2 Advantages and Disadvantages .................................. | 30 |
| 2.3 Previous Research ....................................................... | 31 |
| 2.3.1 Jet Parameters and Flow Characteristics ................... | 32 |
| 2.3.2 Specific Energy and Jet Pressure ................................ | 33 |
| 2.3.3 Fiber Type .............................................................. | 36 |
| 2.3.4 Forming Wire ......................................................... | 37 |
| 2.3.5 Other Work ............................................................ | 38 |
| 2.4 Summary and Conclusion ............................................. | 38 |
| 2.5 Research Objectives .................................................... | 40 |
| 3 THEORETICAL ANALYSIS ................................................ | 41 |
| 3.1 Concepts of Unit Knuckle and Unit Cell ....................... | 41 |
| 3.2 Drag Force ................................................................. | 43 |
| 3.2.1 Drag Force Calculation ............................................ | 43 |
| 3.2.2 Calculation of Water Jet Velocity and Normal Force ... | 44 |
| 3.2.3 Drag Force Analysis in Hydroentanglement ............... | 46 |
| 3.3 Resisting Factors and Force Mechanisms ....................... | 48 |
| 3.3.1 Fiber Flexural Rigidity and Bending Energy .............. | 48 |
| 3.3.2 Fiber-to-Fiber Friction Force ................................. | 51 |
LIST OF FIGURES

Figure 2.1: Shape Factor ................................................................. 6
Figure 2.2: Schematic of Spunlace Flow Sheet (Courtesy of Kasen Nozzle) .......... 11
Figure 2.3: Cross-section of Hydroentanglement Unit [30] ............................... 12
Figure 2.4: Two Shed (1x1) Plain Weave Pattern ........................................... 14
Figure 2.5: Three Shed (1x2) Semi-Twill Weave [70] ...................................... 15
Figure 2.6: Apertured Hydroentangling [70] .................................................... 16
Figure 2.7: Fluid Flow Behavior through an Orifice ........................................... 19
Figure 2.8: Effect of Jet Pressure and Cone Angle on Coefficient of Velocity [25] ...... 22
Figure 2.9: Effect of Jet Pressure and Cone Angle on Coefficient of Discharge [25]..... 22
Figure 2.10: Typical configurations of hydroentanglement unit (Fleissner) .......... 27
Figure 2.11: Property map of shear modulus and strength ............................. 28
Figure 2.12: Two kinds of single cone-capillary Nozzles ................................. 32
Figure 3.1: Two-dimensional Forming Wire and Unit Knuckle ......................... 42
Figure 3.2: Fabric with different hole textures .................................................. 43
Figure 3.3: Fluid Flow Through an Orifice ..................................................... 45
Figure 3.4: Water jet flow through web ............................................................ 46
Figure 3.5: Drag Coefficient for Cylinders [42] ................................................ 47
Figure 3.6: Bending of a fiber .......................................................................... 48
Figure 3.7: Schematic of strain to form a unit hole ........................................... 52
Figure 3.8: Formation of Unit Hole ................................................................... 54
Figure 3.9: Stress-strain curve of PET fiber ..................................................... 59
Figure 4.1: Textechno FAVIMAT Single Fiber Tester [7] ................................. 64
Figure 4.2: Measuring Unit of Textechno FAVIMAT Tester [7] .......................... 64
Figure 4.3: Staple Pad Friction Test Apparatus on Instron [18] ......................... 66
Figure 4.4: Stress-Strain Curves of All Fibers ................................................... 67
Figure 4.5: Stress-Strain Curves in the Range [0, 20%] ....................................... 68
Figure 4.6: Forming Wire Geometry ................................................................. 70
Figure 4.7: A Simple Sketch of Honeycomb Hydroentangling Machine .......... 72
Figure 4.8: Three Jet Manifolds .................................................................... 72
Figure 5.1: Effect of Vacuum Level on Water Content in PET Fabrics ............. 75
Figure 5.2: Effect of Vacuum Level on Tear Strength ....................................... 76
Figure 5.3: Fabric Basis Weight ...................................................................... 76
Figure 5.4: Tensile Strength in MD ................................................................. 77
Figure 5.5: Tensile Strength in CD ................................................................. 77
Figure 5.6: Fabric Basis Weight (Trial 2) ....................................................... 79
Figure 5.7: Tensile Strength in MD (Trial 2) ..................................................... 79
Figure 5.8: Tensile Strength in CD (Trial 2) ..................................................... 80
Figure 5.9: Elongation in MD (Trial 2) ............................................................. 80
Figure 5.10: Elongation in CD (Trial 2) ............................................................ 81
Figure 5.11: Fabric Image (2.76MPa in Trial 2) .............................................. 83
Figure 5.12: Fabric Image (5.52MPa in Trial 2) .............................................. 83
Figure 5.13: Fabric Images (8.27MPa in Trial 2) ............................................ 84
Figure 5.14: Fabric Image (8.27MPa in Trial 1) .............................................. 84
Figure 5.15: Fiberweb Orientation Distribution Function .................................. 85
Figure 5.16: Effect of Number of Pass on fabric ODF (2.76MPa)................................. 86
Figure 5.17: Effect of Number of Pass on fabric ODF (8.27MPa)................................. 86
Figure 5.18: Effect of Jet Pressure on Fabric ODF (2 Passes)..................................... 87
Figure 5.19: Effect of Jet Pressure on Fabric ODF (6 Passes)..................................... 87
Figure 5.20: Load-Strain Curves of Fabrics (8.27 MPa)............................................. 88
Figure 6.1: Fabric Basis Weight (PET2)..................................................................... 91
Figure 6.2: Fabric Basis Weight (PET4)..................................................................... 92
Figure 6.3: Fabric Basis Weight (PTT)..................................................................... 92
Figure 6.4: Fabric Basis Weight (Nylon 6).................................................................. 93
Figure 6.5: Fabric Basis Weight (PP) ........................................................................ 93
Figure 6.6: Fabric Tensile Strength on 100 Mesh......................................................... 94
Figure 6.7: Fabric Tensile Strength on 36 Mesh........................................................... 95
Figure 6.8: Fabric Tensile Strength on 14 Mesh............................................................ 96
Figure 6.9: Fabric Tensile Strength on 10 Mesh............................................................ 97
Figure 6.10: Fabric Tensile Strength (PET2) ................................................................. 98
Figure 6.11: Fabric Tensile Strength (PET4)................................................................. 99
Figure 6.12: Fabric Tensile Strength (PTT)................................................................. 100
Figure 6.13: Fabric Tensile Strength (Nylon 6)............................................................ 101
Figure 6.14: Fabric Tensile Strength (PP)................................................................. 102
Figure 6.15: Wrinkle on PP Fabric ............................................................................. 103
Figure 6.16: Fabric Images (PET2)............................................................................. 104
Figure 6.17: ODF of PET2 Fabrics............................................................................... 106
Figure 6.18: Effect of Flexural Rigidity on Fabric Stretch Ratio ................................... 109
Figure 6.19: Fabric Tensile Strength in MD on 100 Mesh (Regression)...................... 111
Figure 6.20: Effect of d/FR on Increasing Rate (Flexural Rigidity Mechanism).......... 113
Figure 6.21: Effect of d/ET on Increasing Rate (Stress-Strain Mechanism).............. 113
Figure 6.22: Fabric Tensile Strength Potential in MD (100 Mesh)............................... 114
Figure 6.23: Fabric Tensile Strength in MD on 36 Mesh (Regression)....................... 115
Figure 6.24: Tensile Strength Potential in MD (10 Mesh)............................................. 116
Figure 6.25: Fabric Tensile Strength in MD on 36 Mesh (Regression)....................... 116
Figure 6.26: Flexural Rigidity Mechanism (36 mesh).................................................. 117
Figure 6.27: Stress-Strain Mechanism (36 mesh)....................................................... 118
Figure 6.28: Fabric Tensile Strength in MD on 14 Mesh (Regression)....................... 118
Figure 6.29: Tensile Strength in CD on 100 Mesh (Regression)................................. 119
Figure 6.30: FR Mechanism in CD (100 Mesh).......................................................... 120
Figure 6.31: SS Mechanism in CD (100 Mesh)............................................................ 121
Figure 6.32: Tensile Strength in CD on 36 Mesh (Regression)...................................... 122
Figure 6.33: Tensile Strength in CD on 14 Mesh (Regression).................................... 123
Figure 6.34: Tensile Strength in CD on 10 Mesh (Regression).................................... 124
Figure 6.35: Schematic of tensile energy calculation.................................................. 126
Figure 6.36: Fabric Tensile Energy ............................................................................. 127
## LIST OF TABLES

Table 2.1: Comparison of metal and plastic wires [63,70,71] ............................................. 13
Table 2.2: Examples of hydroentanglement machine parameters [12] ............................... 18
Table 2.3: Costs between Spunlaced and Mechanically Needled Fabrics [64] .................. 31
Table 3.1: Forming Wire Parameters .................................................................................60
Table 3.2: Fixed Parameters ..............................................................................................60
Table 3.3: Calculated Energies and Maximum Jet Force Required ................................. 61
Table 4.1: Fiber Tensile Properties Summary .................................................................. 69
Table 4.2: Fiber Properties ................................................................................................. 69
Table 4.3: Forming Wire Parameters ................................................................................ 69
Table 4.4: Constant Variables ......................................................................................... 71
Table 5.1: Experimental Variables ................................................................................... 74
Table 6.1: Fiber Properties ................................................................................................. 89
Table 6.2: Actual Fiberweb Basis Weight .......................................................................... 90
Table 6.3: Jet Pressure Levels .......................................................................................... 90
Table 6.4: Specific Energy under Different Jet Pressure .................................................... 91
Table 6.5: Fabric Dimensional Change in Hydroentanglement ......................................... 108
Table 6.6: Effect of Fiber Type and Forming Wire on Fabric Dimension ......................... 108
Table 6.7: Effect of Fiber Flexural Rigidity on Fabric Stretch ........................................... 109
Table 6.8: Regression Parameters (100 mesh, MD) ............................................................ 111
Table 6.9: Factors of Mechanisms (100 mesh) ................................................................. 112
Table 6.10: Regression Parameters (10 mesh, MD) ......................................................... 115
Table 6.11: Regression Parameters (36 mesh, MD) .......................................................... 117
Table 6.12: Regression Parameters (14 mesh, MD) .......................................................... 119
Table 6.13: Regression Parameters (100 mesh, CD) ......................................................... 120
Table 6.14: Regression Parameters (36 mesh, CD) .......................................................... 122
Table 6.15: Regression Parameters (14 mesh, CD) .......................................................... 123
Table 6.16: Regression Parameters (10 mesh, CD) .......................................................... 124
Table 6.17: Percentage of TE/SE ..................................................................................... 127
NOMENCLATURE

\( A_p \) = projected fiber area in direction of motion, m\(^2\)
\( C_d \) = coefficient of discharge
\( C_v \) = coefficient of velocity
count = number of wire in CD, \(/\)inch
\( d_1 \) = orifice diameter, m
\( d_{CD} \) = forming wire diameter in cross-machine direction, mm
\( d_{fiber} \) = diameter of fiber, mm
\( d_{M} \) = moment in the element, Nm\(^2\)
\( d_{MD} \) = forming wire diameter in machine direction, mm
\( E \) = specific modulus, Nm/kg or cN/dtex
\( \bar{E} \) = average secant modulus, cN/dtex
\( E_b \) = bending Energy, J/kg
\( E_f \) = friction Energy, J/kg
\( E_{ss} \) = stress-Strain Work, J/kg
\( F \) = normal force acted by the water jet on the fibers, N
\( F_d \) = drag force, N
\( F_f \) = jet force required overcoming friction, N
\( F_s \) = fiber strain force, cN
\( F_t \) = tension force in element, N
\( F_w \) = water jet force, cN
g = gravity, 9.8 m/sec\(^2\)
l = fiber length, m
\( l_b \) = bending length to form a unit hole, mm
\( l_{b,avg} \) = average bending length, mm
\( l_f \) = friction length to form a unit hole, mm
\( l_{f,avg} \) = average friction length, mm
\( L_p \) = projected fiber length in the direction of motion, m
\( V_2 \) = outlet velocity, m/s
\( M \) = moment of the cross-section, Nm\(^2\)
m = water mass, kg
mesh = number of wire in MD, \(/\)inch
\( N \) = total number of fibers passed through one single unit cell
\( N_1 \) = number of fibers passed through a unit cell in one layer
\( N_L \) = total number of layers
\( N_U \) = total number of unit cell for 1kg fabrics
\( P_1 \) = inlet pressure, N/m\(^2\)
\( P_2 \) = outlet pressure, N/m\(^2\)
\( P_{CD} \) = forming wire spacing in cross-machine direction, mm
\( P_g \) = gauge pressure, Pa
\( P_{MD} \) = forming wire spacing in machine direction, mm
\( P_{wire} \) = forming wire space, mm
\( Q \) = water mass flow, kg/s
\( Re \) = Reynolds number, dimensionless
\( R_k \) = radius of unit knuckle, mm
r = radius of curvature, m or mm
\( T \) = fiber linear density, kg/m or dtex
t = time, s
\( u \) = relative velocity between fiber and fluid, m/s
\( U \) = bending energy, J
\( U_b \) = bending energy to form a unit cell, J
\( U_f \) = friction energy to form a unit hole, J
\( U_{ss} \) = stress-strain work for one unit hole, J
\( V_a \) = actual outlet velocity, m/s
\( V_1 \) = inlet velocity, m/s
\text{W} = \text{web basis weight, gsm}
\text{W}_{\text{strain}} = \text{fiber strain work, cN*mm or J}
\text{W}_{\text{ss, avg}} = \text{average strain work for one single fiber, cN*mm or J}
\text{x} = \text{distance to neutral plane, m}
\chi_D = \text{drag coefficient, dimensionless}
\text{Y} = \text{Young’s modulus, N/m}^2
\varepsilon = \text{strain, dimensionless}
\varepsilon_{\text{max}} = \text{maximum strain for a jet force}
\delta A = \text{area of cross-section element, m}^2
\rho = \text{fiber density, kg/m}^3 \text{ or g/cm}^3
\rho_w = \text{density of water, 10}^3\text{kg/m}^3
\mu = \text{fiber-to-fiber coefficient of friction, dimensionless}
\mu_w = \text{wet fiber-to-fiber coefficient of friction, dimensionless}
\eta_w = \text{water viscosity, kg/(ms)}
\Phi_{FR} = \text{flexural-rigidity mechanism factor}
\Phi_f = \text{friction mechanism factor}
\Phi_s = \text{stress-strain mechanism factor}
1 INTRODUCTION

Hydroentanglement, water jet needling, spunlacing, and hydraulic needling are synonymous terms used to describe a versatile process for bonding fiberwebs to form nonwoven fabrics with aesthetics properties similar to those of woven or knitted fabrics. In the hydroentanglement process, a web of loose fibers is subjected to multiple rows of high energy fine water jets on a porous forming surface (usually woven or knitted metallic wires or polymeric threads) to form a nonwoven fabric. During hydroentanglement, fibers from the fiberweb surface are inserted into the fibrous web due to the impact of the water jets. Hydraulic drag forces bend and twist fibers and fiber bundles around themselves and the forming wires forming a series of small, interlocking knots at the interstices between wires and voids (holes) at the wire crossover points (knuckles). The interlocked knots and the voids and their geometry provide the entanglement needed for the structure integrity, properties and aesthetics (texture and appearance) of the hydroentangled fabrics.

Hydroentanglement technology has existed for over forty years in its various forms. Its development has allowed high-speed production and produced aesthetically sound hydroentangled fabrics, therefore expanded the market for hydroentangled fabrics. Hydroentangled fabrics are characterized by relatively high strength, softness, drape, and conformability and represent one of the most exciting growth opportunities for nonwovens. They hold the promise of delivering a soft feel and comfort with a hand similar to those of woven and knits at the economics of nonwovens.

The literature review in the second chapter of this thesis gives an overview of current hydroentanglement technologies and previous research, explains the importance of understanding the hydroentanglement process variables, and analyzes the advantages and disadvantages of hydroentangled fabrics. Despite the great importance of understanding hydroentanglement process variables for improving fabric performance, little research has been reported to relate fiber properties and hydroentanglement process parameters to fabric performance and aesthetics. For example, it is well known fact that fiber mechanical properties contribute both to the fiber behavior in processing and final product properties,
and forming wire geometry strongly affects fabric aperture formation and fabric properties. Despite this, research in public domain did not address the effect of fiber properties, forming wire geometry and their interaction on the fabric performance and aesthetics.

Water energy is the main energy consumption in hydroentanglement technology. An important criterion of an installation’s economic efficiency is the specific energy. Too high specific energy might damage hydroentangled fabrics. The knowledge of interaction between hydroentanglement parameters and specific energy provides guidance in deciding the optimum specific energy, which minimizes the usage of water, therefore cost of product. Some prior researchers considered the hydroentanglement process as energy transfer process and postulated that the level of specific energy is a major parameter to the properties of the final product. However water jet force may play a more important role than specific energy in forming spunlace fabrics because it is the impact force that causes the fibers to move, entangle and conform to the forming wire. While previous research addressed the relationships between pressure, specific energy and fabric performance, no work has been reported in the area of energy required to form the fabric (or energy absorbed by the fabric).

Thus it is necessary to develop a systematic experimental investigation of the principal process and fiber variables which qualifies approaches likely to yield aesthetics and mechanical properties approaching woven fabrics, thereby providing leads to expanding hydroentanglement applications. To achieve this goal, the first step is to identify independent hydroentanglement variables of jet design, jet flow, fiber characteristics, forming screen parameters, and foam binder addition to determine those variables most effective in realizing interesting fabric properties and next, based on this identification, establish fundamental relationships between those identified major variables and fabric properties and aesthetics. A physical model need to be developed to describe the formation of fabric aperture and to predict the energy needed to form the fabric. The current research addresses issues that are not dealt with in previous publications.
2 LITERATURE REVIEW

2.1 Development of Hydroentanglement Technology

Hydroentanglement, water jet needling, spunlacing, and hydraulic needling [68, 69] are synonymous terms used to describe a versatile process for bonding nonwoven fabrics. In the hydroentanglement process, a web of loose fibers is subjected to multiple rows of fine jets of highly pressurized water on a porous forming surface (endless belt or perforated drum) to form a nonwoven fabric. During hydroentanglement, fibers from the surface are inserted into the fibrous web by high velocity water jets. Hydraulic drag forces will bend and twist fibers and fiber bundles around themselves and other fibers, forming a series of small, interlocking knots. Hydroentanglement is considered as an energy transfer process by many researchers [68, 69]. It strengthens the array of loose fibers and imparts desired physical, tactile and aesthetics properties. Hydroentangled fabrics rely primarily on fiber-to-fiber friction to achieve physical integrity and are characterized by relatively high strength, softness, drape and conformability [36,52,59].

This technology in its various forms has existed for over forty years [26,35,56,68]. The basic concepts were developed by Chicopee in the early 1950’s using a low-energy patterning process although the principle of binding fibrous webs with water energy was established back in 1968 by DuPont researchers. DuPont started up the first high-energy hydroentangled plant in 1974 using proprietary high-speed web forming and hydraulic needling technology. From 1963 onto the 1970s, DuPont obtained five patents that were to become the core of hydroentanglement. It is believed that these patents led to further developments in the field of hydroentanglement, especially in Japan (such as Asahi Chemical Industry). Other companies have since developed their own entanglement systems.

The development of hydroentanglement technology has allowed high-speed production and produced aesthetically sound hydroentangled fabrics, therefore expanded the market for hydroentangled fabrics. There are currently 110 hydroentanglement plants in production worldwide and additional lines are scheduled to start up [11]. The hydroentanglement process is possibly the fastest growing technology in the nonwovens industry. This global industry, with estimated worldwide consumption approaching 2.7 million tons and more than
6% volume growth per year, is expected to reach about 3.5 million tons by 2003 [40,73]. Industry experts estimate that approximately 12% of nonwovens produced in the world are made through a hydroentanglement process [11]. It is also estimated that, while the nonwovens industry is increasing with a growth rate of 7-8% per year, that for hydroentanglement is believed to be as much as 20% [20]. This technology is penetrating new markets and has been used for treating woven fabrics in order to improve hand, cover, and impart 3D designs [14,57,61,66].

Various elements are of importance in the hydroentanglement process. While some elements are typical in nonwoven process, other elements are unique to the hydroentanglement process. There are several steps that are required to produce a hydroentangled fabric. These steps are: selection of fiber, formation of fiberweb, entanglement of fiberweb, drying of entangled fiberweb, finishing of fabric, and winding.

### 2.1.1 Fiber Selection

In hydroentanglement, the fabric producer must pay significant attention to fiber (which is the main constituent of the fabric) selection because fiber type influences the behavior of the end use product. The fiber mechanical properties are key parameters that influence the processing and behavior (performance and texture) of the resultant hydroentangled fabric [38]. Many different fibers can be entangled by the hydroentangling process [17, 35], but the fiber or fiber blends selected should be determined by the desired fabric attributes. Such attributes may include chemical and physical properties, such as absorbency, abrasion resistance, tensile strength, tear resistance, thermal stability, air permeability, and wash durability. Additionally, fiber type has a significant effect on the amount of entanglement achieved, cost, and productivity.

In hydroentanglement, high-velocity water jets insert fibers from the surface into the body of the fibrous web. Hydraulic drag forces cause the fibers and fiber bundles to twist, bend and rotate around themselves and other fibers forming a series of small, interlocking knots. Fibers are required to bend easily around small radii and have some degree of wet mobility. A particular fiber’s wet mobility and its ability to bend around small radii determine the ease of fiber entanglement; hence, the ability of achieving a well entangled fabric. The following
sections address fiber properties that are believed to be the most important properties that affect the ease of fiber entanglement [35,56,59].

