

ABSTRACT

XIANG, PING. Numerical Modeling and Experimental Investigation of the Hydroentanglement Process. (Under the direction of Dr. Andrey V. Kuznetsov and Dr. Abdel-Fattah M. Seyam.)

The purpose of this research is to investigate the hydroentanglement process. In this process, a fiberweb composed of initially loose fibers, which is supported by forming wires, continuously passes under several manifolds of multiple high-pressure fine water jets. The impact of the jets causes fiber entanglement in the fiberweb and produces a high-quality nonwoven fabric. A theoretical model of the hydroentanglement process is developed. The fiberweb is modeled as a porous layer, and the realistic geometry of the forming wires is accounted for. The model is based on the assumption that the degree of fiber entanglement and, consequently, the strength of the fabric are proportional to the average water vorticity in the fiberweb. This assumption is validated by comparing modeling results with experimental data. The model is used to investigate the effect of the process parameters on the fiber entanglement. The investigated process parameters include the water jet diameter, jet pressure, and jet count, the fiberweb thickness and permeability, and the forming wires geometry. The model is also used for revealing the optimal parameters to manufacture fabrics with high degree of entanglement and performance while minimizing the energy consumption.

The peeling force required for the separation of the hydroentangled fabric from the forming wires is also investigated experimentally and numerically. 3D simulations of water jets passing through the fiberweb and forming wires are performed to predict fibers behavior close to the forming belt. Experimental measurements of the peeling force are also

performed, based on which a mathematical model for the peeling force prediction is developed. The effect of the fiberweb thickness on the entanglement of fibers around the forming wires and their entrapment in the knuckles is investigated. The effect of the forming belt geometry on the peeling force is also analyzed.

NUMERICAL MODELING AND EXPERIMENTAL INVESTIGATION OF THE HYDROENTANGLEMENT PROCESS

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1 INTRODUCTION

1.1 INTRODUCTION TO NONWOVENS

In textile industry, nonwoven industry is organized differently and separately from the traditional woven or knitting industry. Nonwovens are engineered fabrics, and have higher production rate, larger availability, and lower cost than traditional woven and knitting fabrics. So in many industries nonwoven fabrics are replacing the traditional fabrics.

Today's nonwovens are highly engineered solutions made up of a variety of materials including fibers, powders, particles, adhesive, films and other materials that provide a multitude of functionalities, such as hospital supplies, hygiene applications, horticultural applications, consumer products, interlinings, geotextiles, carpet backings, automotive parts, filters, wipes, etc. Applications of nonwoven fabrics are still growing [1].

The steps for producing nonwoven fabrics include: web formation, web entanglement, web drying and optional further treatments. Fibers or polymers are first processed to form webs. There are several processes to produce webs, such as dry-laid, wet-laid, air-laid, sponbonding, and melt-blowing process. Then webs are bonded to produce nonwoven fabric through the bonding processes, such as needle punching, hydroentangling, thermal, chemical and adhesive bonding. Figure 1.1 shows the typical flow chart in producing nonwoven fabrics [1].

1.2 HYDROENTANGLEMENT PROCESS AND MACHINE COMPONENTS

Hydroentanglement is a mechanical bonding process designed to produce nonwoven fabrics with texture and appearance that resemble woven and knitted fabrics. In a typical hydroentanglement process, a row or multiple rows of highly pressurized, fine, closely spaced water jets impinge on a fiberweb which is supported by forming wires (Figure 1.3). Due to the impact of water jets, fibers from the surface are inserted into the fibrous web, and fibers are displaced and rotated around other fibers that surround them, resulting in fibers twisting and entangling around the neighboring fibers. The fabric produced is held together by the fiber-to-fiber friction [2, 3].

It has been over forty years since the hydroentangling technology was developed [4-7]. In the early 1950's Chicopee developed the basic concept of hydroentangling technology using a low energy patterning process. In 1968 the technology for high energy entangling and patterning processes of fibers was established by Dupont researchers. Using proprietary high speed web forming and hydraulic needling technology, DuPont started the first high energy hydroentangled plant in 1974. Since the 1990's, the technology has been made more efficient and affordable for more manufacturers [5]. Currently there are 110 hydroentanglement plants in production worldwide and additional lines are scheduled to start up [8].

In the nonwovens industry, the hydroentanglement process is the fastest growing technology. It is estimated that approximately 12% of nonwovens produced in the world are made through a hydro-entanglement process [8], and the hydroentanglement is increasing with a growth rate of 20% per year, while that for the nonwovens industry is 7-8% [9].

There are many different hydraulic 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 [10, 11]. No matter how the hydroentangling systems may change from one manufacturer to another, the entanglement of fiberweb requires: web supporting substrate, water jet nozzles, water extraction, and water circulation and filtration [12, 13]. The schematic of hydroentanglement bonding technology is shown in Figure 1.2. The cross-section of the hydroentanglement zone is shown in Figure 1.3 [14].

Fibers are carded in the carding machine and entangled in the hydroentangling unit. After hydroentanglement, the water in the fabrics are removed through the drying process. There is a finishing process if desired, and the fabrics are then wound on rolls for future processing.

1.3 FEATURES AND BENEFITS OF HYDROENTANGLEMENT

The hydroentanglement process yields the most textile-like product of any of the current processes for producing nonwoven fabrics. Figure 1.4 shows the picture of a hydroentangled fabric which has similar structure and comfort as woven fabrics. Hydroentanglement holds the promise of delivering a soft feel and comfort with a hand similar to those of woven and knits at the economics of nonwovens. Hydroentangled fabrics have the following characteristics [5]:

- ♦ 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

Hydroentangled nonwovens, depending upon the fibers processed, are strong, soft and pliable and can be dense or open and are typically absorbent. So they are mostly used for fine fiber webs intended for the medical, personal care, baby care and consumer and hygiene markets.

1.4 PREVIOUS RESEARCH IN HYDROENTANGLEMENT PROCESS

Although many papers on the hydroentanglement process and products are published in trade journals [15-20], there are very few papers published in the open literature in the area of impact of processing parameters on the hydroentanglement efficiency and fabric properties. This may be because the information of hydroentangled fabric producers is highly proprietary.

Research on technology for hydroentanglement products and process parameters is conducted to achieve improved jet injector, better web forming system and fibre composition, piping and vacuum system design, and efficient high pressure pumping system [21].

Ghassemieh et al. [22] used the velocity coefficient C_v and discharge coefficient C_d to describe the fluid flow behaviors from an orifice. The effect of cone angle on the discharge and velocity coefficients was investigated in [22]. Begenir et al [23, 24] designed experiment to measure discharge coefficient and breaking length of water jets. Three nozzle geometries, so-called cone-up, cone-down, and cylindrical, are examined at different jet pressures. The effect of the nozzle geometry on the water jet breakup and impact force in the hydroentanglement process was investigated experimentally and numerically in [25, 26]. The cavitation and hydraulic flip inside hydroentanglement nozzles were also studied in [27, 28].

Effects of the initial fiberweb geometry and pressure distribution between different manifolds of water jets on the properties of hydroentangled fabric were studied experimentally in [29]. The experimental investigation of the effect of fiberweb and fiber properties on the critical water jet pressure and energy consumption was presented in [30].

The fiber orientation and fiber length distribution in hydroentangled fabrics were evaluated in [31] by analyzing two-dimensional SEM images. The relationships between the microstructural variables and fabric mechanical properties (strength and modulus), which were used to estimate the degree of entanglement in hydroentangled fabrics, were also analyzed. The structure-process-property relationships in hydroentangled nonwovens were developed through experimental studies reported in [32].

Research and development work was also focused on saving the energy consumption in this process. Improving the injector, developing an efficient high pressure pumping system, better fiber composition and web forming method, as well as designing improved piping and vacuum system were all used to reduce energy consumption [21].

The development of texture during hydroentanglement was examined in [33] as a function of hydroentangling energy. Research reported in [5] showed that hydroentanglement can be combined with other bonding processes, such as chemical, thermal or hydrogen, to improve fabric properties and reduce the amount of hydraulic energy required.

1.5 DISSERTATION STRUCTURE

The organization of this dissertation involves a total of six chapters. The present chapter provides a general introduction to the nonwoven fabrics and nonwoven industry, hydroentanglement process and machine, hydroentangled fabrics, and previous research on hydroentangling technology, as well as the structure of the dissertation itself.

Chapter 2 (published as ref. [34]) develops a model of the hydroentanglement process, which is based on the first principles of fluid mechanics. The fiberweb and forming wires are modeled as two different layers of porous medium. This model proceeds from the assumption that fiber entanglement in the hydroentanglement process is proportional to the average vorticity in the fiberweb. 2D simulations of the water flow through fiberweb and forming surfaces are performed in the plane perpendicular to the machine direction (MD). 3D simulations are also performed to account for the realistic geometry of the computational domain. The influence of the forming surface permeability is investigated.

Chapter 3 (published as ref. [35]) furthers the modeling study in Chapter 2. The fiberweb is modeled as a porous layer, and the realistic structure of the forming wires are accounted for. The model accounts for the water ricochet by the wires, so there is a thin

fluid layer above the porous fiberweb layer due to the water reflection. Numerical simulations are performed to study the water flow field and the vorticity in the fiberweb. The effects of the thickness of the porous fiberweb layer, its permeability, and the inlet water jet velocity on the degree of fiber entanglement are investigated.

Chapter 4 (published as ref. [36]) performed experimental and numerical investigation of the effects of the jet pressure and forming belt geometry on fiber entanglement. Extensive comparisons of simulations with experimental data are reported and analyzed to give a clear understanding of the effect of fiberweb and forming belt properties on the critical jet pressure. The modeling results are in good correlation with experimental data for a wide range of jet pressures, which validate the assumption that fiber entanglement in the hydroentanglement process is proportional to the average vorticity in the fiberweb. The effect of the jet count per unit length on the degree of fiber entanglement is investigated as well.

Chapter 5 (published as ref. [37]) experimentally measured the peeling force required for separating hydroentangled fabrics from the forming wires. Numerical simulations of the hydroentanglement process are also carried out to predict the probability of fibers to be pushed in the knuckles of the forming wires. By correlating experimental results with simulations, a mathematical model, which is based on simulating average vorticity around the forming wires, is developed to predict the peeling force. The effect of the thickness of the fiberweb layer on the peeling force is investigated as well.

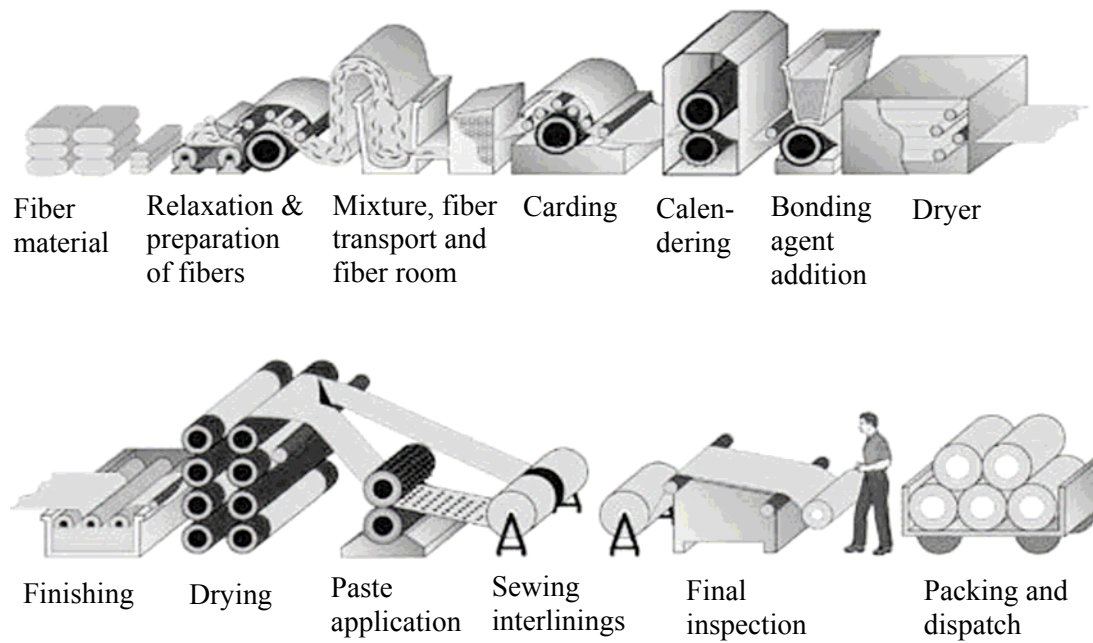


Figure 1.1 Typical process in producing nonwoven fabrics.

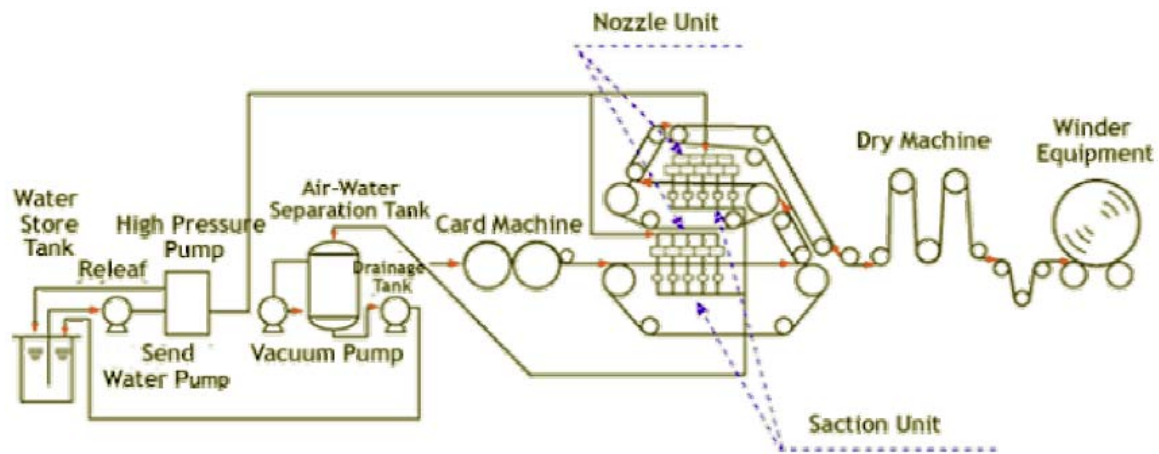


Figure 1.2 Schematic of Spunlace Flow Sheet (Courtesy of Kasen Nozzle).

http://www.kasen.co.jp/e-kasen/seihin/fusyoku/fsyo_f7/seih_fu_7_2.html

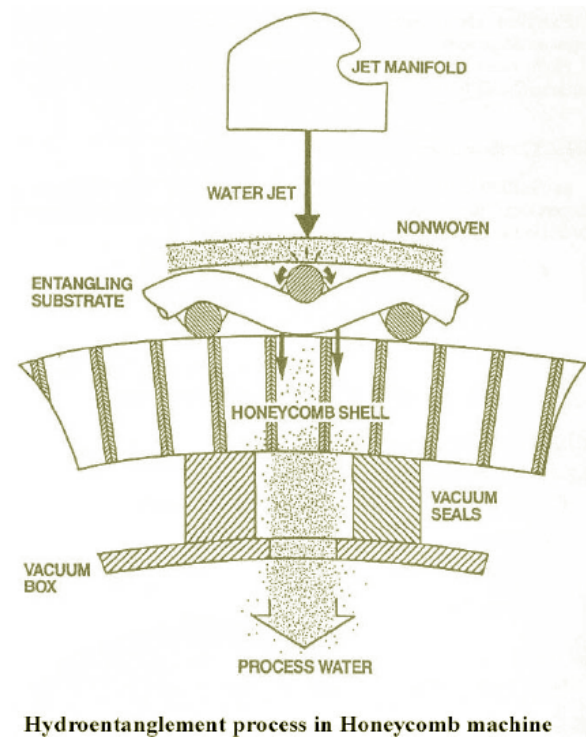


Figure 1.3 Cross-section of Hydroentanglement Unit.

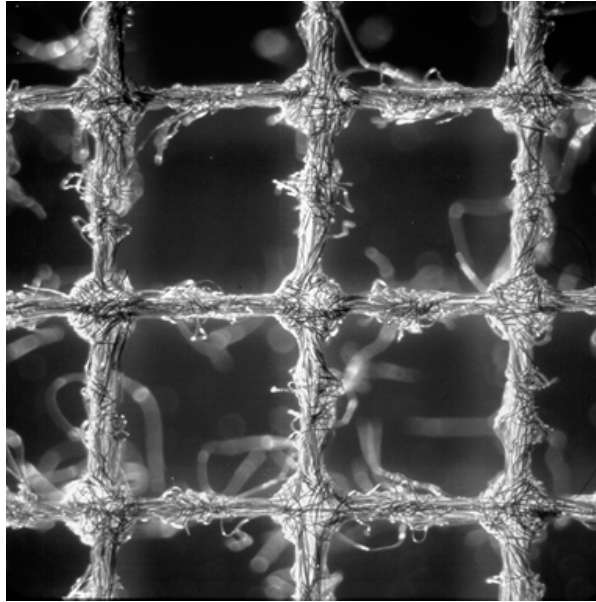


Figure 1.4 Hydroentangled fabric with similar structure and comfort as woven fabrics.

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2 SIMULATION OF FIBER ENTANGLEMENT BY MODELING VORTICITY IN WATER FLOW FIELD

ABSTRACT

This chapter develops a model of the hydroentanglement process, which is based on the first principles of fluid mechanics. This model proceeds from the assumption that fiber entanglement in the hydroentanglement process is proportional to the average vorticity in the fiberweb. 2D simulations of the water flow through fiberweb and forming surfaces are performed in the plane perpendicular to the machine direction (MD). In these 2D simulations, the time-dependent development of the flow field is investigated, and it is found that the vortices induced by the water jets are influenced by the jet pressure and diameter. It is shown that the maximum average vorticity in the fiberweb occurs at a water jet diameter of 0.127 mm which explains why jets of such diameter are commonly used in industry. 3D simulations are also performed to account for the realistic geometry of the computational domain. The influence of the forming surface permeability is investigated. It is shown that the fiber entanglement increases as the open area of the forming surface decreases.

Nomenclature

A	area of the outflow boundary, m^2
b_0	reference length used in simulations (10% of empirical inlet water jet diameter in hydroentanglement process), m

c_F	Forchheimer coefficient
D_j	water jet diameter, m
h_1	thickness of the thin fluid layer above the fiberweb, m
h_2	thickness of the fiberweb, m
K	permeability of the matrix composed by the fiberweb or forming wires, m ²
p	water jet pressure, Pa
Q	volume flow rate, m ³ /s
Ri	Ricochet parameter
t	time, s
U_0	inlet water jet velocity, m/s
u, v, w	water filtration velocities in the x -, y -, and z -directions, m/s
V	volume of the porous fiberweb layer within the computational domain, m ³
x, y, z	Cartesian coordinate
X_L, Y_L, Z_L	length of the computational domain in the x -, y -, and z -directions, m

Greek symbols

ε	dissipation rate of turbulence kinetic energy, m ² /s ³
ε_0	inlet dissipation rate, m ² /s ³
k	turbulence kinetic energy, m ² /s ²

k_0	inlet turbulence kinetic energy, m^2/s^2
μ	dynamic viscosity of water, $\text{kg}/(\text{m}\cdot\text{s})$
μ_t	turbulent viscosity, $\text{kg}/(\text{m}\cdot\text{s})$
ν	kinematic viscosity of water, m^2/s
ρ	water density, kg/m^3
ϕ_1	porosity of fiberweb (calculation example in Appendix A)
ϕ_2	porosity of the layer formed by forming wires

Superscripts

*	dimensionless variable
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2.1 INTRODUCTION

In the hydroentanglement process, high-energy fine water jets are directed toward a web of loose fibers that is supported by a forming surface (forming wires) to impinge on the pattern of the forming surface. As a result of the impact of the jets, the fibers entangle together forming an integrated web in which the fibers are held together by friction forces. Hydroentanglement is the fastest growing nonwoven fabric bonding technology, with an annual growth rate of 20% [1], because it achieves excellent fabric performance with aesthetics similar to those of woven and knitted fabrics at the cost of nonwovens. This technology is penetrating new markets and has also been used for treating woven fabrics in order to improve hand and cover and impart 3D designs [2-5].

Despite the growth of the technology, little research has been reported in the scientific literature that relates fiber properties, forming surface geometry, and jet parameters to fabric performance and strength. Most of the research in regards to the hydroentanglement process focuses on experimental studies. In [6], the development of texture during hydroentangling is examined as a function of hydroentangling energy. Preliminary experiments aimed at the development of structure-process-property relationships in hydroentangled nonwovens are reported in [7]. However, there is currently no theory or model for this process, which could be used to establish the role that hydro-entanglement process parameters (such as forming surface geometry, process speed, jet pressure, and vacuum pressure) play in controlling the performance of the fabric, how efficient the entanglement is, and how entanglement is translated into tensile strength and other physical properties. The theory can also help understand the role of the intrinsic fiber and web properties in the process.

It is known that experimental studies of the hydroentanglement process are costly and elaborate because of a large number of parameters affecting the entanglement process. Controlling all these parameters in real-life experiments is difficult. Using Computational Fluid Dynamics (CFD) can aid in better understand the hydroentanglement process without conducting expensive experiments. Additionally, numerical simulations allow for modification of a single parameter without altering any other parameters.

In this chapter a model for one manifold of the hydroentanglement process is developed. In this model, the forming surface and the fiberweb are treated as two different porous layers. Since 2D simulations save CPU time (the computational time is

about 1/10 of that for a 3D simulation) and still predict many critical characteristics of the water flow field, 2D simulations of the water flow through the fiberweb and forming surface are first performed, and the influence of the water jet diameter and pressure on the water flow field is investigated. Then, to account for the realistic geometry of the computational domain, 3D simulations of the water flow through the fiberweb and forming surface are performed. The influence of the forming surface on the degree of entanglement is also investigated.

2.2 MATHEMATICAL MODEL

Since the water flow through the fiberweb and the forming surface is very complex, and the microstructure of the fiberweb is complex as well, a macroscopic model is developed based on the assumption that the fiberweb and forming surface can be simulated as two different porous layers with uniform porosities, ϕ_1 and ϕ_2 , respectively. Only one manifold is investigated in this chapter.

2.2.1 MODEL GEOMETRY

In the hydroentanglement process, water jets with a diameter of 0.127mm impact on the forming wires. Since some of the water splashes back after the impact with the forming wires, it is assumed that there is a very thin fluid layer over the fiberweb. The computational domain thus consists of a very thin fluid layer, a fiberweb layer, and a layer that is composed by the forming wires. Both the fiberweb and forming wires are modeled as porous layers.