2.1.1.1 Fiber Flexural Rigidity

The flexural rigidity (or stiffness) of a fiber is defined as the couple required to bend the fiber to unit curvature, which is the reciprocal of radius of curvature [38]. Fibers with low flexural rigidity can bend easily around small radii and require less entangling energy than those with high flexural rigidity. The fiber flexural rigidity in Nm² can be calculated from [38]

\[
\text{flexural rigidity} = \frac{1}{4\pi} \frac{\eta ET^2}{\rho}
\]

Equation 2-1

Where

- \( \eta \) = shape factor, dimensionless
- \( E \) = fiber specific modulus, N* m/kg
- \( T \) = fiber linear density, kg/m
- \( \rho \) = fiber density, kg/m³

Equation 2-1 shows that modulus, fiber fineness, and fiber cross-section shape all have effect on fiber flexural rigidity and are discussed in detail below.

2.1.1.1.1 Fiber Modulus

Fiber flexural rigidity is proportional to fiber Young’s modulus since specific modulus is the ratio of Young’s modulus to fiber density. Because of the wet condition of hydroentanglement, wet modulus should be used. Low wet-modulus fibers such as rayon and cotton would entangle more easily than polyester or an aramid. Most researchers focus on the contribution of initial modulus to bending. It must be noticed that fibers are so fine and pure bending causes very small strain. The model developed by the author (Chapter 3) shows that pure bending energy is very small compared with friction energy and stress-strain work. This raises a question: whether fiber bending or fiber strain plays the more significant role in forming fabric aperture. If large strain is more important, fiber secant modulus should be emphasized rather than initial modulus in hydroentanglement.
2.1.1.2 Fiber Fineness
Since the fineness comes in as a squared term in Equation 2-1, the choice of fiber linear density (fiber diameter) is important in deciding fiber flexural rigidity. For a given polymer type, fibers with larger diameter have greater bending rigidity than those with smaller diameter, and hence, they are more difficult to entangle. For example, a fiber with a linear density of 6-dtex is 16 times stiffer than a fiber with linear density of 1.5-dtex although their diameter difference is four times. The optimum fiber linear density for polyester ranges from 1.38 dtex to 1.70 dtex. Practically, blends of them can achieve the desired end use properties. For example, when higher dtex fibers are required for some attribute such as bulk, low dtex fibers can be blended to improve fabric integrity [35].

2.1.1.3 Fiber Cross-section Shape
Fiber flexural rigidity increases with increasing fiber shape factor as shown in equation 2-1. The greater the fiber shape factor becomes, the more distant the material is from the center as shown in Figure 2.1.

![Figure 2.1 Shape Factor](image)

The shape factor for a circular fiber (Fiber B in Figure 2.1) is 1. For a given polymer type and fiber linear density, a triangular shaped fiber will have 1.4 times the bending stiffness of a round fiber. Fibers with same shape may have different shape factor depending on the bending direction. For example, in Figure 2.1, fiber C has much higher shape factor than fiber A. An extremely flat, oval or elliptical shaped fiber could have only 0.15 times the bending stiffness of a round fiber around its short axis [35,38].

2.1.1.2 Fiber Length
Shorter fibers are believed to have more mobility and more entanglement points per unit fiber length than longer fibers. However, it is believed that fabric strength is proportional to fiber
length [35]. Therefore, fiber length must be selected to give the best balance between the number of entanglement points and fabric strength. Typical fiber length for polyester is 19-38 mm. Blends or composites of short and long fibers can produce strong and well-entangled fabrics; for example, woodpulp fibers blended with polyester staple web [35].

2.1.1.3 Fiber Crimp
Crimp is required in staple fiber processing systems (opening, blending, carding and web formation) and contributes to fiber bulk. However, too much crimp may cause neps during processing and make drafting difficult [16]. These neps can reduce fiber mobility and causes difficulty during formation; hence result in lower fabric strength and entanglement.

2.1.1.4 Fiber Wettability and Surface Friction Behavior
Hydrophilic fibers cause higher hydraulic drag forces and can be entangled more easily than hydrophobic fibers. To improve entanglement, suitable finishes can be applied in fiber production process to increase the wettability of synthetic fibers [35]. During hydroentanglement, finishes can be washed away partially by high-pressure water jet. The portion of finish remnant on the fiber surface can be a function of finish type, polymer type, and jet properties. Fiber surface friction plays two roles in hydroentanglement: 1) hydroentangled fabrics rely primarily on fiber-to-fiber friction to achieve physical integrity [36,52]; and 2) wet fiber-to-fiber friction must be overcome to form the hydroentangled fabric texture of interest. Therefore, both dry and wet fiber-to-fiber frictions are important. Although there are numerous research publications regarding fiber surface frictions, few have been related to the process of hydroentanglement. The modeling in chapter 3 shows that friction energy is much greater than bending energy in forming hydroentangled fabric. A suitable finish, if it remains on the fiber during hydroentanglement, can reduce the friction and make entanglement easier.

2.1.1.5 Fiber Types in Application
Most of the commercial hydroentangled fabrics produced are made from these or combination of these fibers [35]:

- Cotton: Absorbent, soft, bulky, flexible, dyeable;
Polyester: Thermoplastic, hydrophobic, strong, resilient, wrinkle resistant;
Rayon: Absorbent, soft, low strength;
Woodpulp: Absorbent, opaque, reactive, dyeable;
Polypropylene: Low melt temperature thermoplastic, hydrophobic, strong, low
density, very short fiber length;
Lyocell: Absorbent, strong, biodegradable, fibrillates in hydraulic needling.

Specialty fabrics have also been made containing these fibers [35]:
Nylon: Thermoplastic, strong, abrasion resistance, resilient;
Acrylic: Excellent bulk, resilient, resistant to sunlight, oil and chemicals;
Binder fibers: Low melt temperature thermoplastic;
Splittable fibers: Ultra fine fibers;
Silk: Soft hand, high water retention;
Aramid: Very high strength, low flammability, high temperature stability, such as
Kevlar® and Nomex®;
Fluoropolymer: Excellent chemical resistance, high temperature stability.

2.1.2 Fiberweb Formation

Properties of hydroentangled nonwovens fabrics depend to a large extent on a complex
interrelation between fiber arrangement and fiber properties. While knowledge of fiber
properties is essential to an understanding of the properties of hydroentangled fabrics, it is
not in itself sufficient. There will be some effects that are caused by the inherent properties of
the structural arrangement, and the fiber properties may be modified by the presence of
neighboring fibers. In order to achieve good performance of hydroentangled fabrics, the
related method of fiber preparation and web formation should be chosen carefully. The
necessary properties for the precursor web are good evenness, isotropic webs, and three-
dimensional formation [60]. Hydroentanglement cannot eliminate the defects of the precursor
web. Actually it makes those defects more pronounced. Poor original web formation makes it
almost impossible to entangle or requires the expenditure of too much energy to achieve
good physical properties. To get high productivity rates, the ideal system is a high-speed web
former capable of producing a randomly oriented and uniform structure. Turi [56] suggested that it is the web former that limits the line speed in practice and jet manifolds may be added with increasing line speed, eliminating entanglement as a speed limited process. This may not be true since too high a line speed may cause insufficient entanglement, hence lower fabric strength. Chicopee and Dupont are the first United States’ producers of hydroentanglement nonwovens and have developed their own proprietary forming systems. They have recognized the need for good initial web formation for many years [35, 60].

In practice, precursor webs for hydroentanglement can be produced by any dry-laid, wet-laid, direct-laid, or combinations of these web web-forming processes with varying degrees of success. The method chosen will significantly affect the types of fibers that can be used, the physical properties that can be achieved, productivity rates, and fabric cost. Systems that are currently used to form fiberweb for hydroentanglement are briefly described in the following sections.

2.1.2.1 Dry-laid

Mechanical, centrifugal-dynamic, and air lay are all dry-laid staple fiber processes. When mechanical and pneumatic process elements are required for dry-laying staple fibers to separate and deliver fibers to web former, one or combination of these methods are chosen to form web. Practically, air-laid random webs generally provide better results than conventional carded webs and are considered particularly suitable to the hydroentanglement process. The energy required to obtain similar physical properties using these two processes also might vary from two to three times. [35,60,68]

2.1.2.2 Wet-laid

The formation of the precursor web for entanglement is best achieved by using wet-formed nonwoven systems. Fibers are dispersed in water at very high dilution and then deposited on a screen to separate the water from fibers. Hence, uniform, almost perfectly isotropic sheet structures for hydroentangling can be formed by wet-forming systems. Wet-forming systems are fast and efficient compared with other web forming technologies. Most woodpulp/polyester fabrics, which represent the largest volume of hydroentangled products,
are made by one of two methods involving wet-laid precursors. Basis weight of wet-formed precursor webs can vary from 10 g/m² up to 1000 g/m². However, web weights below 30 g/m² are too light for effective entanglement because there are too few fibers per unit mass [68]. Medeiros [35] concluded that increased fiber length requires higher dilution rates to uniformly disperse the fibers for a given water handling capacity; hence, productivity will decrease. Medeiros [35] also thought that most commercial machines are practically limited to fiber lengths less than 12.7mm (1/2 inch) resulting generally in lower fabric strengths than from dry-laid web forming process. It is doubtful. In fact, longer fibers are used in practice and aspect ratio (the ratio of fiber length to fiber diameter) not fiber length is important.

2.1.2.3 Direct-laid
These processes include spunbond, flashspun, and melt-blown systems. Fibers are continuously spun from molten polymer and deposited on a moving conveyor to produce web directly. Since the continuous fibers are not very mobile, webs produced by these processes do not entangle well by themselves. Composite fabrics with excellent three-dimensional strength can be made by hydroentangling dry-laid or wet-laid staple-fiber webs into a direct-laid fabric that serves as a reinforcing scrim for the structure. In the past, this was not economical because differences in speed prohibited combining spunbonding and hydroentangling. Spunbonding technology had already reached high speeds, while hydroentangling technology was operating at moderate speeds caused by the limited water pressures resulting from line design. But now, with the development in hydroentangling and spunbonding technology, new lines have been created combining both, thus allowing producing new product qualities. By using these methods, weights from under 10 g/m² to more than 600 g/m² can be bonded [65].

Choosing the right web-forming equipment can significantly reduce the number of injectors, associated water quantities, and filtration equipment, therefore reducing the total capital investment required. Today almost all suppliers of carding equipment develop cards capable of producing uniform, isotropic, random webs at high production speeds with three-dimensional (movement of fibers in x-y plane as well as in z-direction) formation [60].
2.1.3 Fiberweb Entanglement

There are many different hydraulic needling systems used to produce hydroentangled fabrics – some are proprietary and many are available from commercial equipment suppliers. Honeycomb Systems in the United States, Fleissner in Germany, Spunlace Technologies Ltd in England, and Perfojet in France are among the top-known equipment manufacturers [12,37]. Figure 2.2 is a schematic of hydroentanglement bonding technology. No matter how the hydraulic needling systems may change from one manufacturer to another, the entanglement of fiberweb requires: web supporting substrate, water jet entangling (nozzles), water extraction, and water circulation and filtration [63,67].

After hydroentanglement, there is a drying process to remove the water in the fabrics, a finishing process if desired, and the fabrics are then wound on rolls for future processing. Figure 2.3 shows the cross-section of the hydroentanglement zone.

![Figure 2.2 Schematic of Spunlace Flow Sheet](http://www.kasen.co.jp/e-kasen/seihin/fusyoku/fsyo_f7/seih_fu_7_2.html)
2.1.3.1 Web Supporting Substrate

The web supporting system plays an important role in the formation of hydroentangled fabrics. Belt, drums, or flat rolls have been used to carry the loose webs into the hydroentanglement system. In the hydroentanglement operation, water is jetted through the orifice in the manifolds into the web of unbonded fibers or filaments. The fibers move, swirl and tangle as the high velocity water penetrate the web. The fibers conform to the topography of the support medium, for example, a woven forming belt. A “mirror image” of the support structure is produced in the fabric. This structure performs several functions including: holding the web in place, increasing needling efficiency, and creating non-apertured or apertured fabrics (creating desired texture). The properties and aesthetics of the resultant fabric are a direct result of the configuration of the web supporting substrate in the bonding region. [27,35,70,71]

 Basically there are two ways that forming wires are used to make hydroentanglement products. One hydroentanglement manufacturing method is to use forming wire as a moving
belt. The forming wire must be stable, flat, and durable. Another method is to use the forming wire as a drum cover. In this case the actual installation of the wire is very critical. Unless a metal wire is brazed on the drum, the size of the finished drum cover must be very precise. A plastic wire could be used in some cases and it may be shrunk onto the drum using heat. That may change some of surface characteristics of the wires. A comparison of metal and plastic wires is listed in Table 2.1.

<table>
<thead>
<tr>
<th>Plastic wire</th>
<th>Metal wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good flex resistance</td>
<td>Poor flex resistance</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Heavyweight</td>
</tr>
<tr>
<td>Easy to install</td>
<td>Difficult to install</td>
</tr>
<tr>
<td>Corrosion resistant</td>
<td>Corrosion prone</td>
</tr>
<tr>
<td>Difficult to seam (may cause seam marks)</td>
<td>Non-marking seams</td>
</tr>
<tr>
<td>Shower damage prone</td>
<td>Shower damage resistant</td>
</tr>
<tr>
<td>Difficult to control knuckle height</td>
<td>Easier to control knuckle height</td>
</tr>
</tbody>
</table>

Two quite different products can be made by hydroentanglement:

- A nonapertured product, which essentially is a way of bonding fibers together.
- An apertured or patterned end product.

The requirements of the forming wires in these two end uses are vastly different.

In manufacturing a nonapertured product, the main goal is to give hydroentangled product strength. Two or more different webs can also be combined into a composite end product. In this case, a fine mesh, smooth top surface in the forming wire is required so that little or no forming wire marks are produced in the final product. A fine mesh forming with small diameter strands can meet these requirements and will have good product support and minimal wire mark, however wire durability may be sacrificed, especially at high water-jet pressures. A top wire surface with short, tight knuckles, such as two-shed (Figure 2.4) and three-shed weaves (Figure 2.5), gives good support for fiber bonding. Longer knuckles, such as four-shed and five-shed weaves, frequently have problems with fiber buildup in the wire because of fiber entanglement with the long floated (loose) wire. Under high water-jet
pressures, the longer strand knuckles deflect and tend to pinch fibers. For nonapertured application, relatively fine mesh wire designs are used — 28–39 per cm (70–100 mesh) in single-layer configuration, both metal and plastic. Multi-layer wire designs have also been introduced, which work well in some cases, in order to produce textures that are beyond the ability of weaving and knitting technologies.

The apertured nonwovens manufacturing process is totally opposite to the nonapertured process and a textured product surface with a distinct mark from the forming wire is desired. The nonwovens producer and the forming wire supplier need to work closely in this area because the surface topography of the forming wire has a direct influence on what the nonwovens product will look like. In apertured hydroentanglement, a “mirror image” of the forming wire is produced in the fabric, which means that whenever there is a high knuckle in the forming wire, there will be a corresponding aperture hole in the nonwovens web. There used to be a popular misconception that a hole in the forming wire gives a hole in the nonwovens product.

![Figure 2.4 Two Shed (1x1) Plain Weave Pattern](http://trcs.he.utk.edu/textile/nonwovens/f99images/spunlace/fig3.gif)
The initial web is supported on the top of the forming wire and the high-pressure water-jets go through the web, hit, and are deflected by the high knuckles in the wire. The deflected water-jets push the fibers down away from the high knuckle into the open or lower portion of the wire, thus creating a hole in the web. The clarity and definition of the hole is dependent on a number of parameters such as basis weight, fiber type and size, water pressure, and wire knuckle shape (Figure 2.6). Since there exists an exact “mirror image” between strand knuckle of forming wire and hole in the fabric, different height levels of the strand knuckle in the forming wire will cause different hole configurations in a nonwovens product. Hence, the plane difference in the forming wire is very important. The plane difference is the difference in knuckle height between a strand knuckle in machine direction (MD) and a strand knuckle in cross-machine direction (CD). Because of these differences, it is possible to get a nonwoven product with well-defined primary holes as well as less defined secondary holes. By working with different weave patterns and strand shapes, different shape apertures, such as round, oval, square or rectangular, can be produced in the final product.
Different lines, such as straight, diagonal, or herringbone shaped, can also be produced in the product. By introducing watermark technology from papermaking to hydroentanglement process, hydroentangled product can be made with virtually any designed character in it. Since the forming wire produces an exact mirror image in the nonwovens product, its quality and uniformity requirements are exceptional and the seams in the wires in particular must be perfect. All of this has posed quite a challenge to the wire manufacturer [67,70,71]. Albany International Corporation and National Wire in the United States and Asten Johnson in Canada are among the wire suppliers.

A fine-mesh stainless steel, bronze or plastic screen is usually used when hydroentangling the first side of a nonwoven web. The mesh size selected must be fine enough to minimize fiber losses and maximize water reflection back into the web to increase entanglement while, at the same time, be open enough to adequately drain the water from the jets. A rotary drum process on the second stage of water needling gives more versatility in the types of fabric patterns available than a flat conveyor system does because drum sleeves with a variety of
coarse screens or perforated metal plates can be used. Forming surfaces that are not rectangular produce fabrics with varying degrees of stretch and recovery.

The interactions between the water jets, forming wire and fibers are the governing mechanism behind hydroentanglement process [10]. It is believed that two different mechanisms can give rise to fiber entanglement.

- Water jet/Fiber interaction: As the water jet passes through the fiberweb it will encounter fibers and force them out of the way. This will be predominantly be towards the holes in the forming wires. As the jet penetrates deeper into the web, turbulent effects will increase. Entanglement can be created as the fibers interact with one another or react to eddy within fluid medium.

- Water jet/Forming wire interaction: If the water jet reaches the conveyor belt without being significantly dispersed, it will be deflected by the rigid forming wire. Deflection will be partially upwards, back into the fiberweb. Through interactions outlined above, rebounded jets will give rise to further entanglements. This mechanism will predominantly affect fibers from the underside of the web.

Newer methods of forming the support media have greatly expanded the possibilities for the fabric structure to enhance fabric capabilities. The Miratec™ Brand of fabrics that use the APEX process is an example of these new possibilities. Solid forming surfaces as described by Unicharm and PerfoJet do not provide a pattern or design in the entangled fabric. However, the ricochet effect of the jet passing through the web and then bouncing back through the web has been shown to significantly reduce the amount of entangling energy required to form a fabric [27,35].

2.1.3.2 Water Jet Entangling

In the hydroentangling process, fiber entanglement is accomplished at the water jet entangling unit by directing fine, columnar, high-energy water jets from orifices in a series of manifolds, arranged perpendicular to the machine direction, against a fiber-web supported by a substrate. The orifice jet is designed to produce a steady column of water at high pressure
and high velocities. These columns of water act like the needles of a needle loom; however, the jets are continuously striking the passing web.

In the first jet needling stage, the pre-formed web usually is compressed, de-aerated, pre-wetted and entangled to a controlled degree under low jet pressures, without adversely damaging or shifting the layers of fiber. The degree of pre-wetting and hydroentangling depends on the pressure selected on the first jet head. Hydroentangled webs are usually needled by water jets acting alternatively from both sides. This maximizes strength, eliminates two-sidedness, and minimizes fiber loss associated with a one-side treatment. Two-sided means one side is entangled and the other is “fuzzy” [63,64].

The number, size, and pressure level of the jets depends on the fiber types and desired amount of entanglement. Orifice sizes typically range from 0.10 to 0.18 mm in diameter arranged in single or multiple rows, and hole densities, from 12 to 24/cm (30 ~ 60/inch). 200 bar (2940psi) pressure is very common in modern hydroentanglement machines [1,35]. New equipment technology could make it possible to offer as high as 1000 bar water jet injectors with high efficiency and quality [51]. Table 2.2 gives the machine parameters from different manufacturers [12].

<table>
<thead>
<tr>
<th>Designation</th>
<th>Manufacturer</th>
<th>Working width (m)</th>
<th>Pressure (bar)</th>
<th>Web weight (g/m²)</th>
<th>Production speed¹ (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetlace 2000</td>
<td>ICBT Perfojet</td>
<td>3.5</td>
<td>400</td>
<td>20-400</td>
<td>300</td>
</tr>
<tr>
<td>Aquajet</td>
<td>Fleissner</td>
<td>4.2</td>
<td>600</td>
<td>10-600</td>
<td></td>
</tr>
<tr>
<td>Hydrolace</td>
<td>Spunlace Technologies</td>
<td>3.5</td>
<td>200</td>
<td>450³</td>
<td>600²</td>
</tr>
</tbody>
</table>

¹ With lowest possible web weight
² With lightweight spunbonded nonwovens
³ Maximum basis weight

An important criterion of the installation’s economic efficiency is the specific energy (SE), which is the energy consumed to produce one kilogram of hydroentangled fabric (kJ/kg). It is an independent variable that significantly affects fabric properties and performance and a function of the number of manifolds, jet pressure, process speed, surface design, and fabric
basis weight [17]. To derive the equation for specific energy, the fluid flow behavior through an orifice needs to be described first; then three kinds of energies are discussed.

2.1.3.2.1 Fluid Flow Behavior through an Orifice
An orifice is an opening with a closed perimeter through which a fluid flows [32]. Figure 2.6 represents a cross-section of a vertical sharp edged orifice discharging a liquid from a reservoir into atmosphere. This is the situation of the water jet in the hydroentanglement process. When the particles of the liquid converge from all directions to the orifice, they have inertia caused by the velocity components parallel to the plane of the orifice. Those particles can not make abrupt changes in their direction when they reach the orifice. They continue to move in curvilinear paths, thus causing the jet to contract for a short distance beyond the orifice. This phenomenon is called contraction of the jet. Vena contracta is the section AB (Figure 2.7) where the contraction caused by the orifice ceases.