Figure 2.1 shows the schematic diagram of the problem and the computational domain. The x -axis is directed in the cross machine direction (CD), the y -axis is in the

machine direction (MD), and the z -axis is directed across the thickness of the fiberweb and the forming surface.

This chapter assumes that the water flows through the fluid layer (the upper layer in Figure 2.1 of thickness h_1), the middle fiberweb layer (the porous layer in Figure 2.1 of thickness h_2), and the forming surface (the porous layer in Figure 2.1 of thickness h_3).

Since the turbulent water jet flow induces vortices within the fluid region, the fiberweb, and the forming wires, and the distance between any two water jets is very small, the vortices caused by two neighboring water jets interact with each other within the computational domain. The fibers in the fiberweb entangle in a specific manner under the influence of the water flow. It is assumed that the degree of fiber entanglement is proportional to the average vorticity in the fiberweb region.

In the study in this chapter there are three different regions, namely, a turbulent fluid layer and two porous layers which represent the fiberweb and the forming surface, respectively. It is assumed that in the porous layers, the water flow is also turbulent; therefore, the turbulent flow model is used to simulate the flow in all three layers.

The two-dimensional (2D) turbulent flow through the fiberweb and forming surface in the plane perpendicular to the MD is first investigated. Then three-dimensional (3D) simulations are performed, accounting for a realistic 3D geometry of the computational region.

2.2.2 GOVERNING EQUATIONS AND BOUNDARY CONDITION

Governing equations with modifications to account for turbulence effects within the porous medium [8] are given below. These equations describe the water flow through

porous media (fiberweb and forming surface) in Cartesian coordinates. This form of equations is similar to the equations for the fluid flow; the momentum equation (Equation (2.2)) for flow in the porous layers (fiberweb and forming surface) becomes identical to the momentum equation in the fluid layer when the Darcy and Forchheimer terms are dropped and the porosity, ϕ , is equal to unity. Similarly, the turbulence kinetic energy, k , and the dissipation rate, ε , equations reduce to the familiar k and ε equations for a fluid layer when the Darcy Modification (DM) and Forchheimer Modification A/B (FMA/FMB) terms are dropped from these equations and ϕ is unity.

In the simulation in this chapter, the k - ε turbulence model proposed by Jones and Launder [9] (the JL model) is used. In the k and ε equations for the porous medium, the DM is the additional Darcy damping term, and the Forchheimer term is split into two parts, namely, the FMA and FMB terms.

Continuity equation:

$$\phi \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (2.1)$$

Momentum equation:

$$\rho \frac{\partial u_i}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial u_i}{\partial x_j} = -\nabla p + \frac{\partial}{\partial x_j} \left[(\mu J + \mu_t) \left(\frac{\partial u_i}{\partial x_j} \right) \right] - \frac{\mu \phi u_i}{K} - \rho \frac{c_F \phi u_i Q}{\sqrt{K}} \quad (2.2)$$

where ρ is the water density, $\mathbf{v}$ is the seepage velocity of the water through the forming wires, t is the time, x_i ($i=1,2,3$) are the Cartesian coordinates, p is the pressure, ϕ is the porosity of the forming wires (ϕ_1) or fiberweb (ϕ_2) (depending on the layer for which equations are used), and c_F is the dimensionless Forchheimer coefficient [10]. The

coefficient K is the permeability of the porous medium, μ is the dynamic viscosity of water, and μ_t is the turbulent viscosity which is obtained from the following turbulence model (the JL model):

k equation (turbulence kinetic energy):

$$\begin{aligned} \rho \frac{\partial k}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho J \varepsilon + \rho D \\ - \frac{2\mu\phi k}{K} - \frac{8}{3} \frac{\rho c_F \phi (2Q)k}{\sqrt{K}} + \frac{2c_F \phi \mu_t}{\sqrt{K}} \left(\frac{2}{Q} \right) \left(u_i u_j \frac{\partial u_j}{\partial x_i} \right) \end{aligned} \quad (2.3)$$

Darcy modification (DM)
Forchheimer modification A (FMA)
Forchheimer modification B (FMB)

ε equation (dissipation rate of turbulence kinetic energy):

$$\begin{aligned} \rho \frac{\partial \varepsilon}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + (C_{\varepsilon 1} f_1 P_k - \rho J C_{\varepsilon 2} f_2) \frac{\varepsilon}{k} \\ + \rho E - \frac{4\mu\phi\varepsilon}{K} - \frac{2c_F \phi}{\sqrt{K}} \left\{ \frac{4}{3} (2Q) \rho \varepsilon + \frac{5\mu}{6} \left(2 \frac{\partial k}{\partial x_j} \frac{\partial Q}{\partial x_j} \right) \right\} \end{aligned} \quad (2.4)$$

Darcy modification (DM)
Forchheimer modification A (FMA)

where

$$\begin{aligned} \mu_t &= \rho c_\mu f_\mu \frac{k^2}{\varepsilon}, & \nu_t^* &= c_\mu^* \frac{k^2}{\varepsilon}, & \text{Re}_t &= k^2 / \nu \varepsilon \\ P_k &= \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2, & Q &= \sqrt{u_i u_i}, & f_\mu &= \exp \left(\frac{-2.5}{1 + \text{Re}_t / 50} \right) \\ f_1 &= 1.0, & f_2 &= 1 - 0.3 \exp(-\text{Re}_t^2), & D &= 0, & E &= 0 \\ c_\mu &= 0.09, & c_{\varepsilon 1} &= 1.44, & c_{\varepsilon 2} &= 1.92, & \sigma_k &= 1.0, & \sigma_\varepsilon &= 1.3 \end{aligned}$$

In computations, the above governing equations are solved in their dimensionless form, obtained by defining the following dimensionless variables:

$$\begin{aligned} u^* &= \frac{u}{U_0}, & v^* &= \frac{v}{U_0}, & w^* &= \frac{w}{U_0}, & t^* &= \frac{t}{b_0/U_0} \\ x^* &= \frac{x}{b_0}, & y^* &= \frac{y}{b_0}, & z^* &= \frac{z}{b_0}, & \rho^* &= 1, & p^* &= \frac{p}{\rho_0 U_0^2} \\ Re &= \frac{\rho_0 b_0 U_0}{\mu}, & \mu^* &= \frac{\mu}{\rho_0 b_0 U_0}, & k^* &= \frac{k}{U_0^2}, & \varepsilon^* &= \frac{\varepsilon}{U_0^4} \end{aligned}$$

where U_0 is the inlet water jet velocity; $b_0 = 0.0127\text{mm}$, which is ten percent of the inlet water jets diameter; and ρ is the density of water.

The following inlet, outflow, and symmetry boundary conditions are utilized:

Inlet section ($0 \leq x \leq X_L$, $0 \leq y \leq Y_L$, $z=0$):

$$\begin{cases} k_0 = 0.001U_0^2, & \varepsilon_0 = 0.1643(k_0^{1.5}/0.35D_j) & \text{within the water jets} \\ k_0 = 0, & \varepsilon_0 = 0 & \text{outside the water jets} \end{cases} \quad (2.5)$$

where U_0 is the known velocity of the water jet.

Outflow section ($0 \leq x \leq X_L$, $0 \leq y \leq Y_L$, $z=Z_L$) (a uniform suction boundary condition):

$$u_z = Q/A, \quad u_x = u_y = 0, \quad \frac{\partial k}{\partial z} = \frac{\partial \varepsilon}{\partial z} \quad (2.6)$$

Symmetry plane ($x=0$ or $x=X_L$, $0 \leq y \leq Y_L$, $0 \leq z \leq Z_L$):

$$\frac{\partial u_i}{\partial x} = \frac{\partial u_i}{\partial y} = 0, \quad \frac{\partial k}{\partial y} = \frac{\partial \varepsilon}{\partial y} = 0, \quad \frac{\partial k}{\partial x} = \frac{\partial \varepsilon}{\partial x} = 0 \quad (2.7)$$

In the outflow boundary condition, Q is the volume flow rate, which is calculated from given inlet mean velocity of the water jet flow, and A is the area of the outflow boundary, which is assumed to be of unit width in the y -direction in 2D simulations.

Explicit boundary conditions at the porous/fluid interface are unnecessary since the momentum equation, as well as k and ε equations, are valid in both porous and fluid regions, however additional damping terms are introduced in the turbulence transport equations in the porous layers. Thus, the fluid filtration velocity as well as the k and ε functions are inherently continuous across the interface.

The above numerical method is based on unsteady Reynolds-averaged Navier-Stokes (URANS) equations. Breuer et al. [11] found that URANS equations can reliably and efficiently predict flows consisting of regions with thin attached boundary layers but cannot simulate reliably boundary layer flows with separation. Schwarze [12] found that for the oscillating mould flow, the mean values, amplitudes, and frequencies which are deduced from solving URANS equations are in agreement with corresponding experimental observations and data obtained from LES simulations. Since the geometry simulated in this chapter does not include any boundary layers, it is expected that solving URANS equations reasonably reproduces the unsteady characteristics of the flow field.

2.2.3 NUMERICAL METHOD AND GRID SYSTEM

For the discretization of governing equations, the second-order upwind finite-difference scheme is used for the convection terms, whereas the diffusion terms are discretised using the second-order central finite-difference scheme. The SIMPLE algorithm described in Patankar [13] is used to solve the discretized partial differential equations. To avoid divergence, an under-relaxation factor of 0.5 is used for the velocities

and pressure, whereas for the turbulent quantities, k and ε , the under-relaxation factor is set to 0.3. All equations are solved in their dimensionless form.

For 2D simulations, computations are performed on a uniform grid of 249×259 nodes in the streamwise direction (z -direction) and CD (x -direction), respectively. For 3D simulations, the number of nodes is limited due to computer memory and computational time restrictions. A uniform grid system of $35 \times 50 \times 102$ nodes is used in the MD, CD, and thickness directions, respectively. A typical CPU time on a single 2.8GHz Intel processor for a 2D simulation is 2 hours and for a 3D simulation is 26 hours.

2.3 RESULTS AND DISCUSSION

2.3.1 TWO-DIMENSIONAL SIMULATIONS

In 2D simulations, the computational domain is in the plane perpendicular to the MD. The time-dependent development of the water flow field is investigated in the fluid layer, the fiberweb layer, and the layer composed by forming wires.

The diameter of the water jet is 0.127mm, and there are 15.8 jets/cm (40 jets/inch), hence the distance between the centerline of two jets is 0.635mm. The measured thickness of the fiberweb is 0.711mm, and the thickness of the forming wires layer is 0.30mm. The fluid region is very thin and assumed to be twice the fiber diameter (0.0254 mm). The inlet centerline velocity of the water jet is 200 m/s and the pressure is 200×10^5 Pa.

The fiberweb selected to verify the model is carded and crosslapped and made of polyester (PET) fibers of density 1.39 g/cm^3 and linear density of $1.67 \times 10^{-4} \text{ g/m}$ (1.67 dtex). The fiberweb basis weight is 50 g/m^2 . The thickness of the fiberweb was measured

and found to be 0.711 mm. From these parameters the volume fraction of voids and the permeability K of the fiberweb were calculated and found to be 95% and $2.915 \times 10^{-10} \text{ m}^2$, respectively. Details of the calculations are shown in Appendixes A and B).

2.3.1.1 Model validation

For model validation, data obtained by Zheng [14] are used. Computations are performed for different jet pressures. The diameter of the water jet is 0.127mm. Since vorticity is a measure of the local rotational effect (its value is equal to twice the local fluid angular velocity) in the flow field, it is assumed that the degree of entanglement increases with vorticity. Average vorticity in the fiberweb layer, which is defined as

$$\frac{1}{T} \int_0^T \left[\frac{\iiint_V |\nabla \times \mathbf{v}| dV}{V} \right] dt, \text{ where } V \text{ is the volume of the fiberweb layer and } T \text{ is the total}$$

computational time, is calculated for different water jet pressures.

Since the fabric tensile strength can be used as a measure of the fiber degree of entanglement, the predicted results of average vorticity are compared with the tensile strength results for different jet pressures [14]. The results are given in Figure 2.2(a-c). The positive values of average vorticity indicate that the direction of the vortex is clockwise.

From Figure 2.2(a), it is found that the average vorticity in the fiberweb (hence the fiber degree of entanglement) increases with the jet pressure, which is consistent with the effect of the jet pressure on fabric tensile strength (Figure 2.2(b)), observed in experiments [14].

2.3.1.2 Influence of the jet diameter and jet pressure

In the following 2D simulations, the forming wires parameters are given as type A in Table 2.3.

Besides a water jet diameter of 0.127mm, computations are also performed for jet diameters of 0.1905mm and 0.0635mm. To investigate the influence of water pressure, the results for four different water pressures: 150×10^5 , 180×10^5 , 220×10^5 , and 250×10^5 Pa are compared with those for 200×10^5 Pa.

Figures 2.3 through 2.5 compare velocity and vorticity distributions in the flow field for three water jet diameters at two different moments of time. The x (CD) and z (thickness) axis scales in these figures are dimensionless (to obtain a dimensional position, a dimensionless coordinate must be multiplied by $b_0 = 0.0127$ mm). In the contours depicting vorticity distributions, the values of vorticity are also dimensionless (to obtain a dimensional vorticity, a dimensionless vorticity must be multiplied by $U_0/b_0 = 15.75 \times 10^6 \text{ s}^{-1}$).

It is evident that in the three computed cases, the velocity and vorticity distributions are not symmetrical, which indicates that the fluid flow is strongly unsteady and unstable. There are some vortices induced by the water jets and the streamlines in the vortex regions are strongly curved.

A free fiber within the fiberweb is involved in vortices induced by the water jets and aligns itself along the water flow streamlines because the water flow velocity is high and fiber inertia is small. If there is a free fiber in this region, it follows the flow streamlines and swirls in the plane perpendicular to MD. Since most of the fibers are in

(or parallel to) the MD-CD plane, the free fiber involved in vortices in the CD-thickness plane is entangled around the neighboring fibers. This fiber entanglement mechanism is the main assumption for the model developed in this chapter.

Comparing Figure 2.3 (jet diameter of 0.127mm) with Figure 2.4 (jet diameter of 0.1905mm), there are more vortices in Figure 2.4 but the vortices are smaller in diameter. When the jet diameter is 0.0635 mm (Figure 2.5), there are almost no vortices induced by water jets in the central portion of the computational domain however there is a concentration of vortices near the centerline of the water jet. It is predicted that the fiber degree of entanglement in this case is not sufficient to create a strong fabric.

From the visualization of the flow field for the different jet diameters, it is not evident which has the greatest rotational potential. To illuminate this, average vorticity in the fiberweb layer is calculated for different water jet diameters. The results are given in Table 2.1. It is found that the average vorticity for the jet diameter of 0.127 mm is the largest. Since vorticity is a measurement of the local rotational effect (its value is equal to twice the local fluid angular velocity) in the flow field, it is assumed that the fiber entanglement increases with vorticity. It follows that the fiber entanglement is the largest for the jet diameter of 0.127mm, which is equivalent to the jet diameter used in industry.

The average vorticity in the flow field for different inlet water pressures with a jet diameter of 0.127 mm is calculated. The results are given in Table 2.2. It is found that when the water jet pressure is less than 220×10^5 Pa, the average vorticity increases with the pressure, but as the water jet pressure continues to increase to 250×10^5 Pa, the average vorticity decreases dramatically. From the assumption that the fiber entanglement increases with vorticity, it is predicted that there is an optimal water jet

pressure at which the entanglement is maximized. If the pressure is too high, then water passes through the fiberweb without causing any vorticity and entanglement. However, this optimal pressure may not always coincide with the current prediction because the entanglement is influenced by other factors, such as fiber rheological properties and fiberweb basis weight, which are not fully accounted for in the current model.

2.3.2 THREE DIMENSIONAL SIMULATIONS

Time-dependent development of the water flow field in the clear fluid layer, the fiberweb, and the forming surface is investigated in 3D simulations.

As in 2D simulations, the diameter of the water jet is 0.127mm, and there are 40 jets/inch, hence the distance between centerlines of two neighboring jets is 0.635mm. The thickness of the layer composed by the forming surface is 0.30mm, and that of the fiberweb is 0.711mm. The thickness of the fluid layer is the same as that in 2D simulations (0.0245 mm). The MD length in the 3D simulations is 0.445 mm. The inlet centerline velocity of the water jet is 200 m/s and the pressure is 200×10^5 Pa. The forming wire is moving with a velocity of 2m/s in the machine direction. Figure 2.6 schematically illustrates the geometry of the computational region, positions of the water jets, and the velocity of the moving forming wire.

Figures 2.7 through 2.9 show velocity and vorticity distributions in the flow field in different cross-sections at $t = 1.905 \times 10^{-5}$ s. (The characteristic timescale in this process is $(h_1 + h_2 + h_3)/U_0 = 0.518 \times 10^{-5}$ s.) Since the velocity and vorticity fields are both three-dimensional, the distributions in the figures are all the projections on three different planes. As for the 2D results, all three axis scales in the figures are dimensionless.

It is found that there are some vortices in all directions of the flow field, which indicate that the fibers in the fiberweb are entangled in the MD-CD plane as well as in the fiberweb thickness direction.

From Figures 2.8(a) and 2.8(b), it is evident that in the plane perpendicular to MD at $z = 12$, there are not many vortices. This is because the inlet water jet is located in that region and the local flow field in this cross-section is dominated by the inlet water flow. Similar results are found in the plane perpendicular to CD at $y = 4$, as shown in Figures 2.9(a) and 2.9(c).

From the visualization of the flow fields in the cross-sections in different directions, it is apparent that vortices in the MD-CD plane are the strongest, which is confirmed by computations of the average vorticity in the fiberweb layer. Average vorticity perpendicular to the MD-CD plane is $5.15 \times 10^6 \text{ s}^{-1}$, which is much larger than the average vorticity in the other two directions ($1.29 \times 10^6 \text{ s}^{-1}$ in the MD-thickness plane and $1.16 \times 10^6 \text{ s}^{-1}$ in the CD-thickness plane, respectively). Thus it is predicted that the fiber entanglement in the MD-CD plane is much stronger than that in the fiberweb thickness direction, that is, most of the fibers in the fiberweb are entangled in the MD-CD plane.

From Figures 2.7 through 2.9, it is evident that the vorticity decreases along the streamwise direction, which suggests that the kinetic energy of the water jets is dissipated during the hydroentanglement process.

2.3.3 INFLUENCE OF THE OPEN AREA OF FORMING WIRES

As the layer composed by the forming wires is treated as a porous layer, the influence of the forming wires could be investigated by changing the permeability of this

layer. Computations are carried out for four different forming belts provided by Albany International Corporation [14]. The geometrical parameters of these forming surfaces are listed in Table 2.3. The porosity and permeability of the forming surfaces are calculated in a manner similar to those of the fiberweb (see Appendixes A and B).

The geometry of the computational domain is the same as in the previous 3D simulations (Figure 2.6). The time-dependent development of the water flow field in the clear fluid layer, fiberweb, and layer composed by forming wires is investigated.

Figures 2.10 through 2.12 show the vorticity distributions in the flow field for the forming wires of types B, C, and D at $t = 1.905 \times 10^{-5}$ s. Compared with the results of type A forming surface (Figures 2.7 through 2.9), the non-symmetrically distributed vortices induced by the water jets are found in these four cases. It is evident that for the forming surfaces with different open areas, vorticity distributions are very similar.

A special case has also been investigated assuming that the forming surface is a solid plane with 0% open area (impermeable surface, listed as type E in Table 2.3), so that all water is splashed back by this solid forming surface (water ricochet). The visualization of the vorticity distribution in this case at $t = 1.905 \times 10^{-5}$ seconds is shown in Figure 2.13. There are more vortices in the fiberweb compared to the four previous cases of forming surfaces with an open area. Because the water cannot go through the forming surface it instead splashes back, which means that it goes through the fiberweb twice and causes more vortices. Since the fiber is entangled under the impact of vortices, it is predicted that the degree of fiber entanglement is larger. This result is consistent with what is observed in industry [15]; however, this is only true if there is no water accumulation above the fiberweb (no growth of the fluid layer thickness).

The above results are summarized in Table 2.4, which gives the calculated average vorticity at different planes for forming surfaces with different open areas. With the increase of the open area of the forming surface, the vorticity in the flow field does not change significantly; the difference does not exceed 5%. This may be attributed to the fact that the model developed in this chapter does not account for the realistic geometry of the forming surface and simply treats it as a porous layer. However, the absolute value of the average vorticity for type A forming surface (open area 10%) is larger than for other forming surfaces, and the average vorticity of the solid forming surface is the largest. From these simulations, it follows that the degree of fiber entanglement is larger when the open area of the forming surface is smaller, which is consistent with industry observations for the cases of the perfojet forming surfaces [15].

These results show that when the forming wires are treated as a layer of porous material, the open area (porosity) of the forming wires has some impact on the local rotational property and the degree of fiber entanglement. Future work should address simulation of the water flow through realistic forming surface geometry.

2.4 CONCLUSIONS

A model for one manifold of the hydroentanglement process is developed. The water flow field is investigated using this model by simulating the fiberweb and forming wires as porous layers.

The time-dependent development of the water flow field shows the non-symmetrical distribution of velocity and vorticity fields. Vortices are induced by the water jets and the streamlines in the vortices are strongly curved. Assuming that a free

fiber in the flow field is involved in vortices and aligned along the flow streamline under the influence of the vortices, it is hypothesized that the mechanism of fiber entanglement is such that the fiber gets involved in a vortex and entangles around neighboring fibers.

Obtained computational results provide evidence that the degree of entanglement in the hydro-entanglement process, which is measured by the average vorticity in the fiberweb layer, is influenced by the jet pressure and diameter. The investigation of the influence of the water jet diameter verified that the 0.127 mm diameter used in industry is the optimal parameter.

In addition to 2D simulations, 3D simulations are performed, which account for the realistic geometry of the computational region and the constant velocity of the forming surface. Using 3D simulations, vortices distributions in the MD-CD planes, MD-thickness planes, and CD-thickness planes are obtained. The results indicate that most of the fibers in the fiberweb are entangled in the MD-CD plane.

The investigation of the influence of the open area of forming wires shows that the open area (porosity) of the forming wires has small impact on the average vorticity (hence on fiber entanglement) in the process. It is found that the degree of fiber entanglement increases as the open area of forming wires decreases. If the forming surface is solid (0% open area), the degree of fiber entanglement would be the largest due to the effect of water ricochet from the forming surface, causing more entanglement.