Figure 2.7 Fluid Flow Behavior through an Orifice

Three coefficients are used to describe the fluid flow behavior through an orifice:

- Coefficient of contraction, \( C_c \), is the ratio of the cross-sectional area of the vena contracta, \( A_{AB} \), to the cross-sectional area of the orifice, \( A_O \).

\[
C_c = \frac{A_{AB}}{A_O}
\]

Equation 2-2

where

- \( C_c \) = coefficient of contraction, dimensionless
- \( A_{AB} \) = cross-sectional area of the vena contracta, m\(^2\).
- \( A_O \) = cross-sectional area of the orifice, m\(^2\).
Coefficient of velocity, $C_v$. By assuming that the fluid-friction energy loss is negligible, an ideal velocity can be calculated using the Bernoulli equation. The actual velocity in the jet is less than the ideal velocity because of the frictional resistance that occurs as the fluid enters and passes through the orifice. The ratio of the actual velocity, $V_{AB}$, to the ideal velocity, $V_O$, is called the coefficient of velocity, $C_v$, of the orifice and is given as

$$C_v = \frac{V_{AB}}{V_O}$$

Equation 2-3

where

- $C_v =$ coefficient of velocity, dimensionless
- $V_{AB} =$ actual velocity of the vena contracta, m/s
- $V_O =$ ideal velocity at the orifice, m/s.

Coefficient of discharge, $C_d$. The product of $C_c$ and $C_v$ is usually replaced by a single coefficient, $C_d$, called the coefficient of discharge.

$$C_d = C_c \cdot C_v$$

Equation 2-4

The Coefficient of discharge can also be defined as the actual discharge, $Q_{AB}$, to the ideal discharge, $Q_O$.

$$C_d = \frac{Q_{AB}}{Q_O} = \frac{V_{AB} \cdot A_{AB}}{V_O \cdot A_O} = C_c \cdot C_v$$

Equation 2-5

Where

- $Q_{AB} =$ actual volume flow rate, m$^3$/s.
- $Q_O =$ ideal volume flow rate, m$^3$/s.

Since Volume flow rate is the product of fluid velocity and fluid area, substitution of volume flow rate by those products in equation 2-5 finally leads to the same result as that in equation 2-4. The definition in equation 2-5 may describe better what it is called coefficient of discharge than that in equation 2-4.

2.1.3.2.2 Three Types of Energy

Three types of energy are defined and discussed in this section: total specific energy, $E_T$, total energy delivered to the fiberweb by water jets, $E_d$, and energy absorbed by fiberweb, $E_a$. If neglecting energy losses in the pumps and water supply ducting, the theoretical formula for specific energy (SE) consumed in a manifold is given by [22]
where \( C_d \) is the coefficient of discharge, \( d \) is the diameter of jet orifice, \( m \), \( N \) is the number of jets per m per manifold, \( P \) is the water pressure in the manifold, Pa, \( \rho \) is water density, kg/m\(^3\), \( W \) is the basis weight of the web, g/m\(^2\), and \( S \) is the line speed in m/min.

The total specific energy, \( E_T \), can be calculated by

\[
E_T = \sum_{i=1}^{p} \sum_{j=1}^{m} E_{ij}
\]

where \( E_{ij} \) is the specific energy consumed by manifold, \( j \) (\( j=1,2,\ldots,m \)), calculated by equation 2-6, in the pass (\( i=1,2,\ldots,p \)). Here \( m \) and \( p \) are the number of manifolds and passes respectively. Sometime, specific energy ratio, \( E_f/E_T \), which is the ratio of specific energy applied on the first side (face) of fabric to the total specific energy, is used to describe the effect of applying different energy on two sides. Here \( E_f \) is the part of total specific energy applied on first side (face side) \[54\].

Many researchers misunderstood that the energy calculated from equation 2-6 is the specific energy applied to the fiberweb by water jets \[54, 55\]. It is not true. Because of the energy losses caused by friction and viscosity, the total energy delivered to the fiberweb by water jets, \( E_d \), can be calculated by

\[
E_d = C_v^2 E_T
\]

where \( C_v \) is the coefficient of velocity.

Ghassemieh, Versteeg, and Acar \[25\] measured \( C_v \) and \( C_d \) of the nozzle type (cone down) used in hydroentanglement as shown in Figure 2.8 and 2.9. Results show that both \( C_v \) and \( C_d \) change with cone angle and jet pressure. \( C_v \) has a range between 0.94-0.98. The friction energy loss can be as great as 12% and is not negligible. Therefore, the total specific energy calculated from equation 2-7, \( E_T \), is the input energy consumed by manifold rather than energy delivered to fiberweb. Figure 2.9 shows that, when a suitable cone angle such as 15° is used, the coefficient of discharge does not change significantly with jet pressure. By this
way, a constant $C_d$ can be achieved to investigate the effect of jet pressure on fabric performance.

Figure 2.8 Effect of Jet Pressure and Cone Angle on Coefficient of Velocity [25]

Figure 2.9 Effect of Jet Pressure and Cone Angle on Coefficient of Discharge [25]
The total energy delivered to the fiberweb, $E_d$, plays a more important role than energy consumed, $E_T$, since it is delivered energy that act on the fiberweb and entangle it rather than energy consumed. Since the value of $C_v$ varies with orifice geometry, care must be taken when comparing results from different machines. It may be a good way to compare those results from different machines by using the equal delivered energies.

No theoretical work has been done to calculate the energy absorbed by fiberweb. In hydroentanglement, some water jets hit the knuckle of forming wires and rebound to push the fibers away from the top of the knuckles forming entanglement points; others may pass through the open area of forming wires and have no effect on hydroentanglement. This kind of energy is lost. Since it is not practicable to measure the energy absorbed by fiberweb, some theoretical work is needed to calculate what portion of energy delivered is absorbed by fiberweb. Even though some researchers considered hydroentanglement as an energy transfer process [68,69], it is still unclear whether jet force or specific energy plays the more important role in hydroentanglement. If theoretical work shows that the absorbed energy is very small compared with delivered energy, efficiency of energy can be improved to save water consumption; hence cost of product.

The principal cost for the hydroentanglement process is the energy consumed to provide a high pressure water jet. Many manufacturers have been trying to optimize the process to reduce the water consumption, hence product cost. For example, the total energy consumption in Fleissner’s Aquajet process is minimized by the following measures [64]:

- Optimization of the jet head by a computer-simulated flow calculation;
- Selection of the wire mesh most suitable for the material and a corresponding drum jacket of micro-porous structure;
- Use of individual pumps for each jet head. Various jet pressures can be provided by the individual injectors.
- The Aquajet hydroentanglement installations are supplied for the desired web weight range and product characteristics as one-step, two-step or multi-step installations.
2.1.3.3 Water Extraction

There is a diversity of vacuum levels and airflow associated with the various types of hydroentangling [27,35]. For the manifold over belt configuration, there are separate vacuum slots for each jet manifold. These vacuum slots are underneath the hydroentangling substrate and remove water penetrating the web. Vacuum levels of – 7468 Pa (–30 inches of water) are required to pull the water through the web and the belt. Insufficient vacuum level can cause standing water on the surface of the fiberweb. Standing water is violently disrupted when stuck by subsequent orifice water jets. This disruption distorts the fabric and causes “chicken tracks”. Insufficient water removal can also result in flooding and loss in entangling efficiency.

Microporous drum systems have very low open area in the range of 3%. Vacuum is used to hold the web to the drum. This low open area and air flow cause the majority of the process water to splash off the surface of drum and cascade down the web and drum. The change in entangling system has significantly improved the energy efficiency. Compared with other systems, it can develop desired fabric properties at much lower energy inputs. This process water must be collected and reintroduced to the entangling system [27, 35].

Additional water may be removed to reduce the drying load by a high-vacuum flat belt or rotary vacuum extraction systems or mangle rolls.

2.1.3.4 Water Circulation and Filtration

The hydroentangling process requires large amounts of water that must be treated to remove contamination before being recycled. Each time the water jets strike a fibrous mat, some contamination, such as fiber particles, fiber contamination as in cotton, fiber finish and/or system erosion is created. The contamination could also be bacteria living in the water reservoir tank. These contaminates must be completely removed to prevent orifice clogging and erosion. A clogged orifice will create a streak in the fabric that subsequent passes may not erase. The type of water treatment required depends on the raw materials being used. Fabrics containing woodpulp fibers or meltblown fibers release more fines than those made from 100% synthetic staple fibers and therefore require more complex filtration systems.
water treatment system might include some combination of the following elements: de-\acrators after the suction boxes, clarifiers or dissolved air flotation systems, sand filters, precoat filters, cartridge filters, bag filters, deionizing units, heat exchangers and bacterial treatment systems.

A variety of systems have been developed for filtering process water. Both Fleissner and Perfojet currently use a combination of sand filters, bag filters and final filters. Contamination levels of less than 1 part-per-million are desired [27,34].

Treated water is returned to a storage tank and then delivered to the high-pressure pumps. Many of the older, large commercial processes use a single centrifugal pump that develops a high system pressure, which must then be reduced by control valves at each jet manifold. Many of the newer turn-key systems use separate reciprocating pumps for each jet manifold and claim significantly lower energy costs than the single pump systems [27,34].

2.1.4 Drying and Finishing

Once the hydroentanglement process is completed, water contained in the fabrics needs to be removed. In many cases, a vacuum or a mechanical dewatering system is used then the fabric is dried in a conventional manner. Drum drying and hot through-air drying are both used in the hydroentangling processes. Hot through-air drying generally produces bulkier and softer fabrics than drum drying. The fiber type has an effect on the duration of drying. For example, fabrics containing cellulose require more residence time and therefore more investment for drying systems than pure synthetic fiber fabrics [27,34].

Most hydroentangled fabrics receive some additional physical and/or chemical treatments to impart special product attributes for a particular end use. Some may be done in-line with the hydroentanglement process and some must be done off-line. The chemical finishing treatments could be, for example, liquid repellents, flame-retardants, dyes, antistats, resin binders, wetting agents, anti-microbial agents or softeners, and the physical finishing
treatments may include thermal bonding, stitch bonding, creping, printing, calendering, stretching, heat setting, or laminating [27,34].

2.1.5 Multi-Step Hydroentanglement Line

A succession of treatments with impingement alternating from one side to the other yields higher web strength, and lower specific energy consumption. Hence it is possible to operate with fewer jet heads and a smaller water quantity, while achieving better fabric qualities. Especially with the heavier webs, which have recently become interesting for the hydroentanglement process, this is what actually has offered optimum of web bonding. The method of multiple alternating treatments of the web sides reduces energy cost and achieves an increase in the final strength for a minimum energy consumption.

Whether to use a multi-stage hydroentanglement system and where it is useful, depends on various criteria such as web weight, fiber titer, desired strength range, production speed, web support, or investment amount. Needlepunching technology was once considered the only practicable technology for heavy basis weight applications, however, by the raising water pressures in combination with multi-stage process, hydroentanglement has become a viable alternative. Fleissner manifolds can handle water pressures of 600 bar (8,700psi) and ICBT/Perfojet claims 1000 bar (14,500psi) jet pressure. They also use multiple rows of orifices instead of single row and hydroentangle heavy basis-weight webs ranged from 15 up to 600 g/m² at claimed production rates of 300-600 m/min. There is also continuous development in the hydroentanglement unit. There was up to three steps in ITMA ‘99, but now multiple steps (5 or more steps) are produced. Figure 2.10 shows typical configurations of 2-, 3-, 4-, and multi-step (5 or more steps) hydroentanglement unit offered by Fleissner. In order to distribute energy more uniformly on the fabric, manifolds are separated from each other when constructing a multi-step unit and mostly micro-porous shell drum without any additional support is used to carry the web [13].
2.2 Significance of Hydroentanglement Technology

2.2.1 Characteristics and Application of Spunlaced Fabrics

Spunlaced fabrics represent one of the most exciting growth opportunities for nonwovens. They hold the promise of delivering a soft feel and comfort with a textile-like hand at the
economics of nonwovens. Spunlaced fabrics have a balance between strength and shear modulus unique among nonwoven fabrics (Figure 2.11) [50].

![Property map of shear modulus and strength](http://trcs.he.utk.edu/textile/nonwovens/f99images/spunlace/fig4.gif)

**Figure 2.11 Property map of shear modulus and strength [50]**

Microscopic examination of hydroentangled fabric structure reveals that entanglement points are very frequent but the fibers are not tightly entangled. Fibers are driven from the web surface into the web to form high Z-direction strength. The combination of jet orifice spacing and screen patterns produces densely spaced, loosely entangled areas arranged in parallel, straight-line patterns joined by unentangled bundles of fibers. This type of structure has low out-of-plane bending rigidity along any axis and low in-plane shear, tensile and compressive moduli. These properties, combined with other properties, result in the following hydroentangled fabric characteristics [35]:

- Soft, limp, flexible hand
- High drape
- High absorbency
- High bulk
- Comfortable and moldable
- Low linting
- Stretchable without loss in thickness
- High strength without binders
- Delamination resistance

Because of these and other attributes available with different fibers and fabric patterns and surface characteristics, hydroentangled fabrics have found applications in:

- **Medical**: Single-use surgical gowns and drapes from repellent treated nonapertured woodpulp/polyester fabrics. Key attributes are textile aesthetics, comfort and liquid barrier.

- **Medical dressings**: Gauze replacement, bandages, sponges from patterned rayon, lyocell, or cotton and blends of these fibers with polyester. Key attributes are absorbency, low linting, bind-free, and textile-like hand.

- **Wipes**: Industrial, food service, clean room, hygienic and household applications from 100% cellulose fiber or cellulose/synthetic fiber blends. Key attributes are high absorbency, cloth-like appearance and hand, durability and low linting.

- **Home furnishing**: Mattress pad covers, pleated window coverings, tablecloths, bedspreads and curtains mostly from 100% polyester fabrics.

- **Substrates**: Coating, impregnation and laminating fabrics mostly from 100% polyester fabrics. Key attributes are isotropic fiber orientation, softness, conformability and smooth surface.

- **Industrial**: Pultrusion, floppy disc liners, insulation and roofing mostly from 100% polyester fabrics.

- **Apparel**: Garment interlinings from 100% polyester fabrics. Key attribute are softness, bulk and conformability.

- **Heat resistant fabrics**: Aircraft seat fire-blocking, firefighter turn-out jackets, auto hood veiling and high temperature/corrosive filter fabrics from high performance aramid fibers. Key attributes are high temperature and chemical resistance and low weight/high bulk versus woven fabrics.
Undoubtedly, new applications will appear as hydroentanglement technology and related technologies develop.

### 2.2.2 Advantages and Disadvantages

Hydroentanglement technology has the following advantages:

- It does not require binders, and thus hydroentanglement fabrics are recyclable.
- There is no fiber damage. Other mechanical needling, such as needlepunching, uses metal needles and can cause fiber damage.
- It is not limited to certain types of fibers and the fiber length can vary from long fibers up to 6 cm to those short types such as cotton or woodpulp.
- The tensile strength of a hydroentangled fabric can reach 70~80% of that of equivalent woven or knit fabrics with similar basis weight and fiber composition.
- It is capable of producing composite structures (such as interlacing of fibers with reinforced scrims and yarns [61]).
- The process is environmentally friendly.
- Long runs with high production efficiency and low cost are possible.
- Despite higher energy consumption for the hydroentanglement process, considerably higher strength values can be achieved for the same web weight by the hydroentanglement process than by the mechanically needled process. Therefore, the hydroentanglement process produces lighter webs with a considerable saving of fibers and binder, drastically reducing the cost of such products. The example given in Table 2.3 shows that the energy cost of the hydroentanglement process is much less than the raw material cost. In some case, this also applies to comparisons with other bonding processes [64].
Table 2.3 Comparison of Costs between Spunlaced and Mechanically Needled Fabrics [64]

<table>
<thead>
<tr>
<th>Example</th>
<th>Spunlaced Fabric</th>
<th>Mechanically Needled Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g/m²)</td>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td>Strength MD/CD</td>
<td>250N/236N</td>
<td>120N/120N</td>
</tr>
<tr>
<td>Fiber Cost (DM/m²)</td>
<td>0.45</td>
<td>0.81</td>
</tr>
<tr>
<td>Energy Cost (DM/m²) (hydroentangling and drying)</td>
<td>0.028</td>
<td>0.010</td>
</tr>
<tr>
<td>Total Cost (DM/m²)</td>
<td>0.478</td>
<td>0.82</td>
</tr>
</tbody>
</table>

This technology has some disadvantages:

- Poor wash durability
- Lack of acceptable strain recovery and abrasion resistance properties
- High initial investment costs
- Less defined appearance compared to woven and knit fabrics
- Requirement of minimum fabric basis weight
- High water consumption
- The problem of water recycling
- Jet clogging
- Simple designs compared to woven and knitted fabric
- Uneconomic short run
- Jet orifice erosion.

2.3 Previous Research

While there are many articles published in trade journals that describe the process and products [2,23,29,39,53,62], very few articles have been published in the scientific literature in the area of impact of processing and fiber parameters and their interaction on the aesthetics and performance of the hydroentangled fabrics. This may be attributed to the fact that hydroentangled fabric producers consider the information highly proprietary.
2.3.1 Jet Parameters and Flow Characteristics

The main cost of the hydroentanglement process is the energy consumption required to produce the high-pressure water jet. Therefore, any process optimization and cost reduction needs to improve the energy transfer from the water jet to the web in the most efficient way. Jet parameters and flow characteristics have a very important effect on the improvement of energy efficiency. Small differences in these flow parameters could result in great changes in the power consumption [25]. Ghassemieh, Versteeg, and Acar [25] used two coefficients when describing the fluid flow behaviors from an orifice: velocity coefficient $C_v$ and discharge coefficient $C_d$. The velocity coefficient $C_v$ indicates the amount of potential energy converted to kinetic energy. A jet flow with less friction losses results in higher velocity coefficient. Ghassemieh, Versteeg, and Acar [25] believe a low $C_d$, high impact pressure, and high $C_v$ are appropriate criteria for optimizing of the nozzle geometry. Another important factor that affects the characteristic of energy transfer and the entangled fabric is the quality of the water jet at the point of impact with the fabric. To produce a high quality bonding, it is essential for the impact force of the jets to be uniform and stable over the impact area. This cannot be achieved unless the web standoff distance is lower than the break-up length of jet. Downstream of the break-up length of the jet is not coherent and the distribution of energy at the impact area is not uniform resulting in over-impacting some parts of the fabric by high velocity droplets. A similar effect can result from an unstable jet stream.

![Figure 2.12 Two kinds of single cone-capillary Nozzles](image)

Figure 2.12 Two kinds of single cone-capillary Nozzles

Figure 2.12 shows two kinds of single cone-capillary nozzles: cone-up nozzle and cone-down nozzle. When there are many similar nozzles arranged together, they are called multi-hole nozzles. Ghassemieh, Versteeg, and Acar [25] studied the effect of cone angle on flow parameters such as discharge and velocity coefficients by using different cone angles from 10 to 120 degree and a pressure range of 30~200 bar.
Their results showed that:

- The angled nozzles with cone-up configuration result in higher $C_d$ and normally lower $C_v$ in comparison with the cone-down nozzles. The intact length of these nozzles is generally short. For angles higher than critical angle (45 degree) the flow regime changes to lower $C_d$ and longer breakup. However there is still some instability in the flow that cannot be observed for the cone down nozzles. The $C_d$ never reaches as low as capillary side. The pressure has high impact on the flow characteristic for the cone-up nozzles.

- The cone-up nozzles show the lowest $C_d$ values, high $C_v$ and efficiency. These nozzles normally show the longest surface intact length. So from many points of view they are the right geometry.

- The multi-hole nozzles show some variations in $C_d$ and $C_v$ values due to the change of the pattern of the flow and interaction of the flow streams. Different arrangement of the holes in the nozzles did not have great effect on the flow parameters.

Vahedi Tafreshi and Poureyhimi [58] used simulation to investigate the effect of cone angle and nozzle aspect ratio on flow dynamics in nozzles and achieved similar $C_d$ for both types of nozzles. Begenir et al [8, 9] designed experiment to measure $C_d$ and breaking length. Three nozzle geometries, so-called cone-up, cone-down, and cylindrical, under different jet pressures below 241 bar (3500psi) were examined. Their results agree well with Ghassemieh’s. For conventional nozzles used in hydroentanglement, which is cone-down, the coefficient of discharge is almost constant at 0.64 and the jet pressure shows no effect on it.

2.3.2 Specific Energy and Jet Pressure

Energy consumption is a main issue in the hydroentanglement process, so the influence of the specific energy on fabric properties and reducing process energy consumption has been studied by several researchers [15,24,38,54,55]. Connolly and Parent [15] investigated the influence of specific energy on fabric properties. Polyester and rayon blend containing fibers of similar dtexs and staple lengths were selected and different basis weight fabrics were produced under various energy levels. They concluded that higher energy levels result in
stronger fabrics up to a certain point and low specific energy ratio, $E_f/E_T$, which is the ratio of specific energy applied on the first side (face) of fabric to the total specific energy, decreases the fiber loss significantly. They observed that 50% ratio might not be ideal and their results showed that simple carded, cross-lapped hydroentangled fabrics can be comparable in strength to conventional woven and knitted fabrics with the exception of the washing durability.

Ghassemieh et al [24] investigated the relationships among fabric strength, water jet pressure and water energy consumption. Three materials, poly(ethylene terephthalate) (PET), viscose-PET blend, and Twaron, were hydroentangled under various pressure levels. Viscose-PET fabrics with different basis weight were produced. Type of forming wire used was not mentioned in their paper. They concluded that tensile strength of hydroentangled fabrics increases to a maximum at a certain critical water pressure $p_{crit}$ and subsequently levels off as the final water jet pressures is increased. This water pressure corresponding to maximum fabric strength was called critical water jet pressure. This result is similar to that of Connolly and Parent [15]. In their work, there exists a critical energy. These results raise an important question: which one plays more important role in hydroentanglement, jet pressure or specific energy. By changing number of passes or manifolds, fabrics can be produced under equivalent specific energies and different jet pressures. Testing results of those fabric properties may provide answer for this question. Ghassemieh et al also claimed that

- Critical pressure increases with the web density;
- Trends in the magnitude of $p_{crit}$ for webs made from these three fibers are related to the fiber properties. However, they did not explain how they are related.
- The pressure to achieve maximum entanglement on the first side is higher than the pressure to reach maximum entanglement on the second side.
- Pass speed has little effect on fabric strength if the web has been processed at pressures greater than $p_{crit}$.
- The quality of the fabric produced and the efficiency of the energy transfer are highly dependent on the energy transfer distribution. Different pressure profile schemes offer different efficiencies. In order to reduce the energy consumption, and, at the same time, maintain the strength and modulus of the product, the most efficient
profile needs to be identified and this optimum pressure profile depends on the web and fiber properties.

Other research on the influence of specific energy on hydroentanglement fabric properties has been reported [38,54,55]. Gilmore, Timble, and Morton [38] used unbleached cotton and their results showed that:

- Increasing the total specific energy increased strength and reduced elongation, but a maximum tensile strength was not achieved within the range of specific energy applied;
- The fabrics are very strong and trapezoid tear strength are also extremely high. High tear strength combined with high tensile strength causes a very useful combination;
- Flexural rigidity followed the same trend, with stiffness increasing with total specific energy.
- Weight loss is dependent on specific energy ratio, with the lower ratio providing the lower weight loss.

A 60x40 forming wire mesh was used as the supporting screen in their research.

Timble, Gilmore and Morton [54] also used unbleached, bleached, and low micronaire unbleached cotton to investigate: 1) the effect of specific energy and specific energy ratio on weight loss, and 2) the effect of cotton fiber bleaching and linear density of unbleached cotton fiber on fabric properties at various specific energy levels. The supporting screen is a 60x40 wire mesh. They concluded that:

- Weight loss on hydroentangling unbleached cotton fabrics increases with increase in specific energy. Low specific energy ratio results in lower weight loss.
- The strength, stiffness and tear strength of fabric increased whereas fabric elongation decreased with increase in specific energy for all the fibers.
- Tensile strength of hydroentangled fabrics made from unbleached and bleached fibers are the same. Tear strength performance of hydroentangled unbleached cotton fabrics are better compared to bleached cotton.
- Hydroentangled unbleached fabrics made from lower micronaire fiber are stronger but stiffer compared to higher micronaire.
Timble and Allen [55] used polyester/unbleached cotton blends at various specific energy levels to investigate the effect of specific energy on fabric properties and the effect of basis weight of unbleached cotton fiber on the properties of hydroentangled fabric. They found that:

- An increase in polyester content results in increased cross-machine direction strength, increase in machine direction elongation, increase in tear strength and decrease in stiffness of fabrics made from blends of unbleached cotton and polyester.
- A transition of sudden increase in absorption capacity occurred at higher energy levels with increase in polyester content.

2.3.3 Fiber Type

Hwo and Shiffler [28] used poly(trimethylene terephthalate) (PTT) to form hydroentanglement fabrics and investigated the impact of this fiber on fabric properties. They used poly(ethylene terephthalate) (PET) and polyamide (Nylon 6) for comparison. In their study, two kinds of forming wires, 100 mesh and 12x14mesh, were used for comparison. They found that:

- When compared to fabrics made from PET, Nylon, and PET/Nylon blends, fabrics made from PTT or blends have comparable tensile strength, tensile elongation, and tear strength at significantly lower input energy levels;
- In addition PTT provides a favorable strength/flexible rigidity balance which should yield more drapeable fabric;
- PTT fabrics are rated softer than the other blends in subjective aesthetics testing.

Because of its inherent low fiber bending rigidity, fabrics from PTT provides the following characteristics:

- Significant break strength develops at very low specific energy levels (80kJ/kg);
- Significant break strength develops at less than 50kJ/kg;
- Flexible rigidity does not increase with specific energy;
- Significant tear strength develops at 40kJ/kg.
Betram [10] studied the behavior of cellulosic fibers in hydroentanglement. Four fibers, cotton, rayon, tencel and polyester, were used in his study. Fiber properties such as dry and wet tenacity, flexural rigidity, and torsional rigidity were listed but no correlation between fiber properties and fabric properties. Rayon fibers with three cross-section shapes (flat, round, trilobal) were used to investigate the effect of fiber cross-section shape on fabric tensile properties. They observed that

- Rayon fiber produces fabrics with good absorbency and reasonable strength.
- Cotton gives a fabric that retains better wet strength than rayon, in keeping with its fiber properties.
- Tencel fiber gives very good wet and dry fabric properties compared to the other cellulosics studied.
- Polyester gives strong fabrics with particularly good wet strengths.

Acar. et al.[1] produced composites from glass and aramid fibers (Kevlar® and Twaron®), for industrial and composite applications. They concluded that by selecting the right combination of fibers, adjusting pass rate and water pressure, there is a big potential to manufacture composites using hydroentanglement technology.

### 2.3.4 Forming Wire

Few literature references were found regarding the effects of forming wire design on fabric texture and performance, Hwo and Shiffler [28] used two forming wire types in their research. They presented the data, compared critical specific energy and maximum tear strength using these two forming wire types. Since they mainly focus on the application of PTT in hydroentanglement, no correlation equation was given. Some suggestions were given by Widen [70,71] on wire pattern evaluation and wire quality considerations. Because there is such a direct relationship between wire geometry and nonwovens end product, initial patterning evaluations are recommended to be done in the laboratory. These can range from simply using Silly Putty® to make a knuckle impression of the fabric, all the way to
computer simulation. An easy test is to make an ink-print impression of the wire surface against the nonwovens fabric. A high knuckle in the wire will give a black dot on the ink-print which may correspond to an aperture in a hydroentanglement product. An instrument called a perthometer is available to analyze the wire topography in great detail. A statistical process control (SPC) can be used to show knuckle height for a number of individual wires in a particular wire. The mirror image effect of the nonwovens product from the forming wire means that the quality level for forming wires for hydroentanglement must be exceptional.

2.3.5 Other Work

Other work in the published literature deals with theoretical and experimental analysis on the tensile mechanism of suppleaced nonwovens [41] and improving the hydroentanglement fabrics by foamed latex bonding [49]. From the theoretical and experimental analysis on the tensile mechanism, Park and Joo [41] found that

- Higher fiber compactness in hydroentanglement fabrics shows higher slippage factor and the frequency of fiber orientation distribution is gradually increased to the machine direction;

- The tensile strength of the nonwovens is increased as fiber compactness is larger due to increasing the degree of fiber consolidation.

They also claimed that the general trend between the theoretical and experimental strain-stress curves of hydroentangled nonwovens is considerably good agreement.

2.4 Summary and Conclusion

Hydroentangled fabrics’ excellent properties and low cost offer great opportunities in expanding the market. Although they have many advantages as described in Section 2.2, they also have disadvantages such as poor wash durability, lack of acceptable strain recovery and abrasion resistance. Additionally, hydroentanglement fabrics are limited in variety of designs, patterns, and their appearance is fuzzy and less defined as compared with woven and
knitted fabrics. Improvement in initial modulus, stretch recovery, wash durability, and aesthetics are needed to expand the markets for spunlace fabrics beyond their traditional end uses. It is thus critical to investigate the effects of key hydroentanglement process variables and fiber parameters on fabric performance. Despite this, little research has been reported that relates fiber properties, forming wire geometry, and jet parameters to fabric performance and aesthetics. There are two factors that limit the share of research results: one is that hydroentangled fabric producers consider the information highly proprietary; also, various hydroentangled technologies and equipment make the results difficult to compare with each other. Although modeling of the energy required to form the fabric (energy absorbed by the fibers during formation) is helpful to understand the hydroentanglement process, published research work is generally limited to experimental investigations.

The importance of fiber properties has been emphasized in a subjective way by many researchers. There exists a need to objectively evaluate the fiber properties impact on the energy required to form the fabric. This could be achieved by modeling. Modeling may answer many questions such as:

- Does large fiber strain exist during hydroentanglement?
- Which fiber property (bending, friction, or strain) is more important?

A theoretical model may answer such questions. Dry fiber-to-fiber friction is believed to provide hydroentangled fabrics with physical integrity and wet fiber-to-fiber friction is responsible for fabric texture of interest. Both are open areas for researchers to explore. Fiber cross-section shape is usually ignored by researchers. As for the fiber type, only a few are used. More fiber types with various ranges of properties can be used to get correlation of fiber and fabric properties.

Isotropic fiberweb with good evenness are considered necessary properties for forming desired fabrics. It can be described by fiberweb Orientation Distribution Function (ODF), which can be measured by image analysis. This important tool was seldom used by former researchers.
Forming wire geometry is important in deciding fabric properties. In previous work, a limited number of forming wires was used. In fact some researchers did not bother to report the wire types used in their experiment. A systematical experiment work is needed to reveal the effect of wire geometry on the fabric texture and performance.

Energy consumption is a major issue of product cost. There is still misunderstanding between input energy and delivered energy by many researchers. Lack of work on energy absorbed by fibers during formation makes it difficult to understand whether jet force or specific energy plays more important role in hydroentanglement. There also exist open areas to explore in the field of orifice geometry and fluid flow.

Thus it is necessary to develop a systematic experimental investigation of a broad range of hydroentanglement variables such as fiber properties, forming wire geometry, orifice parameters, and jet flow behavior, which have important effects on fabric performance and aesthetics. Modeling of energy required forming the fabric in terms of entangled fabric geometry, which is related to forming wire geometry, and fiber properties can provide knowledge regarding the wasted energy. This may lead to improvement in the hydroentanglement process and products.

### 2.5 Research Objectives

The lack of research in the areas identified in the literature review has motivated undertaking the current research of the following objectives:

1. Identify important fiber and hydroentanglement processing variables such as jet energy, impact force, fiber friction, fiber stress-strain properties, and forming wire geometry;
2. Once the major variables have been identified, to establish fundamental relationships between them and fabric properties,
3. Develop a physical model describing the formation of fabric aperture and predicting energy required to form fabrics, and
4. Identify the key force and/or energy parameters that govern the hydroentangled fabric formation.
3 THEORETICAL ANALYSIS

The main objectives of theoretical analysis are to: 1) develop a physical model; 2) analyze the force factors and energy factors influencing the formation of spunlace fabrics; 3) calculate the required energy to form spunlace fabrics; and 4) analyze the governing mechanism behind hydroentanglement process.

In the hydroentanglement process, the interactions between the water jets, forming wire and fibers are the governing mechanisms behind the process. A “unit cell” model for the hydroentanglement process is first introduced. Water jet drag force is the only driving force to form entangled points. Three resisting factors: 1) fiber bending rigidity, 2) fiber friction force, and 3) fiber stress-strain force, hinder the formation of unit cells. To understand which one is the governing mechanism behind these phenomena, the ratios of drag force to all three resisting factors are calculated and analyzed. The energy consumed by friction, bending, and fiber strain work required to form the unit cell are also calculated for the unit cell. Results show that most of the energy provided by the water jet is lost. Experimental verification on the model and mechanism is required.

3.1 Concepts of Unit Knuckle and Unit Cell

Forming wires play an important role in the spunlace process. In the spunlace process, a web is first formed and then hydroentangled by passing it under very fine diameter, high-pressure water jets. The high-pressure jets hit the forming wires, rebound, and form hole textures on the spunlace fabrics. Usually the holes conform to the knuckles (the crossover points of machine direction and cross-machine direction wires) of the forming wire because they are the highest points on the surface of the forming wire. We call one single knuckle that causes one hole a “unit knuckle”. The hole caused by one single knuckle is defined as a “unit hole”. There are repeat units on wires and fabrics, which are called “forming wire unit cell” and “fabric unit cell”, respectively. Figure 3.1 shows two dimensional forming wire and definitions of unit knuckle and unit cell on wire, here:

\[ d_{\text{MD}} = \text{forming wire diameter in machine direction, mm}; \]
\[ d_{\text{CD}} = \text{forming wire diameter in cross-machine direction, mm}; \]
\( P_{MD} = \) forming wire spacing in machine direction, mm;  
\( P_{CD} = \) forming wire spacing in cross-machine direction, mm.

Figure 3.1 Two-dimensional Forming Wire and Unit Knuckle

The radius of a unit knuckle, \( R_k \), mm, can be calculated by

\[
R_k = \sqrt{\frac{d_{MD}^2 + d_{CD}^2}{2}} \tag{Equation 3-1}
\]

Figure 3.2 shows the definition of the unit hole. The shape and dimension of the hole is a function of the unit knuckle, jet pressure, line speed, and fiber properties. The perfection (or idealized geometry) of the unit cell needs to be considered. In Figure 3.2, hole A has clear shape, hole B exhibits unclear hole texture and hole C has obscure edges.

To build a practical model, we make the following assumptions:

1) The number of unit cells will be the same as the number of knuckles.
2) Because fibers are very fine and easy to bend, the shape of unit hole is assumed to be round with radius \( R \).
Figure 3.2 Fabric with different hole textures

Water jet drag force is the only driving force to form hydroentangled fabrics. Three possible mechanisms in the formation of unit holes that resist drag force and consume energy are:

1) Fiber bending rigidity/Bending energy. Since fibers need to be pushed away from the knuckles to form unit hole, force is required to bend fibers and energy is consumed in fiber bending.

2) Fiber-to-fiber friction/ Friction energy. Force and energy are required to slide fibers over each other to form unit hole.

3) Stress-strain force/Fiber strain work. There are entangled points between fibers. Force and energy is required to stretch the fibers to form the unit hole.

3.2 Drag Force

3.2.1 Drag Force Calculation

Because relative motion exists between fibers and surrounding water in hydroentanglement, the water flow exert a drag upon the fibers. In steady flow, the drag force [33,42] can be calculated by

\[
F_D = \frac{\chi_D A_p \rho_w \mu^2}{2}
\]

Equation 3-2

where

\( F_D = \text{drag force, N} \)
\( \chi_D \) = drag coefficient, dimensionless

\( A_p \) = projected fiber area in direction of motion, m²

\( \rho_w \) = water density, kg/m³

\( u \) = relative velocity between fiber and fluid, m/s.

We assume that it applies to the hydroentangled process. Projected fiber area can be calculated by equation 3-3:

\[
A_p = L_p d_f \tag{Equation 3-3}
\]

where

\( L_p \) = projected fiber length in the direction of motion, m.

\( d_f \) = fiber diameter, m.

Velocity of fibers in hydroentanglement process can be considered as zero and we simply need to calculate the water jet velocity.

### 3.2.2 Calculation of Water Jet Velocity and Normal Force

Figure 3.3 shows the water jet behavior in an orifice. \( P_2 \) is equal to 1atm (1.01x10⁵Pa). To calculate ideal velocity, we assume

1. Water is considered as incompressible fluid;
2. \( V_1 \approx 0 \);
3. There is no potential head difference;
4. \( P_g = P_1 - P_2 \).

Using Bernoulli’s equation:

\[
P_1 + \frac{1}{2} \rho_w V_1^2 = P_2 + \frac{1}{2} \rho_w V_2^2 \tag{Equation 3-4}
\]

where

\( P_1 \) = inlet pressure, N/m²

\( P_2 \) = outlet pressure, N/m²

\( V_1 \) = inlet velocity, m/s

\( V_2 \) = outlet velocity, m/s

\( \rho_w \) = density of water, 10³kg/m³.

\( g \) = gravity, 9.8 m/sec².

\( P_g \) = gauge pressure, Pa.
According to the assumptions, we get equation 3-5 from equation 3-4

\[ P_g = \frac{1}{2} \rho_w V_2^2 \]  

\textbf{Equation 3-5}

Hence,

\[ V_2 = \sqrt{\frac{2P_g}{\rho_w}} \]  

\textbf{Equation 3-6}

In fact, it is an ideal velocity because we assume there are no friction and viscosity in the process of flowing. Hence, we use coefficient of velocity, \( C_v \), to get the actual velocity, \( u \)

\[ u = C_v * V_2 = C_v \sqrt{\frac{2P_g}{\rho_w}} \]  

\textbf{Equation 3-7}

where

\( C_v \) = coefficient of velocity, dimensionless

\( P_g \) = gauge pressure, Pa.

Combined with the definition of discharge coefficient in Equation 2-5, the force acted on the web, \( F \), can be calculated by momentum equation shown in Figure 3.4.

\[ F = \frac{d(mu)}{dt} = (Q du) = Qu = (\rho_w * C_d * \frac{\pi}{4} d_1^2 * V_2)u \]  

\textbf{Equation 3-8}

where
F = force acted on the web, N
m = water mass, kg
Q = water mass flow, kg/s
C_d = coefficient of discharge, dimensionless
t = water jet flowing time, s
d_1 = orifice diameter, m.

\[ F = \frac{\pi}{2} C_v C_d d_1^2 P_g \]  
Equation 3-9

3.2.3 Drag Force Analysis in Hydroentanglement

Substitution of Equation 3-3 and 3-7 into 3-2, we can get
\[ F_D = \chi D C_v^2 L_p d_f P_g \]  
Equation 3-10

Drag coefficient is a function of Reynolds number. Reynolds number can be described as:
\[ \text{Re} = \frac{\rho_w u d_f}{\eta_w} \]  
Equation 3-11

Where
\[ \text{Re} = \text{Reynolds number, dimensionless} \]
\[ \eta_w = \text{water viscosity, kg/(ms)} \{10^{-3}\text{kg/(ms)} \text{ at } 20^\circ\text{C}\}. \]

Figure 3.5 shows the relationship between Reynolds number and drag coefficient for cylinders (infinite length-to-diameter ratio), disks, and spheres [42]. In our study,

- We assume fibers are cylinders.
Fiber length-to-diameter ratio is larger than 2400 and can be considered as infinite.

Coefficient of velocity, $C_v$, is around 0.95 and coefficient of discharge, $C_d$, is 0.62 [8,9,25, 58].

Fiber diameters used in our study have a range of $[1.24 \times 10^{-2} – 1.56 \times 10^{-2}]$ mm;

Jet pressure falls between 3.45 – 8.96Mpa. Using equation 3-7, the relative velocity can be calculated and falls between 78.9—127.2 m/s;

Water viscosity at 20°C ($10^{-3}$kg/ms) is used;

The Reynolds number falls between [1000, 2000] by calculation.

Figure 3.5 shows that, when Reynolds number is in the range of  [1000, 5000], drag coefficient is a constant with value 1.1 for cylinders. Hence, drag coefficient is 1.1 in our study. It keeps constant 1.1 up to 56.9Mpa (570 bar) at which Reynolds number is 5,000.

Since the fiber length is longer than the jet diameter, the projected fiber length is jet diameter. After rebounding back from knuckles, water jet may split and an average jet diameter (project fiber length) can be used. For certain forming wire type, the average jet diameter is
assumed to be a constant. Hence, drag force is proportional to jet pressure and fiber diameter and can be rewritten as equation 3-12 in our study:

\[
F_d = 0.99 \bar{L}_p d f P_g
\]

Equation 3-12

Where \( \bar{L}_p \) = Average projected fiber, m (constant for fixed wire type).

### 3.3 Resisting Factors and Force Mechanisms

#### 3.3.1 Fiber Flexural Rigidity and Bending Energy

The fiber flexural rigidity is defined as the couple required to bend the fiber to unit curvature. Curvature is the reciprocal of radius of curvature. Morton & Hearle [38] modeled fiber bending as beam bending. As shown in Figure 3.6, suppose a specimen of length l is bent through an angle \( \theta \) to a radius of curvature r. Its outer layer will be extended and its inner compressed, but a plane in the center, known as neutral plane, will be unchanged in length. As a result of the extension and compression, stresses will be set up that give an internal couple to balance the applied couple.

\[
\varepsilon = \frac{(r + x) \theta - r \theta}{r \theta} = \frac{x}{r}
\]

Equation 3-13

Where
ε = strain, dimensionless

x = distance to neutral plane, m

θ = bending angle, arc.

r = radius of curvature, m.

and, therefore, tension in element

\[
F_T = \frac{x}{r} Y \delta A
\]

Equation 3-14

where

\( F_T \) = tension force in element, N

\( Y \) = Young’s modulus, N/m²

\( \delta A \) = area of cross-section element, m².

Its moment about an axis in the neutral plane

\[
dM = \frac{x}{r} Y \delta A x = \frac{Y}{r} x^2 \delta A
\]

Equation 3-15

where \( dM \) = moment in the element, Nm².

Hence, the total internal couple is

\[
M = \frac{Y}{r} \sum x^2 \delta A = \frac{YA k^2}{r}
\]

Equation 3-16

The parameter \( k \) is thus analogous to a radius of gyration, taken about the neutral plane.

Finlayson [21] related the radius of gyration \( k \) with the shape factor \( \eta \) of the fiber by the equation:

\[
k^2 = \frac{1}{4\pi} \eta A
\]

Equation 3-17

For the round shape, the shape factor is equal to 1. Here, we assume fibers are round.

Since

\[
A = \frac{T}{\rho}
\]

Equation 3-18

Where

\( \rho \) = fiber density, kg/m³

\( T \) = fiber linear density, kg/m

and \( Y = \rho E \), where \( E \) = specific modulus, J/kg.

Finally, for a round fiber, the total couple is
\[ M = \frac{1}{4\pi} \frac{ET^2}{r\rho} \quad \text{Equation 3-19} \]

Where

\[ \rho = \text{fiber density, kg/m}^3 \]
\[ T = \text{fiber linear density, kg/m} \]
\[ E = \text{specific modulus, Nm/kg} \]
\[ M = \text{moment of the cross-section, Nm}^2. \]

Therefore, fiber flexural rigidity (FR) is

\[ <FR> = \frac{1}{4\pi} \frac{ET^2}{\rho} \quad \text{Equation 3-20} \]

This is the derivation of equation 2-1. In SI units, E is in Nm/kg, T is in kg/m, \( \rho \) is in kg/m\(^3\) and flexural rigidity in Nm\(^2\).

In customary textile units with E in N/dtex, T in dtex, \( \rho \) in g/cm\(^3\), and FR in cN*mm\(^2\), the equation becomes

\[ <FR> = \frac{1}{4\pi} \frac{ET^2}{\rho} \times 10^{-2} \quad \text{Equation 3-21} \]

The results apply only to small strains. It may be noted that, if the neutral plane remains in the center of the fiber, the maximum tensile strain, which will be positive on the outside and negative on the inside of the bend, equals the ratio of fiber radius to radius of curvature of bend. Since fibers are so fine, quite small values of radius of curvature (high curvature) result in fairly small strains, so that, in many practical situations, it is only the initial strain that is relevant.