2.5 APPENDIX

2.5.1 APPENDIX A: POROSITY OF THE POROUS MEDIUM

A porous medium is a material consisting of a solid matrix with interconnected voids. It is supposed that the solid matrix is either rigid or it undergoes a small deformation. The interconnectedness of the voids (the pores) allows the flow of fluids through the material. The pores are usually uniformly distributed within the porous medium.

Effective porosity is defined as the volume fraction of the pore spaces that are fully interconnected and contributing to fluid flow through the material, excluding dead-end or isolated pores that cannot be part of a flow path. Total porosity is the ratio of the total void volume to the total volume of the porous medium. Typically, effective porosity is less than total porosity. In the simulations presented in this chapter, only the total porosity, which is called porosity, is accounted for.

The porosity of the fiberweb is calculated as follows. The selected fiberweb, which is carded and crosslapped, is composed of PET fibers with a density of 1.39 g/cm^3 and linear density of $1.67 \times 10^{-4} \text{ g/m}$ (1.67 dtex). The fiberweb basis weight is 50 g/m^2 . The thickness of the fiberweb is measured and found to be 0.711 mm . To calculate the fiberweb porosity a small piece of fiberweb is considered, as shown in Figure 2.14. The length and width of the fiberweb piece is 1 cm , and the thickness of the fiberweb is $h_2 = 0.0711 \text{ cm}$. The weight of the fiberweb is:

$$m_{\text{fiberweb}} = 50 \text{ g/m}^2 \times 1\text{cm} \times 1\text{cm} = 5 \times 10^{-3} \text{ g}$$

The weight of the fibers in this piece of the fiberweb is the same as that of the fiberweb (the weight of air is neglected):

$$m_{fibers} = m_{fiberweb} = 5 \times 10^{-3} \text{ g}$$

The volume of the fibers in the fiberweb is calculated as:

$$V_{fibers} = \frac{m_{fibers}}{\rho_{fibers}} = \frac{5 \times 10^{-3} \text{ g}}{1.39 \text{ g/cm}^3} = 3.597 \times 10^{-3} \text{ cm}^3$$

The total volume of the piece of fiberweb is:

$$V_{fiberweb} = 1 \text{ cm} \times 1 \text{ cm} \times h_2 \text{ cm} = 0.0711 \text{ cm}^3$$

Thus, the fiberweb porosity is obtained as:

$$\text{Porosity } \phi_2 = \frac{\text{Volume of voids}}{\text{total volume}} = \frac{V_{void}}{V_{fiberweb}} = \frac{V_{fiberweb} - V_{void}}{V_{fiberweb}} = 95\%$$

2.5.2 APPENDIX B: PERMEABILITY OF POROUS MEDIUM

Permeability is a measure of the ability of a porous material to transmit fluid. It is independent of the nature of the fluid but it depends on the geometry of the porous medium. It is also called *specific permeability* or *intrinsic permeability* of the porous medium. It has dimensions (length)². It can be calculated according to the following equation [10]:

$$K = \frac{D_{p2}^2 \phi^3}{180(1-\phi)^2} \quad (2.8)$$

$$\text{where } D_{p2} = \frac{\int_0^\infty D_p^3 h(D_p) dD_p}{\int_0^\infty D_p^2 h(D_p) dD_p}$$

and D_p is the fiber diameter (or the forming wire diameter), $h(D_p)$ is the density function for the distribution of diameters D_p , and ϕ is the effective porosity.

The permeability of the fiberweb is calculated as an example (shown below).

First, the fiber diameter is calculated as:

$$D_{fiber} = \frac{1}{280.2} \sqrt{\frac{N_t}{\rho_f \cdot 1}} = \frac{1}{280.2} \sqrt{\frac{0.167 \text{ tex}}{1.39 \text{ g/cm}^3}} = 0.01237 \text{ cm}$$

where N_t is the yarn number (tex=g/km). The fibers are assumed evenly distributed within the fiberweb; hence, the density function for the distribution of diameter D_{fiber} is a constant.

The permeability of the fiberweb thus is:

$$K_{fiberweb} = \frac{D_{fiber}^2 \phi_2^3}{180(1-\phi_2)^2} = \frac{(0.01237 \times 10^{-2} \text{ m})^2 \times 0.95^3}{180(1-0.95)^2} = 2.9154 \times 10^{-10} \text{ m}^2$$

Table 2.1 Average vorticity for different jet diameters in the flow field in 2D simulations.

Jet diameter (D)	Average vorticity $\times 10^{-6}$ (s ⁻¹)
0.0025 in	2.505
0.004 in	3.47
0.0045 in	2.99
0.00475 in	3.62
0.005 in	4.78
0.00525 in	4.48
0.0055 in	3.56
0.006 in	3.325
0.0075 in	3.41

Table 2.2 Average vorticity in the fiberweb for different jet pressures for 0.127 mm jet diameter in 2D simulations.

Pressure (MPa)	15	18	20	22	25
Average vorticity $\times 10^{-6}$ (s ⁻¹)	1.12	3.53	4.45	7.69	0.81

Table 2.3 Geometrical parameters of forming surfaces.

Type	Count (/inch)	MD wire diameter(mm)	CD wire diameter(mm)	Open Area (Porosity ϕ)	Permeability (m^2)
A	21×18	0.88	0.89	10%	5.372×10^{-12}
B	36×27	0.40	0.40	25%	2.469×10^{-11}
C	100×90	0.11	0.14	29%	4.438×10^{-12}
D	11×11	0.89	1.00	35%	5.035×10^{-10}
E	Solid	N/A	N/A	0%	0

Table 2.4 Average vorticity (s^{-1}) in different planes for the five different forming surfaces in 3D simulations.

Fabric ID	MD-CD Plane	MD-thickness Plane	CD-thickness Plane
A	5.15×10^6	1.29×10^6	1.16×10^6
B	5.13×10^6	1.31×10^6	1.17×10^6
C	5.07×10^6	1.23×10^6	1.14×10^6
D	4.99×10^6	1.29×10^6	1.15×10^6
E	5.77×10^6	1.91×10^6	1.71×10^6

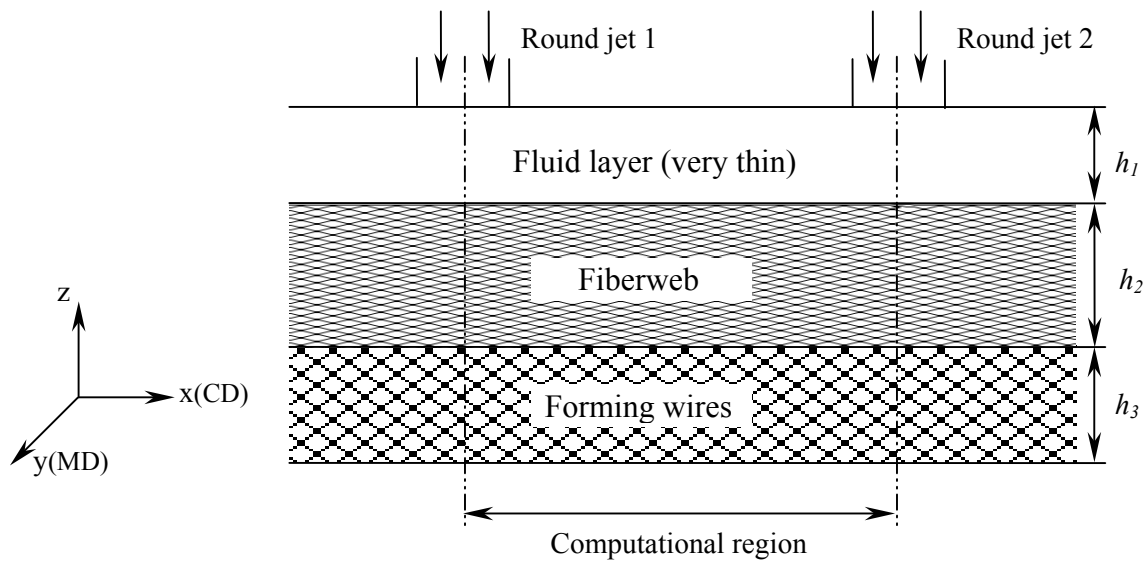


Figure 2.1 Schematic diagram of the problem and the computational domain.

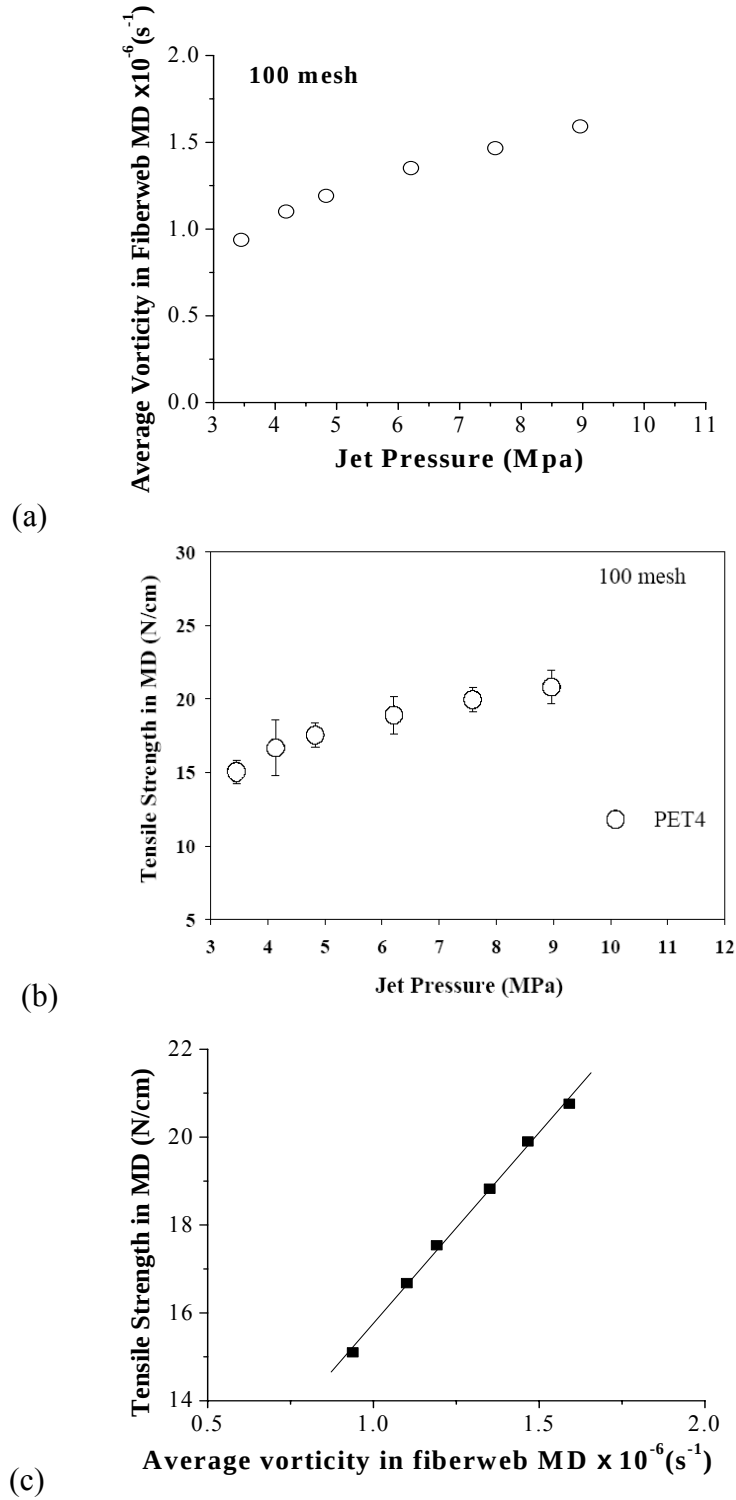


Figure 2.2 Qualitative comparison of simulations with experiments: (a) Predicted average vorticity in fiberweb at different jet pressures; (b) Experimental results of fabric tensile strength at different jet pressures; (c) Linear fit correlation of tensile strength versus average vorticity.