Also, in the process of hydro-entanglement, the assumption of initial flexural rigidity is fairly reasonable. Since the fiber stress-strain curves in the range of strain between 0\% and 2\% are straight lines, it is reasonable to use the 2\% secant modulus instead of Young’s modulus. Hence, 2\% fiber secant modulus will be used in our calculation rather than Young’s modulus, and the relationship between stress and strain in the initial stage (0-2\% strain) is considered to be linear.

Based on linear stress-strain assumption, the bending energy, \( U \), in the fiber with length \( l \), is
\[ dU = \frac{1}{2} \text{tension} \times \text{Elongation} \quad \text{Equation 3-22} \]

Substitution of equation 3-13 and 3-14 into 3-22, then combined with equation 3-15, we can get

\[ dU = \frac{1}{2} \left( \frac{X}{r} \right) Y \delta A \times (\delta l) = \frac{l}{2r} \left( \frac{Y}{r} \right) X^2 \delta A \]

\[ = \frac{l}{2r} dM \quad \text{Equation 3-23} \]

where \( U \) is the bending energy, \( J \), and \( l \) is fiber length, m.

Integration of equation 3-23, we get

\[ U = \frac{l}{2r} M \quad \text{Equation 3-24} \]

Substitution of equation 3-19 into 3-24, the bending energy is

\[ U = \frac{1}{8\pi} \frac{ET^2l}{\rho r^2} \quad \text{Equation 3-25} \]

In customary textile units, the equation can be rewritten as

\[ U = \frac{1}{8\pi} \frac{ET^2l}{\rho r^2} \times 10^{-9} \quad \text{Equation 3-26} \]

with \( E \) in cN/dtex, \( T \) in dtex, and \( \rho \) in g/cm\(^3\), \( r \) in mm, and \( U \) in J.

### 3.3.2 Fiber-to-Fiber Friction Force

In hydroentanglement process, fiber-to-fiber friction needs to be overcome when fibers slide over each other to form the unit cell. Assume fibers slide over each other in a plane and the normal force acted on fibers can be calculated by equation 3-9. Hence, fiber-to-fiber friction force \( F_f \) is

\[ F_f = \mu_w F = \frac{\pi}{2} \mu C_v C_d d_1^2 P_g \quad \text{Equation 3-27} \]

where

\[ F_f = \text{wet fiber-to-fiber friction force}, \text{ N} \]
\[ \mu_w = \text{wet fiber-to-fiber friction coefficient, dimensionless} \]
\[ C_v = \text{coefficient of velocity, dimensionless} \]
\[ C_d = \text{coefficient of discharge, dimensionless} \]
\[ d_1 = \text{orifice diameter, m} \]
\[ P_g = \text{gauge pressure, Pa.} \]

### 3.3.3 Stress-Strain Force

Since fibers are very fine and entangle with each other, there must exist a certain degree of strain in the spunlace process. Assumptions are made below:

1) The entangled points are in the middle of wire spacing, as shown in Figure 3.7.
2) Fibers are extended around unit cell.

![Figure 3.7 Schematic of strain to form a unit hole](image)

In figure 3.7, R is diameter of unit hole, mm, and \( \theta \) is angle to cross-machine direction (for calculation). Based on the assumption, the fiber’s initial length is the length of straight line AB and is extended to the length of curve AB.

The strain, \( \varepsilon \), is

\[
\varepsilon = 2 \frac{R\left(\frac{\pi}{2} - \theta\right) - R \cos \theta}{K_w} \tag{Equation 3-28}
\]

where \( K_w \) is the forming wire space, mm.

The stress-strain force required to form unit cell can be calculated as

\[
F_s = E \varepsilon T = 2ET \frac{R\left(\frac{\pi}{2} - \theta\right) - R \cos \theta}{K_w} \tag{Equation 3-29}
\]
The maximum strain $\varepsilon_{\text{max}}$ is

$$\varepsilon_{\text{max}} = \frac{R(\pi - 2)}{K_w} \text{ at } \theta = 0$$ \hspace{1cm} \text{Equation 3-30}$$

Hence, the maximum stress-strain force required to form unit cell is

$$F_{s, \text{max}} = E\varepsilon_{\text{max}} T = \frac{(\pi - 2)RET}{K_w}$$ \hspace{1cm} \text{Equation 3-31}$$

### 3.3.4 Force Mechanisms

In order to decide which force mechanism is governing force mechanism, flexural rigidity, fiber-to-fiber friction, or stress-strain force, ratios of drag force to those three factors are calculated and named as:

- **Flexural-Rigidity (FR) Mechanism:**
  
  Using equation 3-12, the ratio of drag force to fiber flexural rigidity, $\Phi_{\text{FR}}$, can be expressed as

  $$\Phi_{\text{FR}} = \frac{F_D}{<\text{FR}>} = \frac{0.99\bar{L_p}d_f P_g}{<\text{FR}>}$$ \hspace{1cm} \text{Equation 3-32}$$

  $\bar{L_p}$ is assumed to be a constant for certain forming wire. Hence, when flexural rigidity mechanism dominates, we would expect that: 1) Fabric properties increase with increasing jet pressure, and 2) Increasing rate is proportional to $d_f/\langle\text{FR}\rangle$.

- **Friction Mechanism:**

  Using equations 3-12 and 3-27, the ratio of drag force to fiber-to-fiber friction force, $\Phi_f$, can be calculated as

  $$\Phi_f = \frac{F_D}{F_f} = 0.61 \frac{\bar{L_p}d_f}{\mu_w C_d d_1^2}$$ \hspace{1cm} \text{Equation 3-33}$$

  For the machine used, coefficient of discharge, $C_d$, is 0.62 and orifice diameter, $d_1$, is 0.127mm. Hence, we can get

  $$\Phi_f = \frac{F_D}{F_f} = 6.08 \times 10^7 \frac{\bar{L_p}d_f}{\mu_w}$$ \hspace{1cm} \text{Equation 3-34}$$
When friction mechanism dominates, one can expect that jet pressure has no effect on forming unit cell. It is a function of fiber properties and wire parameters.

- **Stress-Strain (SS) Mechanism:**
  Using equation 3-12 and 3-31, the ratio of drag force to maximum stress-strain force, \( \Phi_{ss} \), can be calculated as

  \[
  \Phi_s = \frac{F_D}{F_s} = \frac{0.87 L_f d_f P_g K_w}{\text{RET}}
  \]  

  **Equation 3-35**

  When stress-strain mechanism dominates, one can expect that: 1) Fabric properties increases with jet pressure, and 2) Increasing rate should be proportional to \( d_f/\text{RET} \) for certain forming wire since \( K_w \) and \( L_p \) are only functions of forming wire.

### 3.4 Energy Factors

#### 3.4.1 Bending and Friction Energy for a Unit Hole

Figure 3.8 shows the movement of a single fiber in forming a unit hole, in which, \( R \) is diameter of unit hole, mm, and \( \theta \) is angle to cross-machine direction (for calculation).

![Figure 3.8 Formation of Unit Hole](image)

The single fiber with length \( CD \) passes through the unit cell by straight line \( AB \) before hydroentanglement. In the process of spunlace, water jet force pushes the fiber away from the
knuckle and bends the fiber around the unit cell. The two ends, C and D, shift to E and F, respectively. The move needs to overcome the fiber-to-fiber friction force at the same time.

To simplify the calculation, we assume that fibers are arranged side by side and there is no space between two fibers. In fact, as a uniform web, the fibers can be distributed randomly through all directions. Hence, the number of fibers passed through a unit cell in one layer, $N_1$, is

$$N_1 = \frac{2R}{d_f}$$  \hspace{1cm} \text{Equation 3-36}

where $d_f$ is the diameter of fiber, mm.

Total number of layers, $N_L$, is

$$N_L = \frac{W * 10000}{T} * (d_f * 10^{-3}) = 10 \frac{Wd_f}{T}$$  \hspace{1cm} \text{Equation 3-37}

where

- $W =$ web basis weight, gsm;
- $T =$ fiber linear density, dtex.

Hence, using equation 3-36 and 3-37, total number of fibers passed through one single unit cell is

$$N = N_1 * N_L = \frac{20WR}{T}$$  \hspace{1cm} \text{Equation 3-38}

Since fibers are very fine, average bending length and slide length are used for calculation. To form a unit hole, all the fibers in the hole regions finally bend around the holes, hence the average bending length is

$$l_{b\_avg} = \frac{2 \int_0^{\pi} (R \cos \theta) R \cos \theta d\theta}{\int_0^{\pi} R \cos \theta d\theta}$$

$$= \frac{\pi R}{2}$$  \hspace{1cm} \text{Equation 3-39}

Here, $l_{b\_avg}$ is average bending length, mm.

Average friction length is
\[ l_{f_{-avg}} = \frac{2 \left[ R \left( \frac{\pi}{2} - \theta \right) - R \cos \theta \right] R \cos \theta \, d\theta}{\int_{0}^{\pi/2} R \cos \theta \, d\theta} \]

Equation 3-40

\[ = \left( 2 - \frac{\pi}{2} \right) R \]

Here \( l_{f_{-avg}} \) is average friction length, mm.

Using equation 3-38 and 3-39, the bending length to form a unit hole is

\[ l_{b} = N \cdot l_{b_{-avg}} = \frac{20WR \cdot \pi R}{T^2} \]

where \( l_{b} \) is bending length to form a unit hole, mm.

All these fibers have same curvature. Hence, by substitution of equation 3-41 into 3-26, bending energy to form a unit hole is

\[ U_{b} = \left( \frac{1}{8\pi} \frac{ET^2}{\rho R^2} \cdot 10^{-9} \right) \left( \frac{10\pi WR^2}{T} \right) \]

Equation 3-42

\[ = 1.25 \cdot 10^{-9} \frac{WET}{\rho} \]

where \( U_{b} \) is bending energy to form a unit cell, J.

Since the water jet acts as a normal force on the web, fiber-to-fiber friction must be overcome to form unit holes. Using equation 3-38 and 3-40, the friction length to form a unit hole, \( l_{f} \), mm, is

\[ l_{f} = N \cdot l_{f_{-avg}} = \frac{20WR}{T} \cdot (2 - \frac{\pi}{2})R \]

Equation 3-43

\[ \approx \frac{8.6WR^2}{T} \]

The friction energy to form a unit hole is
\[ U_f = (\mu F) \times (l_f \times 10^{-3}) = (\mu F) \times \left( \frac{8.6WR^2}{T} \right) \times 10^{-3} \]  
\[ = 8.6 \times 10^{-3} \frac{WR^2 \mu F}{T} \]  
Equation 3-44

where

\( \mu = \) fiber-to-fiber coefficient of friction, dimensionless
\( F = \) normal force acted by the water jet on the fibers, N
\( U_f = \) friction energy to form a unit hole, J.

Substitution of equation 3-9 into 3-44, the friction energy for a unit cell, \( U_f \), J, is

\[ U_f = 1.35 \times 10^{-2} \frac{WR^2 \mu C_f C_d d^2 \rho \gamma}{T} \]  
Equation 3-45

3.4.2 Stress-Strain Work for a Unit Hole

The stress-strain force can be calculated by equation 3-29. Even though the actual fiber stress-strain curve is a curve, we treat it like a straight line and use the average secant modulus \( \bar{E} \). Similar to equation 3-22, the stress-strain work for one simple fiber is

\[ W_{ss} = \frac{1}{2} \times \text{tension} \times \text{elongation} = \frac{1}{2} (\bar{E} \varepsilon T) \times (K_w \varepsilon) \]  
\[ = \frac{1}{2} \bar{E} T K_w \varepsilon^2 \]  
Equation 3-46

where

\( \bar{E} = \) average secant modulus, cN/dtex
\( T = \) fiber linear density, dtex.
\( W_{ss} = \) fiber strain work, cN*mm.

Substitution of Equation 3-39 into Equation 3-46, we get

\[ W_{\text{strain}} = \frac{2 \bar{E} TR^2}{K_w} \left( \frac{\pi}{2} - \theta - \cos \theta \right)^2 \]  
Equation 3-47

When the fiber and forming wire are chosen, other parameters except \( \theta \) are fixed. The average \( W_{\text{strain}} \) is
\[ W_{ss\_avg} = \frac{2\overline{ETR}^2}{K_w} \int_0^\pi \left( \frac{\pi}{2} - \theta - \cos \theta \right)^2 R \cos \theta d\theta \]

Equation 3-48

where

\[ \int_0^\pi \left( \frac{\pi}{2} - \theta - \cos \theta \right)^2 R \cos \theta d\theta \]

Equation 3-49

Combine Equation 3-48 with Equation 3-49, average strain work for one single fiber, \( W_{ss\_avg} \), cN*mm, is

\[ W_{ss\_avg} = 1.49 \times 10^{-1} \overline{ETR}^2 \]

Equation 3-50

Combination of Equation 3-38 with Equation 3-50, stress-strain work for one unit hole, \( U_{ss} \), J, is

\[ U_{ss} = (1.49 \times 10^{-1} \overline{ETR}^2 \times 10^{-5}) \times (20 \frac{WR}{T}) \]

Equation 3-51

\[ = 1.91 \times 10^{-5} \overline{ETR}^3 \]

Hence, Equations 3-42, 3-45, and 3-51 can be used to calculate the energy required forming a unit hole in different forms. These energies can be considered the energy which is actually delivered to the final spunlace fabrics.

3.4.3 Contribution to Specific Energy

In the field of spunlace, specific energy is used to describe the energy consumption to produce the spunlace fabrics. Its unit is kJ/kg. First we will calculate the number of unit cell for 1kg fabrics, then derive the energy equations for those three forms. The total number of unit cell for 1kg fabrics, \( N_U \), is

\[ N_U = (mesh \times count \times \frac{100}{2.54} \times \frac{100}{2.54}) \times \frac{1000}{W} \]

Equation 3-52

\[ = 1.55 \times 10^6 \frac{mesh \times count}{W} \text{ (/kg)} \]
Where

\[ \text{mesh} = \text{number of wire in MD, \$/inch;} \]
\[ \text{count} = \text{number of wire in CD, \$/inch;} \]
\[ W = \text{basis weight, gsm.} \]

From Equations 3-42, 3-45 and 3-51, we can get contributions of these three factors to specific energy are

a) Bending Energy, \( E_b \), J/kg:

\[
E_b = 1.94 \times 10^{-3} \frac{\text{mesh} \times \text{count} \times ET}{\rho_f}
\]

Equation 3-53

b) Friction Energy, \( E_f \), J/kg:

\[
E_f = 2.09 \times 10^4 \frac{\text{mesh} \times \text{count} \times R^2 \times (\mu C_r C_d d_i^2 P_g)}{T}
\]

Equation 3-54

c) Stress-Strain Work, \( E_{ss} \), J/kg:

\[
E_{ss} = 46.2 \frac{\text{mesh} \times \text{count} \times ER^3}{K_w}
\]

Equation 3-55

3.4.4 Estimated Energy Consumption from the Model

Based on the industrial application and our measurements, we fix the values of some parameters for future calculation. The fiber we choose for calculation is PET. The principle of setting the value of fiber properties is that, whenever we have choice, a high value will be chosen. Hence, we use dry fiber-to-fiber friction coefficient, which is greater than wet friction. 2% secant modulus is chosen for \( E \) even though it has much higher value than \( E \) (Figure 3.9). We also assume that

\[
K_w = \sqrt{P_{MD} \times P_{CD}}
\]

Equation 3-56

and

\[
R = \frac{1}{2} \sqrt{d_{MD}^2 + d_{CD}^2}
\]

Equation 3-57

Forming wire parameters and jet parameters are shown in Table 3.1 and 3.2, respectively.
Figure 3.9 Stress-strain curve of PET fiber

Table 3.1 Forming Wire Parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Mesh x Count (/inch)</th>
<th>(d_{MD}) (mm)</th>
<th>(d_{CD}) (mm)</th>
<th>(P_{MD}) (mm)</th>
<th>(P_{CD}) (mm)</th>
<th>(K_{wire}) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech 10</td>
<td>11x11</td>
<td>0.89</td>
<td>1.00</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>Tech 14</td>
<td>14x13</td>
<td>0.88</td>
<td>0.89</td>
<td>1.81</td>
<td>1.95</td>
<td>1.88</td>
</tr>
<tr>
<td>Tech 36</td>
<td>36x27</td>
<td>0.40</td>
<td>0.40</td>
<td>0.71</td>
<td>0.94</td>
<td>0.81</td>
</tr>
<tr>
<td>Tech 100</td>
<td>100x90</td>
<td>0.11</td>
<td>0.11</td>
<td>0.25</td>
<td>0.28</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 3.2 Fixed Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Diameter, m</td>
<td>1.27x10^{-4} (0.005 inch)</td>
</tr>
<tr>
<td>Coefficient of Velocity, (C_v)</td>
<td>~1</td>
</tr>
<tr>
<td>Coefficient of Discharge, (C_d)</td>
<td>0.6</td>
</tr>
<tr>
<td>Jet Pressure, Pa</td>
<td>8.27x10^6 (1200psi)</td>
</tr>
<tr>
<td>Fiber density (\rho_f) (g/cm^3)</td>
<td>1.38</td>
</tr>
<tr>
<td>Fiber Linear Density T, dtex</td>
<td>1.63</td>
</tr>
<tr>
<td>(E), cN/dtex/%</td>
<td>28.1</td>
</tr>
<tr>
<td>(\bar{E}), cN/dtex/%</td>
<td>28.1</td>
</tr>
<tr>
<td>Coefficient of Friction</td>
<td>0.43</td>
</tr>
</tbody>
</table>

The three different energies calculated by equation 3-53, 3-54 and 3-55 and their summation, \(E_{total}\), are listed in Table 3.3. Commercial specific energy (SE) usually is in the range of 5~10x10^6 J/kg. The ratio of \(E_{total}\) to SE is also listed.
Table 3.3 Effect of wire type on calculated energies

<table>
<thead>
<tr>
<th>Type</th>
<th>Bending Energy, $E_b$ (J/kg)</th>
<th>Friction Energy, $E_f$ (J/kg)</th>
<th>Strain Work, $E_{ss}$ (J/kg)</th>
<th>$E_{total}$ (J/kg)</th>
<th>Range of Ratio of $E_{total}/SE$ (x10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech 10</td>
<td>7.8</td>
<td>16,744</td>
<td>20,395</td>
<td>37,147</td>
<td>0.37-0.74</td>
</tr>
<tr>
<td>Tech 14</td>
<td>11.8</td>
<td>22,014</td>
<td>30,748</td>
<td>52,775</td>
<td>0.53-1.06</td>
</tr>
<tr>
<td>Tech 36</td>
<td>62.6</td>
<td>24,018</td>
<td>35,038</td>
<td>59,119</td>
<td>0.59-1.18</td>
</tr>
<tr>
<td>Tech 100</td>
<td>580</td>
<td>16,818</td>
<td>20,530</td>
<td>37,928</td>
<td>0.38-0.76</td>
</tr>
</tbody>
</table>

*$E_{total}$ is the summation of bending energy, friction energy and Strain work

Table 3.3 shows the impact of wire type on calculated energies. It is clear that the calculated bending energy is very small as compared to calculated friction energy or stress-strain work. It also shows that the ratio of the total calculated energy ($E_{total}$) to actual specific energy is in the range of 0.37-1.18x10^{-2} which is extremely small. This despite the fact that high values of fiber parameters (PET fiber) were selected to maximize the values of calculated energies. It seems that most of the water jet energy is lost, and only a very small portion of the energy is delivered to the fabric.

The effect of forming wire type on the calculated energies is not clear. This is due to the fact that low aperture forming wire has large number of knuckles but small size fabric holes are formed. These two factors show mixed effects on the calculated energies.

3.4.5 Conclusion for Energy Calculation

Based on the “Unit Cell” model and energy calculation, we can conclude:

1) Pure fiber bending energy (without large strain) is very small;
2) The efficiency of energy delivered from water jet to fabric is very small, and most energy is lost for the PET fiber considered; and
3) Water jet force may play more important roles in hydroentanglement process.

3.5 Summation

There are two ways to analyze the formation of unit cells: by force or by energy. In order to form unit cells, three factors need to be overcome: fiber flexural rigidity, fiber-to-fiber
friction, and stress-strain force. Hence three kinds of energies are consumed. First, we need to answer a question:

- Which one is governing mechanism: energy delivery or force?

Results of the energy calculation show that the efficiency of energy delivered from water jet to fabric is very small, and most energy is lost. Hence, force may be the governing mechanism. But force mechanism consists of three mechanisms. It then raises the second question:

- Which one is the governing force mechanism: flexural-rigidity, fiber-to-fiber friction, or stress-strain?

Experimental verification is needed for the model and governing mechanism. Nozzle parameters are considered fixed. For a certain type of fiber and forming wire, fiber and forming wire properties are also fixed. When one force mechanism dominates one would expect the process to show the following characteristics:

- Flexural-rigidity (FR) mechanism: Fabric properties increase with jet pressure and increasing rate increases linearly with \( \frac{d}{\phi} < \text{FR} > \).
- Friction Mechanism: Jet pressure has no effect on fabric properties.
- Stress-Strain Mechanism: Fabric properties increase with jet pressure, and increasing rate should increase linearly with \( \frac{d}{\phi} \text{RET} \).

These predictions can be tested with experimental data.
4 MATERIALS AND METHODOLOGY

This study focus on establishing fundamental relationships between fiber properties, water jet properties, forming wire geometry, and fabric properties. First of all, various types of fibers and forming wires were chosen based on their properties and used to make hydroentanglement fabrics at the Nonwovens Laboratory at College of Textiles, North Carolina State University (NCSU). Then fabric properties were measured.

4.1 Materials

The following fibers were considered for this project:

- 4 types of poly(ethylene terephthalate) (PET)
- Poly(trimethylene terephthalate) (PTT)
- Nylon 6
- Nylon 6,6
- Polypropylene (PP).

Several tests were executed to measure different characteristics of the collected fiber types.

4.1.1 Testing of Fiber Parameters

4.1.1.1 Testing with FAVIMAT Tester

Fiber fineness and fiber stress-strain properties were measured using the Textechno FAVIMAT tester, which is shown in Figure 4.1 and 4.2. The sequence of a standard tensile and crimp stability test with count measurement with the FAVIMAT is as follows [19]:

1. Fiber is pre-tensioned with paper weight (approx. 0.01 cN/tex)
2. Load sensor at upper clamp is calibrated to zero
3. Fiber is clamped (initial gage length e.g. 20 mm)
4. Position of lower clamp is adjusted, so that fiber is exactly pre-tensioned with 0.001 cN/tex referred to nominal count
5. Actual crimp test starts:
   -- Lower clamp moves downwards at constant rate of extension (e.g. 20 mm/min)
   -- Until preset “crimp force” (e.g. 1 cN/tex) is reached.
   -- Lower clamp moves upwards
6. Count test is done:
   -- Fiber is loaded at a predefined rate
   -- Fiber is excited acoustically & resonance frequency is detected
7. Fiber is loaded until it breaks

Figure 4.1 Textechno FAVIMAT Single Fiber Tester [7]

- Force Measuring Head
- Upper Clamp
- Optical Fiber Count Measuring Head
- Lower Clamp
- Fiber Clamp for Handling Purposes (For Crimp Tests, Much Lighter Paper Tabs Are Being Used)
- Gage Length Continuously Variable: 5 - 80mm
- Maximum Force: 200cN
+ Force Resolution: ±0.0001cN
- Force Sensitivity: 0.001 cN
- Extension Resolution: ±0.1 μm
- Testing Speeds: 0.1 - 100mm/min

Figure 4.2 Measuring Unit of Textechno FAVIMAT Tester [7]
8. Lower and upper clamp open, fiber drops
9. Lower clamp moves upwards to initial position

4.1.1.2 Fiber Count and Tensile Properties
The FAVIMAT measures the count according to the vibroscopic method ASTM D1577 using a built-in automatic measuring head. The fiber is loaded to a predetermined specific tension at a predefined speed, then exited with an electroacoustic sinusoidal vibration. The resonance frequency is detected with an optoelectronic sensor. For simplicity of the calculation, uniform mass distribution and circular cross-section of the fiber is assumed, and bending rigidity is disregarded.

Fiber strength values obtained from the FAVIMAT tester are simply the peak load of the fiber. For this test, the fiber, which is mounted between the two clamps of the tester, is loaded until it breaks. For the FAVIMAT tester used, ten data points on the stress-strain curve were extracted and fiber modulus was measured using certain points on the fiber stress-strain diagram. Fifty replicates were chosen for each fiber sample.

4.1.2 Fiber Friction Properties
A fiber-to-fiber friction test was conducted at Goulston Technologies’ facilities by their technician using the staple pad friction test method. Figure 4.3 shows the staple pad friction apparatus, which is mounted on an Instron tester and driven by its clamps. The apparatus consists of a metal plate, a dead weight and a length of line (Kevlar® was used because of its high modulus and minimum elongation). One end of the line is tied to the upper clamp of Instron and other end is tied to the dead weight, which sits on the fiber sample. The metal plate is mounted on the top of the lower clamp. By the use of the line and pulley, the vertical displacement of the clamps is transformed to a horizontal movement. A piece of sandpaper was stuck on the top of the metal plate, and a fiber sample was put on the sandpaper. Then the dead weight, which was driven by the line, was located on the top of the sample. The test was carried out by dragging the dead weight for a certain amount of time and the frictional characteristics were obtained from the load-time curve.
4.1.3 Polymer Density

The densities of the fibers were measured by the floating method: Two solvents, acetone and tetrachloroethylene, which have densities of 0.791 g/m³ and 1.623 g/m³ respectively, are chosen. Since all the fibers’ densities fall in the range of the density of these two pure solvents, certain amount of tetrachloroethylene is added in a volumeter, and then the acetone solvent can be added into the volumeter gradually till the fibers float up. From the volumes added in and densities of these two solvents, the density of the mixture can be calculated, which is the fiber density.

4.1.4 Fiber Properties

Fiber tensile strength summary is shown in Table 4.1. The data of fiber count, friction, and polymer density are listed in Table 4.2 and stress-strain data are listed in Appendix A. The stress-strain curves are shown in Figure 4.4 and 4.5.
Figure 4.4 Stress-Strain Curves of All Fibers
Figure 4.5 Stress-Strain Curves in the Range [0, 20%]
Table 4.1 Fiber Tensile Properties Summary

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Stress (cN/dtex)</th>
<th>Break Strain (%)</th>
<th>Break Stress (cN/dtex)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>PET1</td>
<td>0.72</td>
<td>1.02</td>
<td>1.27</td>
</tr>
<tr>
<td>PET2</td>
<td>0.78</td>
<td>1.24</td>
<td>1.80</td>
</tr>
<tr>
<td>PET3</td>
<td>0.56</td>
<td>0.90</td>
<td>1.07</td>
</tr>
<tr>
<td>PET4</td>
<td>0.52</td>
<td>0.88</td>
<td>1.03</td>
</tr>
<tr>
<td>PTT</td>
<td>0.27</td>
<td>0.46</td>
<td>0.56</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>0.25</td>
<td>0.41</td>
<td>0.49</td>
</tr>
<tr>
<td>Nylon 6, 6</td>
<td>0.35</td>
<td>0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>PP</td>
<td>0.44</td>
<td>0.75</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 4.2 Fiber Properties

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Source</th>
<th>Fiber Length (mm)</th>
<th>Density (g/cm³)</th>
<th>Coefficient of Friction</th>
<th>Linear Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Count</td>
</tr>
<tr>
<td>PET1</td>
<td>Wellman</td>
<td>38</td>
<td>1.39</td>
<td>0.38</td>
<td>1.70</td>
</tr>
<tr>
<td>PET2</td>
<td>Wellman</td>
<td>38</td>
<td>1.40</td>
<td>0.39</td>
<td>1.74</td>
</tr>
<tr>
<td>PET3</td>
<td>--</td>
<td>38</td>
<td>1.38</td>
<td>0.42</td>
<td>1.63</td>
</tr>
<tr>
<td>PET4</td>
<td>Shell</td>
<td>38</td>
<td>1.39</td>
<td>0.47</td>
<td>1.67</td>
</tr>
<tr>
<td>PTT</td>
<td>Shell</td>
<td>38</td>
<td>1.32</td>
<td>0.47</td>
<td>1.89</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>Shell</td>
<td>40</td>
<td>1.15</td>
<td>0.49</td>
<td>1.70</td>
</tr>
<tr>
<td>Nylon 6, 6</td>
<td>Shell</td>
<td>40</td>
<td>0.91</td>
<td>0.47</td>
<td>1.74</td>
</tr>
<tr>
<td>PP</td>
<td>Shell</td>
<td>38</td>
<td>1.38</td>
<td>0.47</td>
<td>1.74</td>
</tr>
</tbody>
</table>

4.2 Forming Wire

To determine the effect of forming wire geometry on process and fabric properties, four different forming wires provided by Albany International Corporation were used (shown in Figure 4.6). Their parameters are listed in Table 4.3.

Table 4.3 Forming Wire Parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Count (/inch)</th>
<th>Wire/Filament Shape</th>
<th>MD Wire Diameter (mm)</th>
<th>CD Wire Diameter (mm)</th>
<th>Open Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mesh</td>
<td>Polyester</td>
<td>11 x 11</td>
<td>Round</td>
<td>0.89</td>
<td>1.00</td>
<td>35</td>
</tr>
<tr>
<td>36 mesh</td>
<td>Polyester</td>
<td>36 x 27</td>
<td>Round</td>
<td>0.40</td>
<td>0.40</td>
<td>25</td>
</tr>
<tr>
<td>100 mesh</td>
<td>Stainless Steel</td>
<td>100 x 90</td>
<td>Round</td>
<td>0.11</td>
<td>0.14</td>
<td>29</td>
</tr>
<tr>
<td>14 mesh</td>
<td>Polyester</td>
<td>14 x 13</td>
<td>Rectangle</td>
<td>0.88 x 0.57</td>
<td>0.89</td>
<td>28</td>
</tr>
</tbody>
</table>
4.3 Equipment

4.3.1 Fiberweb Formation
All fibers were provided in bale form. The fibers were processed in the carding and crosslapping line available at the College of Textiles, NC State University. This line has an
opener, flat-top card, crosslapper, tacker, and take-up. The fibers were passed through the opener, the flat-top card, the tacker and finally to the take-up to form the required fiberwebs. Fiberwebs with required quantity of nominal weight of 50 g/m² and 100 g/m² were produced.

In the case of hydroentanglement, it is critical for their commercial use that fabrics should be as uniform as possible in their properties. Basis weight (weight per unit area) is one of most important properties. Keeping the basis weight as close as possible to the target value is difficult to achieve. The quality of hydroentanglement fabrics is largely determined by the quality of the web at the end of the carding process. In this study, the actual basis weight was measured.

4.3.2 Hydroentangling

Fiberwebs were entangled using a 50.8cm(20inch) wide honeycomb model hydroentanglement machine with three manifolds (see Figure 4.7 and 4.8). Fabric samples were produced using different energy levels by varying manifolds pressure and number of passes. The pressure of the first manifold was kept constant at 1.38 Mpa (200psi) for the first pass only to prewet the samples in this study. The manifold pressure can be as low as 1.38Mpa (200psi) for pre-wetting, and as high as 10Mpa (1,450psi) for hydroentangling. The orifice diameter is 0.127 mm and the density of the jets is 16 orifices/centimeter. The machine parameters are listed in Table 4.4. A simple sketch of Honeycomb hydroentangling machine is shown in Figure 4.7. Both sides of fiberweb are hydroentangled alternatively to get good bond.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Density</td>
<td>15.8 jets/cm</td>
</tr>
<tr>
<td>Jet Diameter</td>
<td>0.127mm</td>
</tr>
<tr>
<td>Discharge Coefficient</td>
<td>0.62</td>
</tr>
<tr>
<td>Number of Manifolds/Pass</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 4.7 A Simple Sketch of Honeycomb Hydroentangling Machine

Figure 4.8 Three Jet Manifolds
4.4 Testing

Fabric properties reported in this thesis are basis weight, tensile strength, and image analysis. The fabric mechanical properties and basis weight testing and evaluation were performed according to ASTM standards for nonwoven fabrics. The image analysis testing was performed using software and hardware provided by Nonwovens Cooperative Research Center (NCRC), College of Textiles, North Carolina State University (NCSU).

4.4.1 Fabric Basis Weight

The fabric basis weight was determined using the ASTM D 3776-96 [3]. 10 samples were tested.

4.4.2 Tensile Strength

The tensile test provides much information: breaking load, the percent elongation at peak load, strain at peak load, energy to peak, and modulus of fabrics. The test was performed on a tensile tester, using the ASTM D 5035-95 (strip method): “Standard test method for breaking force and elongation of textile fabrics”[4].

- The sample size was 25.4mm × 203.2 mm (1 inch × 8 inch).
- The gage length was fixed at 76.2 mm (3 inch).
- The speed of elongation was 304.8 mm/min (12 inch/min).
- Five samples in the machine direction and five samples in the cross direction were tested.

4.4.3 Image Analysis

A flatbed scanner (up to 2400 dpi resolution) and image analysis software developed by NCRC [43-47] were utilized to take pictures of fiberweb and fabrics and measure fiberweb and fabric properties such as orientation distribution function (ODF) and hole size. This software performs a Fast Fourier Transform to measure the orientation distribution. Results are illustrated as mean dominant angle of orientation and frequencies of orientation angles.
5 PRELIMINARY EXPERIMENT

Before a series of experiments designed to determine the effect of fiber type, forming wire type, and jet parameters on fabric performance, preliminary experiments were designed to 1) determine optimum process variables such as vacuum levels, line speed, and number of passes, 2) have a general understanding of hydroentangled fabric properties.

5.1 Experimental

Two sets of trials (referred as trial 1 and trial 2 throughout this dissertation) were performed. Experimental variables in trial 1 and trial 2 are listed in Table 5.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Type</td>
<td>PET3</td>
<td>PET3</td>
</tr>
<tr>
<td>Forming Wire</td>
<td>100 mesh</td>
<td>100 mesh</td>
</tr>
<tr>
<td>Fiberweb Basis Weight (g/m²)</td>
<td>Nominal 100</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Actual 99.6</td>
<td>56.9</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>4.1</td>
</tr>
<tr>
<td>Conveyor Speed (m/min)</td>
<td>4.57</td>
<td>9.14</td>
</tr>
<tr>
<td>Jet Pressure (Mpa)*</td>
<td>2.76, 5.52, 8.27</td>
<td>2.76, 5.52, 8.27</td>
</tr>
<tr>
<td>Number of Passes</td>
<td>2, 4, 6, 8</td>
<td>2, 4, 6, 8, 10, 12</td>
</tr>
</tbody>
</table>

* First manifold pressure was fixed at 1.38Mpa (200psi) for the first pass only

5.2 Trial 1

5.2.1 Objectives
The objectives of trial 1 were to
1) Decide the optimum vacuum level;
2) Obtain general understanding of hydroentangled fabric properties.

5.2.2 Major Observations

5.2.2.1 Effects of Vacuum Level on Fiberweb Water Content and Fabric Performance
A set of trials was conducted to test the effect of vacuum levels on water content in fabrics (g/g) to observe if water will be removed promptly. The above carded, cross-lapped webs with basis weight 99.6gsm (nominal 100gsm) were used to produce hydroentangled fabrics at
two line speeds, 4.57 m/min (15 feet/min) and 9.14 m/min (30 feet/min). The weight of fiber-web was measured before and after one pass through the hydroentanglement equipment and the water content was calculated. The results are shown in Figure 5.1.

![Figure 5.1 Effect of Vacuum Level on Water Content in PET Fabrics](image)

**Figure 5.1 Effect of Vacuum Level on Water Content in PET Fabrics**

The water content in PET fabrics decreases with increasing vacuum levels to a certain value (about 3000 Pa or 12 inches of water) after which further increase in vacuum doesn’t change the water content significantly. The results of this experiment prove that the hydroentanglement equipment used can remove the water from fabric effectively at 4978 Pa (20 inches of water) and any increase after this value would not be necessary. While this is clear fact from this experiment, we have studied the fabric performance at different two vacuum levels to check whether the slight difference in water content would have significant effect on fabric performance.

Two vacuum levels, 20 inches of water (4978Pa) and 40 inches of water (9957Pa) were used to test the effects of vacuum level on fabric properties. Figure 5.2 shows such effect on tear strength. It is obvious from the figure that there is no effect of vacuum level on tear strength at all values of specific energy or pressure. The results of other properties (tensile strength and strain at peak load), which are not shown, exhibit no effect on the properties as a result of change in vacuum level. Hence, 4978 Pa (20 inches of water) vacuum level was chosen for all other experiments.
5.2.2.2 Fabric Basis Weight and Tensile Strength

Figure 5.3 shows the effect of jet pressure and specific energy on fabric basis weight.
Figure 5.4 and 5.5 shows the effect of jet pressure and specific energy on fabric tensile strength in machine direction (MD) and cross-machine direction (CD). In general fabric basis weight decreases with increase in specific energy.
5.2.3 Conclusions

The following conclusions can be drawn:

1) Under 4978 Pa (20 inches of water) vacuum level, water was removed promptly and hence the 4978 Pa vacuum level was chosen for all other experiments;

2) Fabric basis weight decreases with increasing specific energy (number of passes), hence normalized tensile strength was used in this dissertation;

3) There exists threshold specific energy (number of passes) for fixed jet pressure, at which maximum fabric tensile strength is reached. Different jet pressure may cause different threshold specific energy.

5.3 Trial 2

5.3.1 Objectives

The second trial (combined with the trial 1) was designed to:

1) Determine the effects of basis weight on fabric properties; and

2) Demonstrate the effects of number of passes on fabric properties.

5.3.2 Major Observations

5.3.2.1 Fabric Properties

As shown in Table 5.1, fiberweb basis weight was reduced to half and line speed was doubled in trial 2 when compared with trial 1. Hence, specific energy remains the same under same jet pressure in both trials so that fair comparison can be expected. Figure 5.6 shows fabric basis weight, figure 5.7 and 5.8 depict fabric tensile strength in MD and CD, and figure 5.9 and 5.10 describe the behavior of fabric elongation.
Figure 5.6 Fabric Basis Weight (Trial 2)

Figure 5.7 Tensile Strength in MD (Trial 2)
Figure 5.8 Tensile Strength in CD (Trial 2)

Figure 5.9 Elongation in MD (Trial 2)
Fabric basis weight decreases significantly with increasing specific energy (Figure 5.6). Tensile strength increases in MD and decreases in CD with specific energy for all jet pressure levels used (Figure 5.7 and 5.8). The elongation at peak load decreases in MD and increases in CD with specific energy at all levels of jet pressures (Figure 5.9 and 5.10). Result also shows that fabric tensile strength in MD is reduced with jet pressure. These results are totally different from trial 1 because of low fiberweb basis weight. Water jet can easily penetrate thin fiberweb, make fibers conform to forming wire. High peeling force is required to remove fabrics from forming wire, and high number of passes cause reduction in fabric tensile strength in CD. To find out if there are changes in the fiber orientation and the structure of fabrics, image analysis was used to determine ODF of crosslapped fiberwebs and hydroentangled fabrics. Further, observing fabrics’ images may lead to understand the reason behind the reduction of tensile strength in MD with jet pressure.
5.3.2.2 Fabric Images

Figures 5.11-5.14 show the images of hydroentangled fabrics processed at different jet pressures and specific energies. The effect of jet pressure on the hydroentangled fabric texture at constant number of passes (two passes) can be noticed from Figures 5.11(a), 5.12(a) and 5.13(a). At 2.76Mpa(400psi) jet pressure the fabric exhibits only small holes texture. At 5.52Mpa(800psi) jet pressure the texture of the fabric shows clear streaks and medium size holes. The 8.27Mpa(1200psi) jet pressure caused the fabric to form the largest size round-shape holes and clear streak. The fact that increasing jet force cause larger size hole is caused by high peeling force needed to remove fabric from forming wires. The effect of the number of passes on fabric texture at low jet pressure of 2.76Mpa(400psi) can be seen by comparing Figures 5.11 (a) and (b). Increasing the number of passes at such low pressure caused the fabric texture to exhibit larger diameter holes. The number of passes at 5.52Mpa(800psi) jet pressure did not show similar effect {Figures 5.12 (a) and (b)}. The clear streaks of the fabric of Figure 5.12 (a) disappeared and the hole size is reduced by increasing the number of passes to 6 {Figure 5.12 (b)}. For the fabrics processed at jet pressure of 8.27Mpa(1200psi), the streaks did not disappear by increasing the number of passes. Additionally, the texture was changed from round-shaped holes to ellipse-shape with the major diameter in the machine direction because high peeling force draw fabrics off from machine direction.
Figure 5.11 Fabric Image (2.76MPa in Trial 2)

Figure 5.12 Fabric Image (5.52MPa in Trial 2)
(a) 8.27MPa, 2 passes, 56.9g/m²
( SE: 3.04x10³kJ/kg)                                            
(b) 8.27MPa, 8 passes, 56.9g/m²
( SE: 33.87x10³kJ/kg)                                            

Figure 5.13 Fabric Images (8.27MPa in Trial 2)

(a) 8.27MPa, 2 passes, 99.6g/m²
( SE:8.50x10³kJ/kg)                                            
(b) 8.27MPa, 8 passes, 99.6g/m²
( SE: 38.70x10³kJ/kg)                                            

Figure 5.14 Fabric Image (8.27MPa in Trial 1)
5.3.2.3 Fiber Orientation Distribution Function (ODF) in Fiberweb and Fabrics

Figure 5.15 shows the orientation distribution function (ODF) of the fiberweb. Machine direction is defined as 90°. The bi-modal fiber orientation distribution is obvious since the web is crosslapped. The two domain angles are around 20° and 160°.

![ODF of Web](image)

Figure 5.15 Fiberweb Orientation Distribution Function

Figures 5.16 ~ 5.19 show the ODFs of hydroentangled fabrics processed at different jet pressures and specific energies. The results of Figures 5.16 and 5.17 indicate that the fiber orientation increases in MD with increasing the number of passes. Although fabrics processed with different jet pressures have different fiber orientation (Figure 5.18), the fiber orientation become quite similar at high number of passes regardless of jet pressure level (Figure 5.19).
**Figure 5.16** Effect of Number of Pass on fabric ODF (2.76MPa)

**Figure 5.17** Effect of Number of Pass on fabric ODF (8.27MPa)
Figure 5.18 Effect of Jet Pressure on Fabric ODF (2 Passes)

Figure 5.19 Effect of Jet Pressure on Fabric ODF (6 Passes)
The results of the ODF explain why the fabric tensile strength in MD is higher than that of the fabric in CD (Figures 5.7 and 5.8). The behavior of fabric elongation at peak load of Figures 5.9 and 5.10 can be also explained in terms of the ODF. With increase in fiber orientation in the MD the fabric strength in MD increases and in the CD decreases. This behavior is reversed for the elongation at peak load. The results of load-strain of Figure 5.20 support this explanation.

![Figure 5.20 Load-Strain Curves of Fabrics (8.27 MPa)](image)

**5.3.3 Conclusions**

The following conclusions can be drawn:

1) Too many hydroentanglement passes change the fiber orientation in fabrics and adversely affect the fabric strength because of stretch by peeling force.

2) While cross-lapped web has bi-modal ODF, hydro-entangled fabrics have uni-modal ODF due to fiber rearrangement in MD caused mainly by peeling of fabrics after each pass and the jet pressure.
6 EXPERIMENTAL

The objective of main experiment was to demonstrate the effect of fiber type, forming wire construction, and jet pressure on fabric mechanical properties. Governing mechanism analyses were conducted.

Results of preliminary experiments showed that too many passes changed the fiber orientation in the fabrics and adversely affected fabric tensile strength. It was decided then that the number of passes must be kept constant at 2 passes for fair comparison. This means that the specific energy can be altered by jet pressure, number of manifold used, and line speed. Specific energy of the range (1.9 - 12 x10³ kJ/kg), which covers the practical specific energy used by industry, was employed to form the hydroentangled fabrics. Line speed was set as 6.1 m/min for all runs.