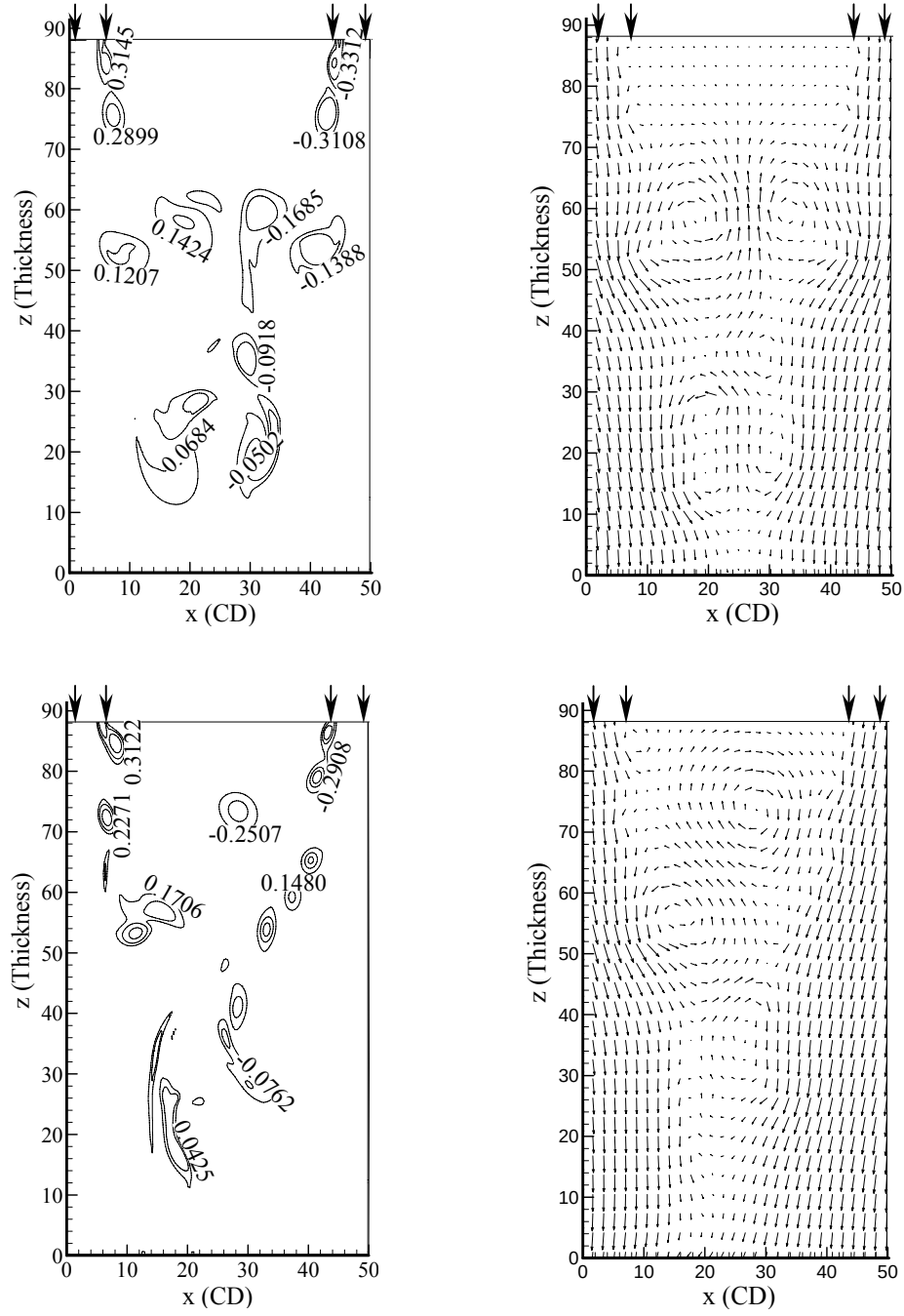


Figure 2.3 Flow field for 0.127 mm jet diameter: (a) vorticity distributions at $t=2.54 \times 10^{-5}$ s; (b) Velocity vector field $t=2.54 \times 10^{-5}$ s; (c) vorticity distributions at $t=5.01 \times 10^{-5}$ s; (d) Velocity vector field $t=5.01 \times 10^{-5}$ s.

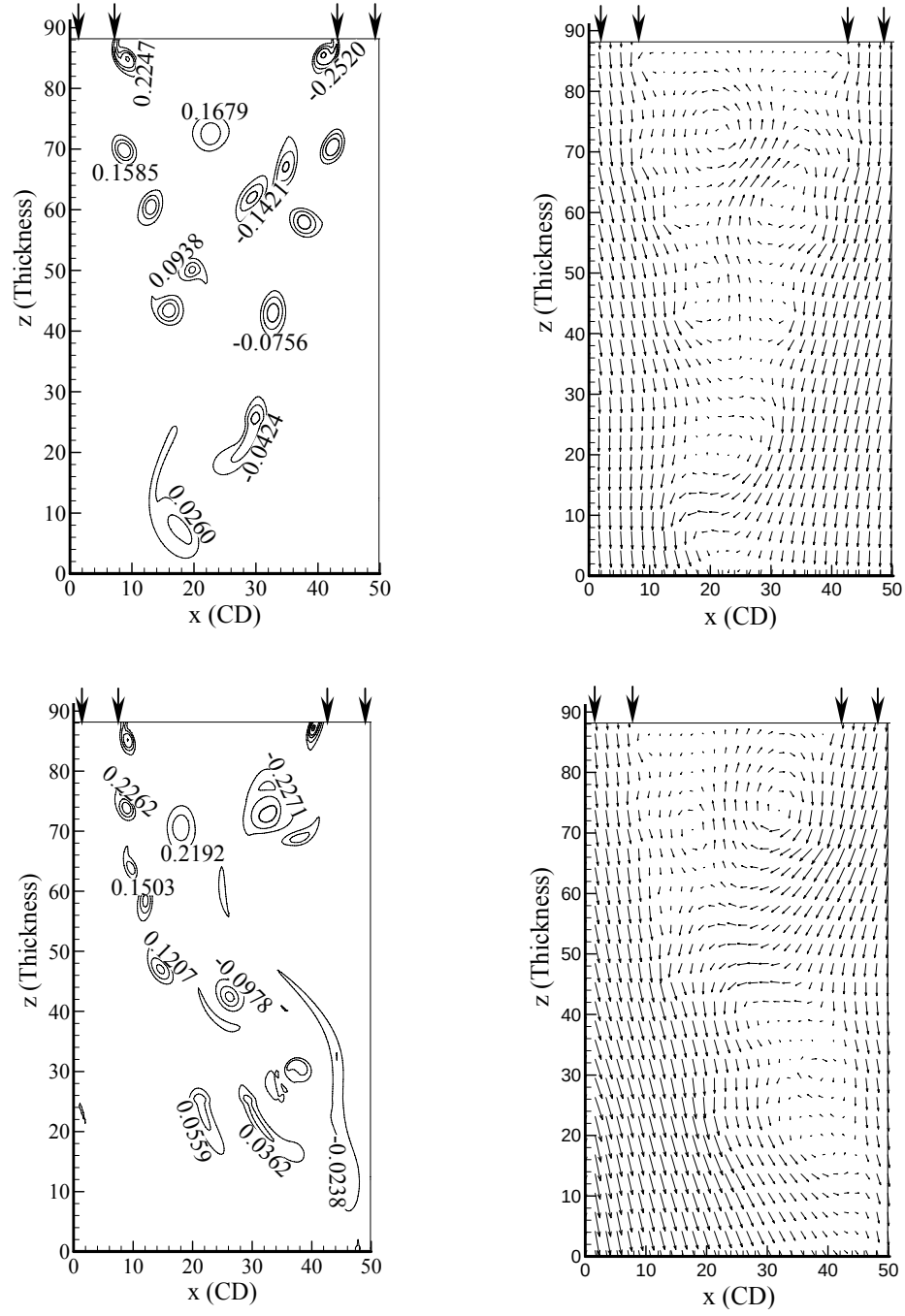


Figure 2.4 Flow field for 0.1905 mm jet diameter: (a) vorticity distributions at $t=2.54 \times 10^{-5}$ s; (b) Velocity vector field $t=2.54 \times 10^{-5}$ s; (c) vorticity distributions at $t=5.01 \times 10^{-5}$ s; (d) Velocity vector field $t=5.01 \times 10^{-5}$ s.

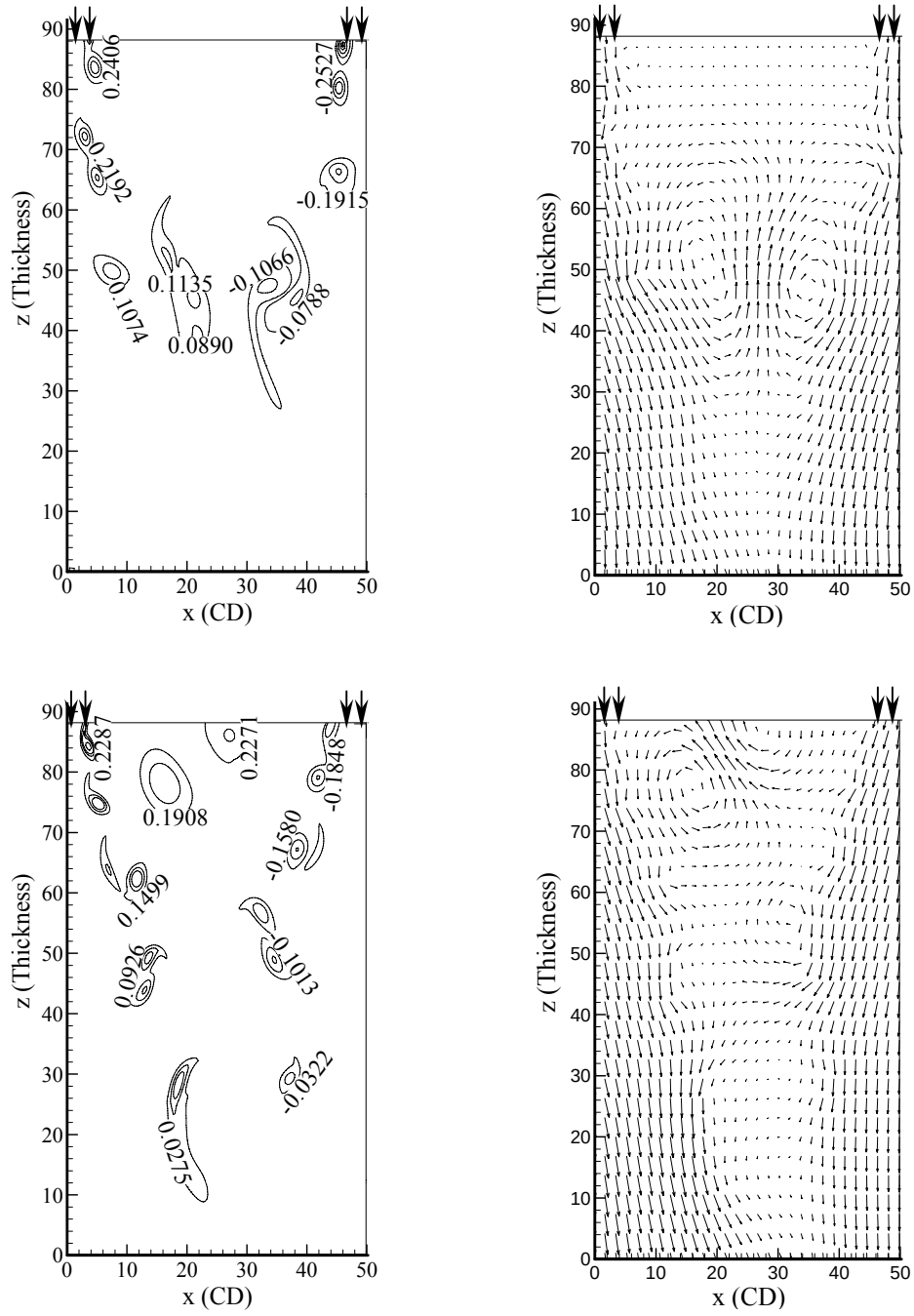


Figure 2.5 Flow field for 0.0635 mm jet diameter: (a) vorticity distributions at $t=2.54 \times 10^{-5}$ s; (b) Velocity vector field $t=2.54 \times 10^{-5}$ s; (c) vorticity distributions at $t=5.01 \times 10^{-5}$ s; (d) Velocity vector field $t=5.01 \times 10^{-5}$ s.