6.1 Experimental Approach

6.1.1 Material

Five fiber types with wide range of properties were used in this trial and their properties are listed in Table 6.1. One carded and crosslapped fiberweb with nominal basis weight of 50 g/m² was produced in enough quantity for all runs. Four different forming wires were used and their construction parameters are listed in Table 4.3.

Table 6.1 Fiber Properties

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Linear density (dtex)</th>
<th>Density (g/cm³)</th>
<th>Diameter (x10⁻²mm)</th>
<th>2% Secant Modulus (cN/dtex/%)</th>
<th>Flexural Rigidity (cN*mm²)</th>
<th>Coefficient of Friction (dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>1.74</td>
<td>1.40</td>
<td>1.26</td>
<td>38.98</td>
<td>6.71</td>
<td>0.40</td>
</tr>
<tr>
<td>PET4</td>
<td>1.67</td>
<td>1.38</td>
<td>1.24</td>
<td>26.14</td>
<td>4.24</td>
<td>0.47</td>
</tr>
<tr>
<td>PTT</td>
<td>1.89</td>
<td>1.32</td>
<td>1.35</td>
<td>13.64</td>
<td>2.94</td>
<td>0.47</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>1.93</td>
<td>1.13</td>
<td>1.47</td>
<td>12.58</td>
<td>3.30</td>
<td>0.55</td>
</tr>
<tr>
<td>PP</td>
<td>1.74</td>
<td>0.91</td>
<td>1.56</td>
<td>22.16</td>
<td>5.83</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Although the nominal fiberweb basis weight was set as 50g/m², the actual fiberweb basis weights varied with fiber type and were listed in Table 6.2. To make fair comparison of
fabric tensile properties, fabric properties were normalized to 50g/m² based on actual sample weight.

Table 6.2 Actual Fiberweb Basis Weight

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Fiberweb Basis Weight (gsm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>48</td>
</tr>
<tr>
<td>PET4</td>
<td>50</td>
</tr>
<tr>
<td>PTT</td>
<td>56</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>60</td>
</tr>
<tr>
<td>PP</td>
<td>42</td>
</tr>
</tbody>
</table>

6.1.2 Jet Pressure and Specific Energy

Table 6.3 shows the jet pressure levels of different manifold for the two passes. Specific energies for different jet pressure and fiber type are listed in Table 6.4. In calculating specific energies actual fiberweb basis weight is considered.

Table 6.3 Jet Pressure Levels

<table>
<thead>
<tr>
<th>Run</th>
<th>Pass</th>
<th>Manifold 1</th>
<th>Manifold 2</th>
<th>Manifold 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Pass 1</td>
<td>1.38</td>
<td>3.45</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>3.45</td>
<td>0</td>
</tr>
<tr>
<td>#2</td>
<td>Pass 1</td>
<td>1.38</td>
<td>4.14</td>
<td>4.14</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>4.14</td>
<td>0</td>
</tr>
<tr>
<td>#3</td>
<td>Pass 1</td>
<td>1.38</td>
<td>4.83</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>4.83</td>
<td>0</td>
</tr>
<tr>
<td>#4</td>
<td>Pass 1</td>
<td>1.38</td>
<td>6.21</td>
<td>6.21</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>6.21</td>
<td>0</td>
</tr>
<tr>
<td>#5</td>
<td>Pass 1</td>
<td>1.38</td>
<td>7.58</td>
<td>7.58</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>7.58</td>
<td>0</td>
</tr>
<tr>
<td>#6</td>
<td>Pass 1</td>
<td>1.38</td>
<td>8.96</td>
<td>8.96</td>
</tr>
<tr>
<td></td>
<td>Pass 2</td>
<td>0</td>
<td>8.96</td>
<td>0</td>
</tr>
</tbody>
</table>

Line Speed: 6.10m/min (20 feet/min)
Table 6.4 Specific Energy under Different Jet Pressure

<table>
<thead>
<tr>
<th>Jet Pressure (MPa)</th>
<th>Specific Energy (x10^3kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PET2</td>
</tr>
<tr>
<td>3.45</td>
<td>2.2</td>
</tr>
<tr>
<td>4.83</td>
<td>3.7</td>
</tr>
<tr>
<td>6.21</td>
<td>5.2</td>
</tr>
<tr>
<td>7.58</td>
<td>7.0</td>
</tr>
<tr>
<td>8.96</td>
<td>8.9</td>
</tr>
</tbody>
</table>

6.2 Results

6.2.1 Fabric Basis Weight

Effects of forming wire and jet pressure on fabric basis weight are shown in Figure 6.1 –6.5.

![Figure 6.1 Fabric Basis Weight (PET2)](image-url)
Figure 6.2 Fabric Basis Weight (PET4)

Figure 6.3 Fabric Basis Weight (PTT)
Figure 6.4 Fabric Basis Weight (Nylon 6)

Figure 6.5 Fabric Basis Weight (PP)
6.2.2 Fabric Tensile Strength

6.2.2.1 Effects of Fiber Type and Jet Pressure on Fabric Tensile Strength

Effects of fiber type and jet pressure on fabric tensile strength are shown in figure 6.6 – 6.9.

Figure 6.6 Fabric Tensile Strength on 100 Mesh
Figure 6.7 Fabric Tensile Strength on 36 Mesh
Figure 6.8 Fabric Tensile Strength on 14 Mesh
Figure 6.9 Fabric Tensile Strength on 10 Mesh
6.2.2.2 Effects of Forming Wire and Jet Pressure on Fabric Tensile Strength

Effects of forming wire and jet pressure on fabric tensile strength are shown in figure 6.10 – 6.14.

![Figure 6.10 Fabric Tensile Strength (PET2)](image_url)

(a) MD

(b) CD

Figure 6.10 Fabric Tensile Strength (PET2)
Figure 6.11 Fabric Tensile Strength (PET4)
Figure 6.12 Fabric Tensile Strength (PTT)
Figure 6.13 Fabric Tensile Strength (Nylon 6)
Figure 6.14 Fabric Tensile Strength (PP)
6.2.2.3 Fabric Images and Orientation Distribution Function (ODF)

6.2.2.3.1 Fabric Images
When high pressure water jet is acted on fiberweb of PP fibers, there is standing water on the surface because of its hydrophobicity, which causes texture imperfection (Figure 6.15). It appears on 100 mesh with 6.21Mpa jet pressure or above and on 36 mesh with 7.58Mpa jet pressure or above. It does not appear on 14 mesh or 10 mesh because its high aperture wire. This phenomenon does not appear for all other four fiber types.

![Figure 6.15 Wrinkle on PP Fabric](image)

Forming wire has significant effect on fabric texture. Figure 6.16 (a)—(b) shows the examples of PET2 on 100 mesh and 10 mesh. Other types of fabrics have similar behaviors.
Figure 6.16 Fabric Images (PET2)

(a) PET2, 100 mesh, 3.45 MPa

(b) PET2, 10 mesh, 3.45 MPa
6.2.2.3.2 ODF
All five types of fibers have similar ODFs. Figure 6.17(a)–(d) show PET2 ODFs on four types of wires. ODFs for other four fiber types are shown in Appendix B.
Figure 6.17 ODF of PET2 Fabrics
6.3 Analysis of Results

6.3.1 Fabric Basis Weight
Results of Figures 6.1–6.5 show that forming wire type affects fabric basis weight significantly. The fabrics produced on lower aperture forming wire have higher fabric basis weight. High aperture forming wire has less number of knuckles and hence less number of entangled points are formed as compared to those forming wires with low aperture. Thus fabrics produced with high aperture can be more easily stretched than those produced on lower aperture forming wire. Also, high aperture wire has larger spaces between wires that allow fibers to bend around the forming wires during the hydroentanglement process than low aperture wire. When peeling off fabrics from the forming wire after each pass, higher force is needed for fabrics produced on high aperture forming wires than those on low aperture. This causes more stretch of fabrics produced on high aperture forming wires than those produced on low aperture forming wires.

After hydroentanglement, fabrics are first subjected to high-vacuum flat belt to remove additional water and reduce the drying load, and then dried at 109°C (228°F) in our experiment. To determine the effects of fiber type and forming wire on fabric dimensions and fabric basis weight, a set of trials were designed. Fiberweb samples from the five fiber types with dimensions 10 cm x 10 cm (MD x CD) were first marked, then hydroentangled with two passes on two types of forming wire (100 mesh and 10 mesh), water-extracted by high-vacuum flat belt, and finally dried. After each step, both MD and CD dimensions were measured and listed in Table 6.5. Sample areas after vacuum and drying are listed in Table 6.6.

Results of Table 6.5 and 6.6 further prove that low aperture wire (100 mesh) causes smaller stretch than high aperture wire (10 mesh). Among fabrics produced on 100 mesh wire, Nylon 6 fabric is the only one to show appreciable heat shrinkage. Three types of fabrics produced on 10 mesh wires, Nylon 6, PTT, and PET 4, show appreciable heat shrinkage. Nylon 6 fabrics show highest heat shrinkage. The balance between stretch and heat shrinkage decides the behavior of fabric basis weight.
Table 6.5 Fabric Dimensional Change in Hydroentanglement

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Wire Type</th>
<th>MD x CD Dimension (cm x cm)</th>
<th>Vacuum</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First Pass</td>
<td>Second Pass</td>
<td></td>
</tr>
<tr>
<td>PET 2</td>
<td>100 mesh</td>
<td>10.6 x 10.2</td>
<td>10.6 x 10.3</td>
<td>10.6 x 10.3</td>
</tr>
<tr>
<td></td>
<td>10 mesh</td>
<td>10.6 x 10.2</td>
<td>10.6 x 10.3</td>
<td>10.6 x 10.3</td>
</tr>
<tr>
<td>PET 4</td>
<td>100 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.2</td>
<td>10.3 x 10.2</td>
</tr>
<tr>
<td></td>
<td>10 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.2</td>
<td>10.3 x 10.2</td>
</tr>
<tr>
<td>PTT</td>
<td>100 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.2</td>
<td>10.3 x 10.2</td>
</tr>
<tr>
<td></td>
<td>10 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.2</td>
<td>10.3 x 10.2</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>100 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.1</td>
<td>10.3 x 10.1</td>
</tr>
<tr>
<td></td>
<td>10 mesh</td>
<td>10.5 x 10.1</td>
<td>10.4 x 10.1</td>
<td>10.3 x 10.1</td>
</tr>
<tr>
<td>PP</td>
<td>100 mesh</td>
<td>10.8 x 10</td>
<td>10.6 x 10.2</td>
<td>10.4 x 10.2</td>
</tr>
<tr>
<td></td>
<td>10 mesh</td>
<td>10.8 x 10</td>
<td>10.6 x 10.2</td>
<td>10.4 x 10.2</td>
</tr>
</tbody>
</table>

Table 6.6 Effect of Fiber Type and Forming Wire on Fabric Dimension

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Area (cm²)</th>
<th>Heat Shrinkage, %</th>
<th>Area (cm²)</th>
<th>Heat Shrinkage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 mesh</td>
<td>Vacuum Dry</td>
<td>10 mesh</td>
<td>Vacuum Dry</td>
</tr>
<tr>
<td>PET2</td>
<td>109</td>
<td>108</td>
<td>0.91</td>
<td>134</td>
</tr>
<tr>
<td>PET4</td>
<td>105</td>
<td>104</td>
<td>0.95</td>
<td>145</td>
</tr>
<tr>
<td>PTT</td>
<td>100</td>
<td>99</td>
<td>1.00</td>
<td>136</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>104</td>
<td>95</td>
<td>8.65</td>
<td>112</td>
</tr>
<tr>
<td>PP</td>
<td>106</td>
<td>105</td>
<td>0.94</td>
<td>135</td>
</tr>
</tbody>
</table>

Since the fabrics with original 10cm x 10 cm size (MD x CD) were stretched by peeling force when removing from forming wires, following analysis focus on correlation of fabric stretch ratio with fiber flexural rigidity. Fabric area ratio is defined as the ratio of hyroentangled fabric area (without drying) to original area (100cm²). The data is listed in Table 6.7 and regression line is shown in Figure 6.18.
Table 6.7 Effect of Fiber Flexural Rigidity on Fabric Stretch

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Flexural Rigidity (cN*mm²)</th>
<th>Fabric Area Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100 mesh</td>
</tr>
<tr>
<td>PET2</td>
<td>6.71</td>
<td>1.09</td>
</tr>
<tr>
<td>PET4</td>
<td>4.24</td>
<td>1.05</td>
</tr>
<tr>
<td>PTT</td>
<td>2.94</td>
<td>1.00</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>3.30</td>
<td>1.04</td>
</tr>
<tr>
<td>PP</td>
<td>5.83</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Figure 6.18 Effect of Flexural Rigidity on Fabric Stretch Ratio

Results show that fabric stretch ratio on 100 mesh increases almost linearly with fiber flexural rigidity. But the trend on 10 mesh is not clear.

The regression equations are:

100 mesh: \( Y = 0.0183X + 0.9638 \quad (R^2 = 0.8235) \)

10 mesh: \( Y = 0.0214X + 1.2254 \quad (R^2 = 0.0810) \)

Fibers with low flexural rigidity are easy to bend around each other and wires. When fiberwebs are hydroentangled on 100 mesh wire, spaces between wires are small and fibers mainly bend around each other. Hence fabrics made of fibers with low flexural rigidity have
tighter entangled knots and are less likely to stretch. When fiberwebs are processed on 10 mesh wire, fibers can easily bend not only around each other, but also around wires. Much higher force is needed to peeling fabrics from wires. Such fabrics undergo high stretch and hence their basis weigh is reduced.

6.3.2 Fabric Tensile Strength

According to theoretical analysis in Chapter 3, there are three possible force mechanisms in forming fabrics:

- **Flexural-Rigidity (FR) Mechanism:**

  \[ \Phi_{FR} = \frac{F_D}{<FR>} = \frac{0.99 \overline{L}_p d_f P_g}{<FR>} \]

  When it dominates, we would expect that: 1) Fabric tensile strength increases with increasing jet pressure, and 2) Increasing rate is proportional to \( d_f/<FR> \).

- **Friction Mechanism:**

  \[ \Phi_f = \frac{F_D}{F_f} = 6.08 \times 10^{-7} \frac{\overline{L}_p d_f}{\mu_w} \]

  When friction mechanism dominates, one can expect that jet pressure has no effect on forming unit cell. It is a function of fiber properties and wire parameters.

- **Stress-Strain (SS) Mechanism:**

  \[ \Phi_s = \frac{F_D}{F_s} = \frac{0.87 \overline{L}_p d_f P_g K_w}{RET} \]

  When stress-strain mechanism dominates, one can expect that: 1) Fabric properties increases with jet pressure, and 2) Increasing rate should be proportional to \( d_f/RET \) for certain forming wire.

To find out the governing mechanism, effect of jet pressure needs to be investigated first. If jet pressure has no effect on tensile strength, friction mechanism can be considered as governing mechanism. If jet pressure is proportional to tensile strength, fiber, wire, and nozzle properties need to be considered to tell which is governing mechanism, flexural-rigidity (FR) mechanism or stress-strain mechanism. Also, high jet pressure causes fabric
stretch and peeling force may lead fibers disentanglement. Hence, only jet pressure less than critical jet pressure was included in this analysis. Tensile strength is used as an indicator of degree of hydroentanglement.

6.3.2.1 Tensile Strength in MD on 100 Mesh

For jet pressure below the strength maximum pressure in Figure 6.6(a), the regression lines are shown in Figure 6.19 and regression parameters are shown in Table 6.8.

![Figure 6.19 Fabric Tensile Strength in MD on 100 Mesh (Regression)](image)

### Table 6.8 Regression Parameters (100 mesh, MD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (Tensile Potential, N/cm)</th>
<th>Slope, $b_1$ (Increasing Rate, N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>21.32</td>
<td>1.26</td>
<td>0.99</td>
</tr>
<tr>
<td>PET4</td>
<td>9.00</td>
<td>1.79</td>
<td>0.97</td>
</tr>
<tr>
<td>PTT</td>
<td>4.89</td>
<td>2.86</td>
<td>1.00</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>8.71</td>
<td>2.61</td>
<td>0.87</td>
</tr>
<tr>
<td>PP</td>
<td>1.29</td>
<td>1.64</td>
<td>0.88</td>
</tr>
</tbody>
</table>
For each fiber type, tensile strength in MD increases linear with jet pressure (Figure 6.19). Hence flexural rigidity and stress-strain mechanisms need to be checked. The correlation coefficients vary in range between 0.87-1.00, which shows good linear behavior (Table 6.8). Each fiber type shows different increasing rate (slope) and initial strength (if extended to zero) and this must depend on fiber properties.

From equation 3-32, if flexural rigidity mechanism dominates, increasing rate needs to be proportional to \( \frac{d_\theta}{<FR>} \) for certain forming wire, which was shown in Table 6.9. For stress-strain mechanism, definitions of unit cell are not clear (Figure 6.16 (a)) and we assume that unit cell diameter, \( R \), is constant for same wire type. Hence mechanism factor that affects increasing rate is \( \frac{d_\theta}{ET} \) for stress-strain mechanism and listed in Table 6.9. Regression curves are shown in Figure 6.20 and 6.21.

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>FR Factor, ( \frac{d_\theta}{&lt;FR&gt;} ) (x10^{-2}cN^{-1}*mm^{-1})</th>
<th>Stress-Strain Factor, ( \frac{d_\theta}{ET} ) (x10^{-4} mm/cN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>0.19</td>
<td>1.86</td>
</tr>
<tr>
<td>PET4</td>
<td>0.29</td>
<td>2.84</td>
</tr>
<tr>
<td>PTT</td>
<td>0.46</td>
<td>5.24</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>0.45</td>
<td>6.05</td>
</tr>
<tr>
<td>PP</td>
<td>0.27</td>
<td>4.05</td>
</tr>
</tbody>
</table>
Results of regression show that flexural rigidity is governing mechanism for tensile strength in MD on 100 mesh ($R^2 = 0.9915$) other than stress-strain mechanism ($R^2 = 0.7977$).
If the regression lines in Figure 6.19 extend to zero, they give the initial strength for each fiber type (intercepts in Table 6.8). The initial strength is called fabric tensile strength potential and its value may depend on fiber tensile strength and fiber-to-fiber friction. Table 6.1 lists 2% secant modulus and fiber-to-fiber friction and Figure 6.22 shows the effect of 2% secant modulus on fabric tensile strength potential. In general fibers with high 2% secant modulus have high initial tensile strength except PP because of its hydrophobicity. Fiber-to-fiber friction also plays important roles. Nylon 6 has lowest 2% secant modulus, but its tensile strength potential is higher PTT because of its highest fiber-to-fiber friction.

### 6.3.2.2 Tensile Strength in MD on 10 Mesh
Using the same procedure as 100 mesh, regression lines are shown in Figure 6.23 and regression parameters are shown in Table 6.10.
Figure 6.23 Fabric Tensile Strength in MD on 36 Mesh (Regression)

Table 6.10 Regression Parameters (10 mesh, MD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
<th>Coefficient of Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>14.38</td>
<td>0.08</td>
<td>0.42</td>
<td>0.40</td>
</tr>
<tr>
<td>PET4</td>
<td>13.93</td>
<td>-0.19</td>
<td>0.61</td>
<td>0.47</td>
</tr>
<tr>
<td>PTT</td>
<td>11.93</td>
<td>-0.16</td>
<td>0.29</td>
<td>0.47</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>17.93</td>
<td>-0.10</td>
<td>0.08</td>
<td>0.55</td>
</tr>
<tr>
<td>PP</td>
<td>4.22</td>
<td>0.18</td>
<td>0.88</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Results show that jet pressure has no effect on fabric tensile strength and fabric tensile strength keeps almost constant with increasing jet pressure. Hence, friction mechanism is the governing mechanism for fabric tensile strength in MD on 10 mesh. The fabric tensile strength potentials are shown in Figure 6.24. Coefficient of friction, which is listed in Table 6.10, plays more important roles on 10 mesh than on 100 mesh. Nylon 6 has the highest tensile strength because of its highest coefficient of friction. PP has the lowest tensile strength because of its hydrophobicity.
6.3.2.3 Tensile Strength in MD on 36 Mesh

Using the same procedure, regression lines are shown in Figure 6.25 and regression parameters are shown in Table 6.11.
Table 6.11 Regression Parameters (36 mesh, MD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>18.96</td>
<td>0.78</td>
<td>0.42</td>
</tr>
<tr>
<td>PET4</td>
<td>9.63</td>
<td>1.76</td>
<td>0.98</td>
</tr>
<tr>
<td>PTT</td>
<td>15.24</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>23.60</td>
<td>-0.16</td>
<td>0.30</td>
</tr>
<tr>
<td>PP</td>
<td>4.47</td>
<td>1.09</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Results show that jet pressure has no effect on fabrics made of PTT and Nylon 6 fibers, which have lowest flexural rigidities among five fiber types used. For three other types of fabrics, tensile strength increases linear with jet pressure. Using the same method as for 100 mesh, the regression results of flexural rigidity and stress-strain mechanisms are shown in Figure 6.26 and 6.27. Flexural rigidity mechanism has better regression result than stress-strain mechanism. Hence governing mechanism on 36 mesh is a transition between two mechanisms: friction mechanism and flexural rigidity mechanism. The imperfection of flexural rigidity mechanism regression should be caused by the mechanism transition.
6.3.2.4 Tensile Strength in MD on 14 Mesh
Regression results are shown in Figure 6.28 and Table 6.12.

![Graph showing stress-strain mechanism for 36 mesh](image)

**Figure 6.27 Stress-Strain Mechanism (36 mesh)**

![Graph showing tensile strength in MD on 14 mesh](image)

**Figure 6.28 Fabric Tensile Strength in MD on 14 Mesh (Regression)**
Table 6.12 Regression Parameters (14 mesh, MD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>12.36</td>
<td>0.44</td>
<td>0.90</td>
</tr>
<tr>
<td>PET4</td>
<td>10.21</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>PTT</td>
<td>11.77</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>18.00</td>
<td>-0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>PP</td>
<td>7.30</td>
<td>-0.18</td>
<td>0.33</td>
</tr>
</tbody>
</table>

It is still a transition period. Friction mechanism becomes governing mechanism for all fiber types except PET2 fabrics, which shows behavior of flexural rigidity mechanism.