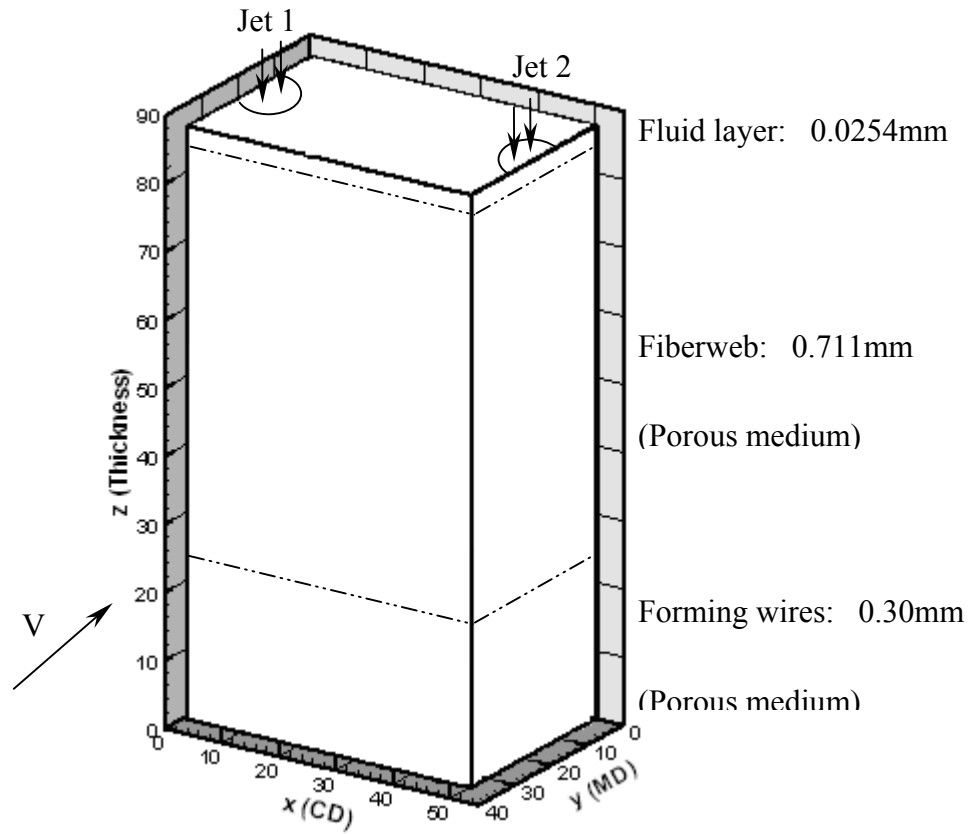
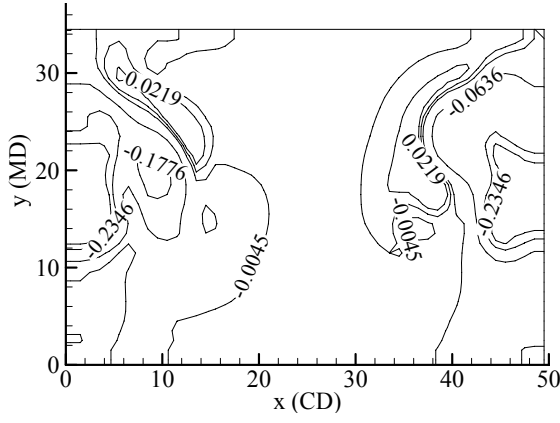
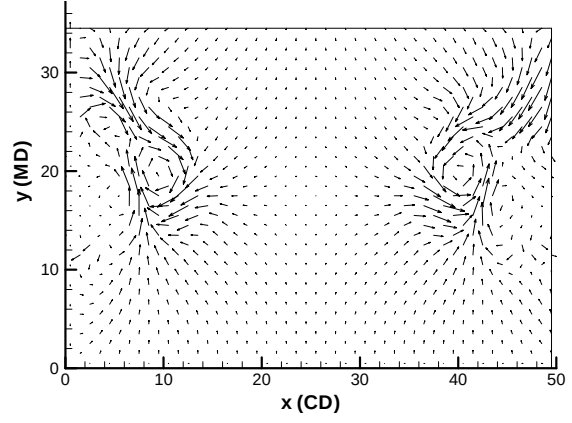


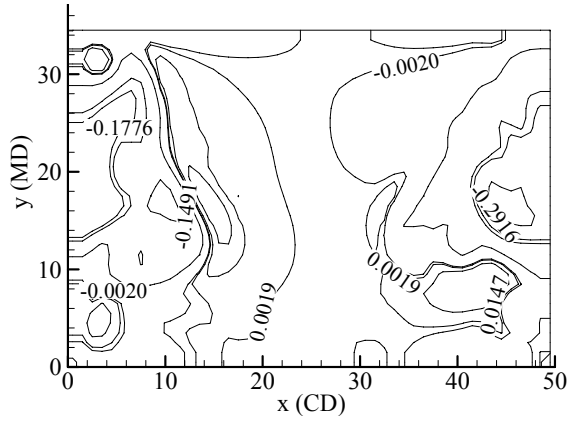
Figure 2.6 Geometry of the computational domain in 3D simulations.



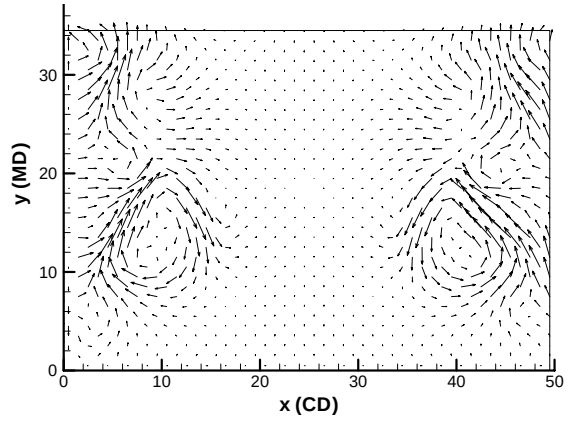
(a) Vorticity projection at $z=75$



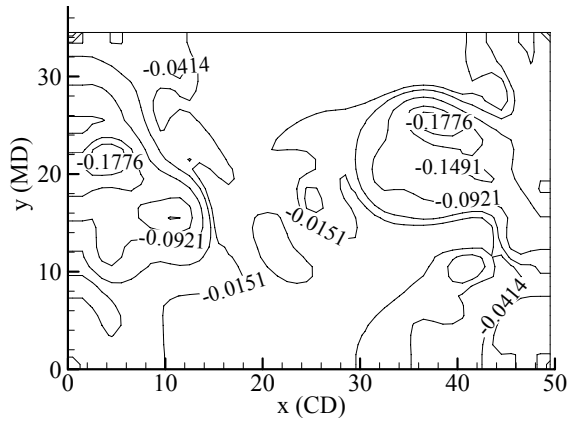
(b) Velocity projection at $z=75$



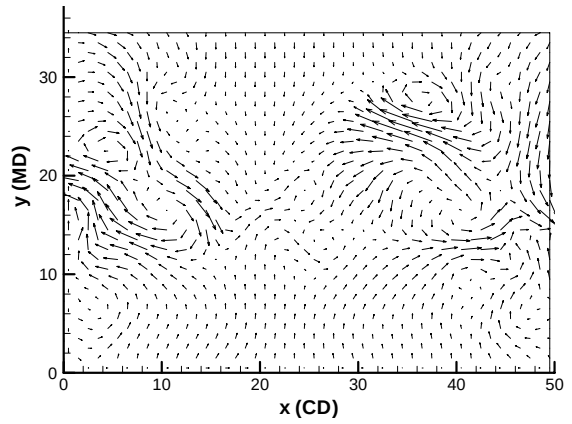
(c) Vorticity projection at $z=60$



(d) Velocity projection at $z=60$



(e) Vorticity projection at $z=40$



(f) Velocity projection at $z=40$

Figure 2.7 Flow field in MD & CD planes.