6.3.2.5 Tensile Strength in CD on 100 Mesh

Figures 6.29 and Table 6.13 show the regression results. PTT fabrics show behavior of friction mechanism. Figures 6.30 and 6.31 test the mechanism for other four fiber types, neither flexural rigidity or stress-strain mechanism is applicable. Hence tensile strength in CD has different governing mechanism as tensile strength in MD on 100 mesh.

Figure 6.29 Tensile Strength in CD on 100 Mesh (Regression)
Table 6.13 Regression Parameters (100 mesh, CD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>18.16</td>
<td>2.26</td>
<td>0.85</td>
</tr>
<tr>
<td>PET4</td>
<td>21.85</td>
<td>2.07</td>
<td>0.94</td>
</tr>
<tr>
<td>PTT</td>
<td>16.66</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>15.38</td>
<td>4.29</td>
<td>0.66</td>
</tr>
<tr>
<td>PP</td>
<td>5.55</td>
<td>4.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>

$Y = 1.4654 + 6.3820X \quad (R^2 = 0.2374)$

Figure 6.30 FR Mechanism in CD (100 Mesh)
6.3.2.6 Tensile Strength in CD on 36 Mesh, 14 Mesh, and 10 Mesh

Regression lines and parameters are shown in Figure 6.32—6.34 and Table 6.14 – 6.16. In general friction mechanism is the governing mechanism. Because of its hydrophobicity, PP shows different behaviors on 36 mesh and 14 mesh. The small variation can be explained by experimental errors. It further proves that governing mechanism in CD on 100 mesh is a combination of friction mechanism and other factors such as peeling force and experimental errors.
Table 6.14 Regression Parameters (36 mesh, CD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>23.07</td>
<td>-0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>PET4</td>
<td>22.45</td>
<td>0.70</td>
<td>0.74</td>
</tr>
<tr>
<td>PTT</td>
<td>16.31</td>
<td>-0.18</td>
<td>0.35</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>31.34</td>
<td>-0.65</td>
<td>0.28</td>
</tr>
<tr>
<td>PP</td>
<td>21.45</td>
<td>1.20</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Figure 6.32 Tensile Strength in CD on 36 Mesh (Regression)
Figure 6.33 Tensile Strength in CD on 14 Mesh (Regression)

Table 6.15 Regression Parameters (14 mesh, CD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>21.65</td>
<td>-0.32</td>
<td>0.21</td>
</tr>
<tr>
<td>PET4</td>
<td>16.08</td>
<td>0.65</td>
<td>0.31</td>
</tr>
<tr>
<td>PTT</td>
<td>14.37</td>
<td>-0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>30.66</td>
<td>-0.59</td>
<td>0.70</td>
</tr>
<tr>
<td>PP</td>
<td>26.57</td>
<td>-1.56</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Figure 6.34 Tensile Strength in CD on 10 Mesh (Regression)

Table 6.16 Regression Parameters (10 mesh, CD)

<table>
<thead>
<tr>
<th>Polymer Type</th>
<th>Intercept, $b_0$ (N/cm)</th>
<th>Slope, $b_1$ (N/cm/Mpa)</th>
<th>Correlation Coefficient, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET2</td>
<td>14.41</td>
<td>0.95</td>
<td>0.49</td>
</tr>
<tr>
<td>PET4</td>
<td>16.26</td>
<td>0.04</td>
<td>0.19</td>
</tr>
<tr>
<td>PTT</td>
<td>12.81</td>
<td>-0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>25.38</td>
<td>-0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>PP</td>
<td>20.07</td>
<td>-0.49</td>
<td>0.23</td>
</tr>
</tbody>
</table>
6.3.3 ODF

The fiber orientation distribution functions (ODF) of PET2 fabrics are shown in Figure 6.17. ODF depends heavily on forming wire type. Fabrics produced on high aperture forming wire (14 mesh and 10 mesh) have similar ODFs. It is also the case for low aperture forming wire (36 mesh and 100 mesh). Although just fiber ODFs of PET2 fabrics are shown in Figure 6.17, those four other fabrics (PET4, PTT, Nylon 6 and PP) have similar fiber ODFs (Appendix B).

There are three domain angles on the ODF curve of fabrics produced on 10 and 14 mesh: one primary peak (90 degree), and two secondary peaks (around 20 and 160 degree). The primary peak is in MD and caused by peeling force in MD. Those two secondary peaks originate from fiberweb which has bi-modal ODF (domain angles: around 20 and 160 degree). These two secondary peaks disappear on the curve of 36 and 100 mesh. When fabrics are produced on high aperture forming wires, fibers bend around forming wire, conform tightly to forming wire geometry, and form apertures in fabrics, hence keep certain degree of fiberweb structure unchanged. In the process of detachment from forming wire, it can be distorted but finally recover from distortion. It is not the case for low aperture forming wire. During hydroentanglement, fibers mainly bend around with each other and are pushed into wire apertures for low aperture wires. When peeling from wire, peeling force changes ODF permanently, hence causes just one domain angle in machine direction. Figures 6.16 (a)–(d) show the fabric conformation on 10 and 14 mesh and unclear aperture definition on 36 and 100 mesh.

Jet pressure has significant effect on ODF and the effect varies with forming wire type. For fabrics produced on high aperture wire, frequency in MD decreases with increasing jet pressure (Figure 6.17 (b)). It is opposite for fabrics produced on low aperture wires, which has increasing frequency in MD with increasing jet pressure. High jet pressure leads to high drag force, which causes fibers conform tightly to high aperture wires and also high peeling force. On high aperture wire, fiber conformation is dominant than stretch by peeling force,
hence causes low frequency in MD with high jet pressure. On low aperture wire, high peeling force caused by high-pressure jet stretches fabrics in MD and leads to high frequency in MD.

6.3.4 Fabric Tensile Energy
Theoretical analysis in chapter 3 shows that absorbed energy is very small and most jet energy is lost. Figure 6.35 shows the calculation of fabric tensile energy, which is the area under fabric stress-strain curve. For the samples with dimension 2.54cm x 20.32cm, figure 6.36 shows the effect of jet pressure on fabric tensile energy. Fabric tensile energy increases at low pressure, and reaches critical point quickly and then levels off. Since the tensile energy in figure 6.35 is for a sample size (2.54cm x 20.32cm), the tensile energy (TE) for 1kg sample can be calculated and divided by actual specific energy (SE). Hence, the ratios of TE/SE for different fiber types and jet pressures can be calculated. The results are shown in Table 6.17.
Although the tensile energy does not represent the absorbed energy, it is helpful to understand the energy absorption. It shows that absorbed portion of energy decreases with increasing specific energy (jet pressure). For all fiber types, the percentage of TE/SE is less than 0.40%. The results agree well with modeling calculation in Chapter 3. Even if we consider that sample size between two clamps in testing is 2.54 cm x 7.62 cm, the absorbed portion is still small. The efficiency of energy delivered from water jet to fabric is very small, and most energy is lost. It agrees well with modeling calculation.

**Table 6.17 Percentage of TE/SE**

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Percentage of Tensile Energy to Specific Energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.45MPa</td>
</tr>
<tr>
<td>PET2</td>
<td>0.17</td>
</tr>
<tr>
<td>PET4</td>
<td>0.21</td>
</tr>
<tr>
<td>PTT</td>
<td>0.21</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>0.36</td>
</tr>
<tr>
<td>PP</td>
<td>0.12</td>
</tr>
</tbody>
</table>
7 CONCLUSION AND RECOMMENDATION

A physical model was developed using the unit cell concept. Unit cells describe the stretches which are developed in the fabric. There are two ways to analyze the formation of unit cells: by force or energy. Drag force and water jet specific energy are the only factors driving unit cell formation in fabrics. In order to form unit cells, three factors need to be overcome: fiber flexural rigidity, fiber-to-fiber friction, and stress-strain force. Hence energy is consumed in three possible processes.

First, the energy mechanism is considered. Three energy components, namely fiber bending energy, fiber-to-fiber friction, and fiber strain energy are considered. Calculation using the “unit cell” model show:

- Energy consumed by all three factors (flexural rigidity, fiber-to-fiber friction, and stress-strain work) is very small;
- The efficiency of energy delivered from water jet to fabric is very small (less than 1.18% for PET fiber);
- Most energy is lost.

Since energy is not the governing mechanism, force mechanism must be studied. Three resisting forces must be overcome to form fabric texture or “aperture holes”. These three resisting forces lead to three force mechanisms:

- Flexural-rigidity (FR)
- Friction
- Stress-Strain

Before a series of experiments designed to determine the governing mechanism and effect of fiber type, forming wire type, and jet parameters on fabric performance, preliminary experiments were designed to determine optimum process variables such as vacuum levels, line speed, and number of passes. Results of preliminary experiments showed that too many hydroentanglement passes changed the fiber orientation in the fabric and increasing number of passes adversely affects fabric strength. It is recommended then that the number of passes be kept low in general and must be constant for fair comparison. Specific energy can be
altered by jet pressure, number of manifold, and line speed. However, the number of passes should always be held constant. Line speed was set at 6.1 m/min (20 feet/min) because of the limitation of the machine used.

Five fiber types with a broad range of bending, friction, and stress-strain behaviors were chosen to be hydroentangled on four forming wires to determine the governing force mechanism and the effect of fiber type, forming wire geometry, and jet pressure on fabric performance. Fiber properties, wire geometry, and fabric properties were measured to correlate these properties. The following conclusions can be drawn:

- Fabrics produced on low aperture forming wire have higher normalized tensile strength.
- MD fabric tensile strength is determined
  - By flexural rigidity when fine forming wire (100 mesh) is used;
  - By friction with coarse mesh (10);
  - By a combination of both with intermediate screens (36 mesh and 14 mesh).
- CD tensile strength is generally governed by the friction mechanism.
- Fabric tensile strength potential is a function of fiber modulus and friction.
- Fabrics produced on 10 and 14 mesh have tri-modal orientation distribution function (ODF) and those produced on 36 mesh and 100 mesh have uni-modal because of wire geometry.
- Ratios of fabric tensile energy to input energy is very small. Efficiency of energy delivery is low, and most energy is lost.

Recommended areas for future study are:

- Interaction between water jet and forming wire. For example, jet behavior after rebounding from wire knuckles.
- Wire vibration and movement in the hydroentanglement process.
- Other wire parameters, such as crimp.
- Understanding the energy loss or waste. From our model, most of jet energy is lost and improvement of energy efficiency may save energy significantly.
8 REFERENCES


3. ASTM D 3776-96

4. ASTM D 5035-95 (strip method).

5. ASTM D 5587-96

6. ASTM D 3884-92


Appendix A: Fiber Stress-Strain Data

Table 1 Stress-Strain Data for PET1

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.72</td>
<td>0.12</td>
<td>5.65</td>
</tr>
<tr>
<td>4</td>
<td>1.02</td>
<td>0.13</td>
<td>16.51</td>
</tr>
<tr>
<td>6</td>
<td>1.27</td>
<td>0.24</td>
<td>12.50</td>
</tr>
<tr>
<td>8</td>
<td>1.63</td>
<td>0.40</td>
<td>18.60</td>
</tr>
<tr>
<td>10</td>
<td>2.06</td>
<td>0.57</td>
<td>24.60</td>
</tr>
<tr>
<td>15</td>
<td>2.84</td>
<td>0.66</td>
<td>27.45</td>
</tr>
<tr>
<td>20</td>
<td>3.27</td>
<td>0.57</td>
<td>23.06</td>
</tr>
<tr>
<td>25</td>
<td>3.55</td>
<td>0.50</td>
<td>17.49</td>
</tr>
<tr>
<td>30</td>
<td>3.71</td>
<td>0.50</td>
<td>14.02</td>
</tr>
<tr>
<td>35</td>
<td>3.87</td>
<td>0.45</td>
<td>13.39</td>
</tr>
<tr>
<td>54.94</td>
<td>4.25</td>
<td>0.24</td>
<td>11.68</td>
</tr>
</tbody>
</table>

Table 2 Stress-Strain Data for PET2

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.78</td>
<td>0.12</td>
<td>15.64</td>
</tr>
<tr>
<td>4</td>
<td>1.24</td>
<td>0.14</td>
<td>11.39</td>
</tr>
<tr>
<td>6</td>
<td>1.80</td>
<td>0.27</td>
<td>14.9</td>
</tr>
<tr>
<td>8</td>
<td>2.62</td>
<td>0.41</td>
<td>15.49</td>
</tr>
<tr>
<td>10</td>
<td>3.46</td>
<td>0.46</td>
<td>13.39</td>
</tr>
<tr>
<td>15</td>
<td>4.38</td>
<td>0.43</td>
<td>9.74</td>
</tr>
<tr>
<td>20</td>
<td>4.76</td>
<td>0.40</td>
<td>8.35</td>
</tr>
<tr>
<td>25</td>
<td>4.91</td>
<td>0.29</td>
<td>5.92</td>
</tr>
<tr>
<td>30</td>
<td>4.93</td>
<td>0.23</td>
<td>4.71</td>
</tr>
<tr>
<td>33.3</td>
<td>5.04</td>
<td>0.30</td>
<td>5.95</td>
</tr>
</tbody>
</table>

Table 3 Stress-Strain Data for PET3

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.56</td>
<td>0.18</td>
<td>31.09</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
<td>0.17</td>
<td>19.33</td>
</tr>
<tr>
<td>6</td>
<td>1.07</td>
<td>0.21</td>
<td>19.95</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
<td>0.35</td>
<td>27.62</td>
</tr>
<tr>
<td>10</td>
<td>1.54</td>
<td>0.50</td>
<td>32.64</td>
</tr>
<tr>
<td>15</td>
<td>2.29</td>
<td>0.53</td>
<td>22.92</td>
</tr>
<tr>
<td>20</td>
<td>2.74</td>
<td>0.35</td>
<td>12.87</td>
</tr>
<tr>
<td>25</td>
<td>2.93</td>
<td>0.32</td>
<td>11.00</td>
</tr>
<tr>
<td>30</td>
<td>3.08</td>
<td>0.32</td>
<td>10.39</td>
</tr>
<tr>
<td>35</td>
<td>3.22</td>
<td>0.29</td>
<td>9.02</td>
</tr>
<tr>
<td>46.9</td>
<td>3.51</td>
<td>0.44</td>
<td>12.54</td>
</tr>
</tbody>
</table>
Table 4 Stress-Strain Data for PET4

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.52</td>
<td>0.14</td>
<td>27.42</td>
</tr>
<tr>
<td>4</td>
<td>0.88</td>
<td>0.14</td>
<td>15.64</td>
</tr>
<tr>
<td>6</td>
<td>1.03</td>
<td>0.09</td>
<td>8.87</td>
</tr>
<tr>
<td>8</td>
<td>1.12</td>
<td>0.08</td>
<td>6.69</td>
</tr>
<tr>
<td>10</td>
<td>1.21</td>
<td>0.09</td>
<td>7.23</td>
</tr>
<tr>
<td>15</td>
<td>1.61</td>
<td>0.20</td>
<td>12.32</td>
</tr>
<tr>
<td>20</td>
<td>2.45</td>
<td>0.48</td>
<td>19.50</td>
</tr>
<tr>
<td>25</td>
<td>3.66</td>
<td>0.73</td>
<td>19.96</td>
</tr>
<tr>
<td>30</td>
<td>4.44</td>
<td>0.69</td>
<td>15.46</td>
</tr>
<tr>
<td>35</td>
<td>4.77</td>
<td>0.59</td>
<td>12.28</td>
</tr>
<tr>
<td>46.3</td>
<td>5.00</td>
<td>0.59</td>
<td>11.70</td>
</tr>
</tbody>
</table>

Table 5 Stress-Strain Data for PTT

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.27</td>
<td>0.06</td>
<td>23.09</td>
</tr>
<tr>
<td>4</td>
<td>0.46</td>
<td>0.06</td>
<td>13.40</td>
</tr>
<tr>
<td>6</td>
<td>0.56</td>
<td>0.04</td>
<td>6.98</td>
</tr>
<tr>
<td>8</td>
<td>0.62</td>
<td>0.04</td>
<td>5.64</td>
</tr>
<tr>
<td>10</td>
<td>0.68</td>
<td>0.04</td>
<td>6.27</td>
</tr>
<tr>
<td>15</td>
<td>0.85</td>
<td>0.07</td>
<td>8.16</td>
</tr>
<tr>
<td>20</td>
<td>1.10</td>
<td>0.12</td>
<td>11.08</td>
</tr>
<tr>
<td>25</td>
<td>1.40</td>
<td>0.19</td>
<td>13.82</td>
</tr>
<tr>
<td>30</td>
<td>1.63</td>
<td>0.26</td>
<td>16.03</td>
</tr>
<tr>
<td>35</td>
<td>1.72</td>
<td>0.29</td>
<td>16.60</td>
</tr>
<tr>
<td>57.5</td>
<td>2.08</td>
<td>0.55</td>
<td>26.62</td>
</tr>
</tbody>
</table>

Table 6 Stress-Strain Data for Nylon 6

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.07</td>
<td>26.75</td>
</tr>
<tr>
<td>4</td>
<td>0.41</td>
<td>0.07</td>
<td>16.67</td>
</tr>
<tr>
<td>6</td>
<td>0.49</td>
<td>0.05</td>
<td>11.06</td>
</tr>
<tr>
<td>8</td>
<td>0.57</td>
<td>0.07</td>
<td>11.40</td>
</tr>
<tr>
<td>10</td>
<td>0.65</td>
<td>0.08</td>
<td>12.78</td>
</tr>
<tr>
<td>15</td>
<td>0.92</td>
<td>0.16</td>
<td>16.91</td>
</tr>
<tr>
<td>20</td>
<td>1.26</td>
<td>0.25</td>
<td>20.2</td>
</tr>
<tr>
<td>25</td>
<td>1.70</td>
<td>0.42</td>
<td>24.72</td>
</tr>
<tr>
<td>30</td>
<td>2.24</td>
<td>0.61</td>
<td>27.19</td>
</tr>
<tr>
<td>35</td>
<td>2.73</td>
<td>0.66</td>
<td>24.21</td>
</tr>
<tr>
<td>67.5</td>
<td>4.04</td>
<td>0.66</td>
<td>16.51</td>
</tr>
</tbody>
</table>
Table 7 Stress-Strain Data for Nylon 6,6

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Stress (cN/dtex)</th>
<th>stdv</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.35</td>
<td>0.08</td>
<td>21.59</td>
</tr>
<tr>
<td>4</td>
<td>0.52</td>
<td>0.06</td>
<td>11.91</td>
</tr>
<tr>
<td>6</td>
<td>0.61</td>
<td>0.05</td>
<td>8.41</td>
</tr>
<tr>
<td>8</td>
<td>0.71</td>
<td>0.07</td>
<td>9.45</td>
</tr>
<tr>
<td>10</td>
<td>0.83</td>
<td>0.09</td>
<td>10.52</td>
</tr>
<tr>
<td>15</td>
<td>1.21</td>
<td>0.15</td>
<td>12.43</td>
</tr>
<tr>
<td>20</td>
<td>1.70</td>
<td>0.26</td>
<td>15.02</td>
</tr>
<tr>
<td>25</td>
<td>2.32</td>
<td>0.40</td>
<td>17.21</td>
</tr>
<tr>
<td>30</td>
<td>2.85</td>
<td>0.43</td>
<td>15.15</td>
</tr>
<tr>
<td>35</td>
<td>3.12</td>
<td>0.41</td>
<td>13.04</td>
</tr>
<tr>
<td>100.7</td>
<td>4.66</td>
<td>0.33</td>
<td>7.12</td>
</tr>
</tbody>
</table>

Table 8 Stress-Strain Data for PP

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress (cN/dtex)</th>
<th>stdv</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.44</td>
<td>0.10</td>
<td>22.11</td>
</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td>0.14</td>
<td>18.27</td>
</tr>
<tr>
<td>6</td>
<td>1.02</td>
<td>0.18</td>
<td>17.52</td>
</tr>
<tr>
<td>8</td>
<td>1.27</td>
<td>0.21</td>
<td>16.65</td>
</tr>
<tr>
<td>10</td>
<td>1.48</td>
<td>0.23</td>
<td>15.53</td>
</tr>
<tr>
<td>15</td>
<td>1.91</td>
<td>0.26</td>
<td>13.49</td>
</tr>
<tr>
<td>20</td>
<td>2.19</td>
<td>0.26</td>
<td>12.23</td>
</tr>
<tr>
<td>25</td>
<td>2.38</td>
<td>0.26</td>
<td>10.89</td>
</tr>
<tr>
<td>30</td>
<td>2.43</td>
<td>0.23</td>
<td>9.46</td>
</tr>
<tr>
<td>35</td>
<td>2.42</td>
<td>0.21</td>
<td>8.85</td>
</tr>
<tr>
<td>171.0</td>
<td>2.76</td>
<td>0.20</td>
<td>7.34</td>
</tr>
</tbody>
</table>
Appendix B: Orientation Distribution Function (ODF)

PET4, 10 mesh

Orientation Angle (degree)

Frequency (%)

PET4, 14 mesh

Orientation Angle (degree)

Frequency (%)

(a) 10 mesh

(b) 14 mesh
Figure 1 ODF of PET4 Fabrics
Figure II ODF of PTT Fabrics

(c) 36 mesh

(d) 100 mesh
Nylon 6, 10 mesh

Orientation Angle (degree)

Frequency (%)

3.45 MPa
4.83 MPa
6.21 MPa
8.96 MPa

(a) 10 mesh

Nylon 6, 14 mesh

Orientation Angle (degree)

Frequency

3.45 MPa
4.83 MPa
6.21 MPa
7.58 MPa
8.96 MPa

(b) 14 mesh
Figure III ODF of Nylon 6 Fabrics
Figure IV ODF of PP Fabrics