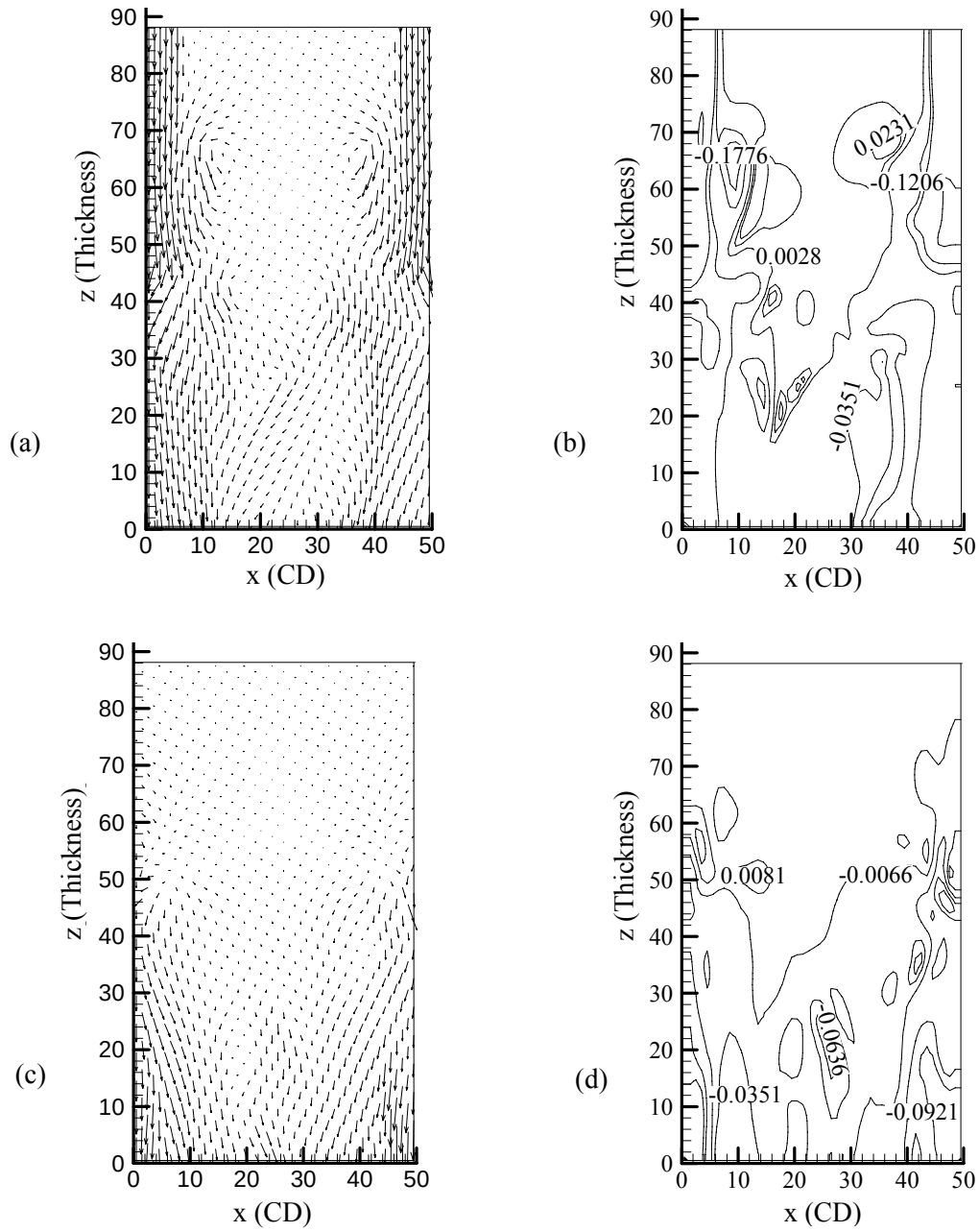


Figure 2.8 Flow field in CD & thickness cross-sections: (a) velocity vector field at $y=12$; (b) vorticity distribution at $y=12$; (c) velocity vector field at $y=23$; (d) vorticity distribution at $y=23$.

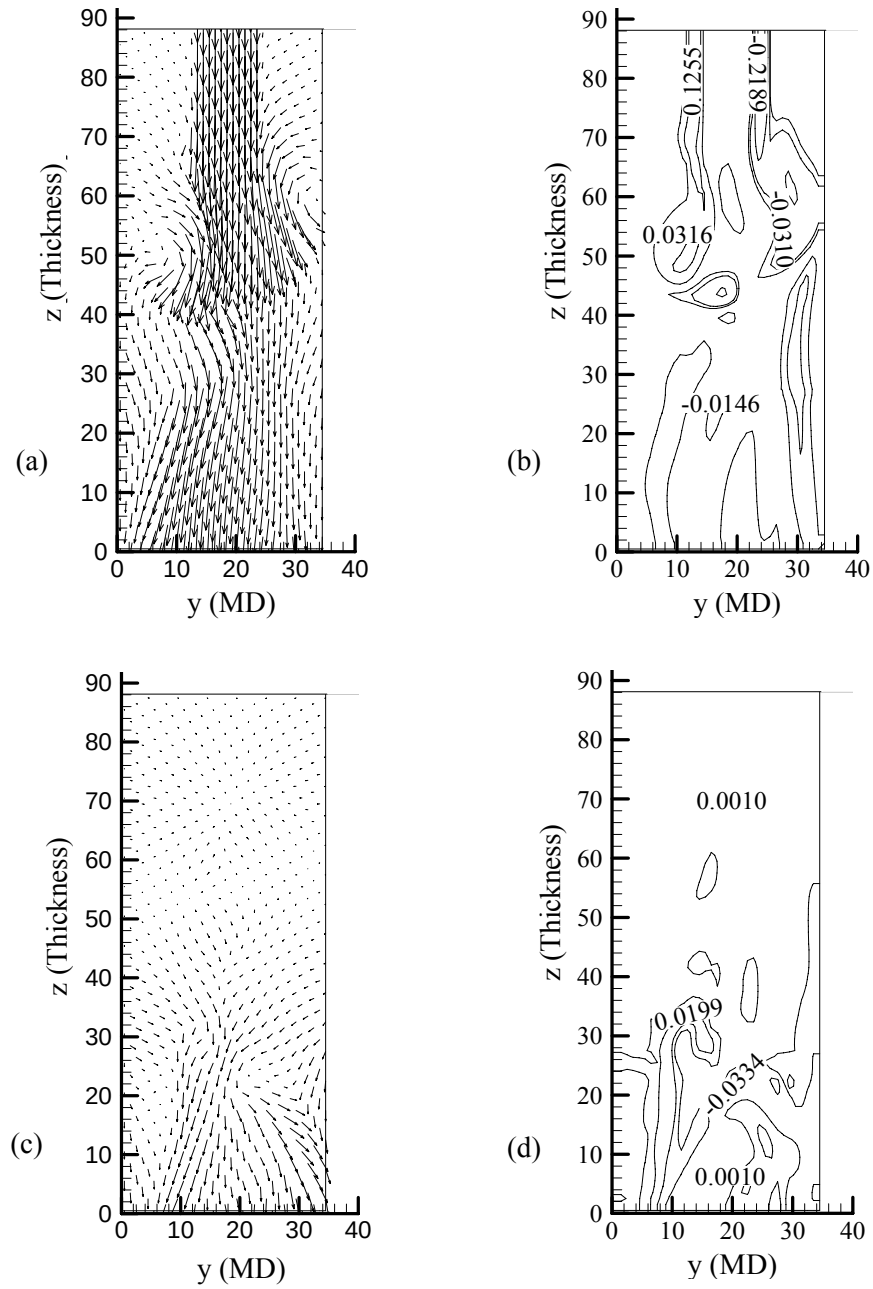


Figure 2.9 Flow field in MD & thickness cross-sections: (a) velocity vector field at $x=4$; (b) vorticity distribution at $x=4$; (c) velocity vector field at $x=18$; (d) vorticity distribution at $x=18$.

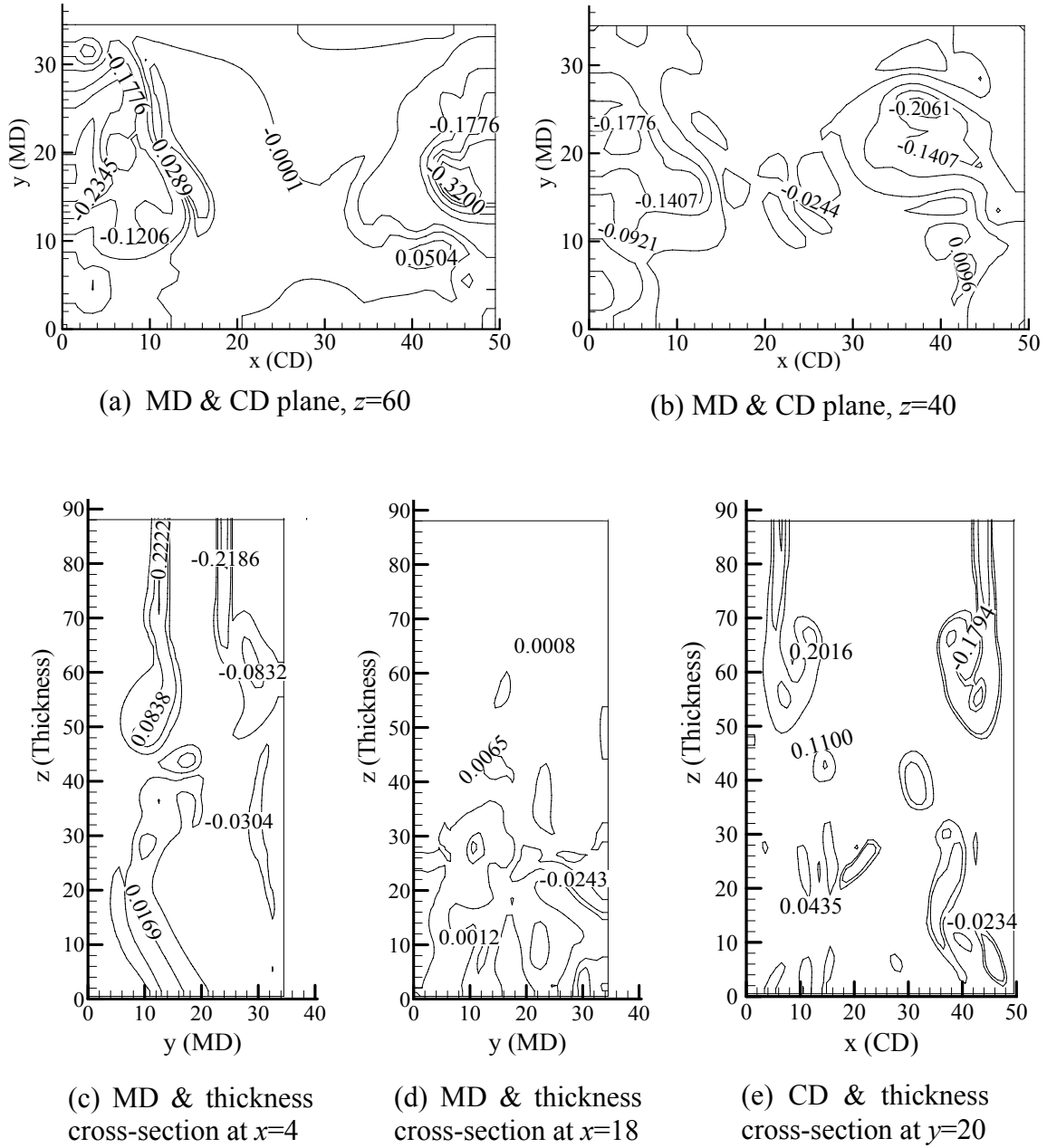
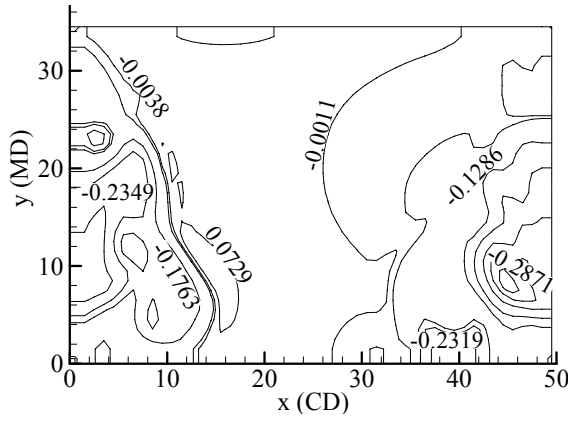
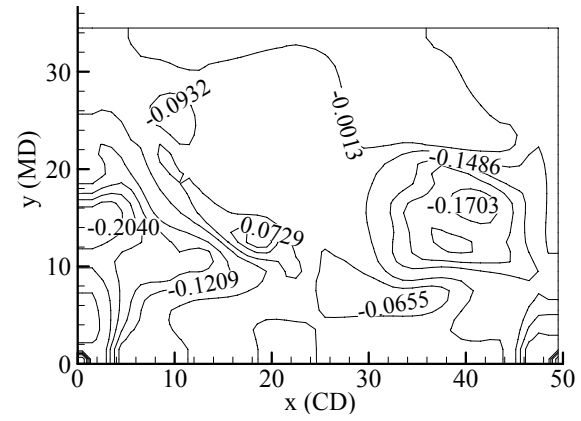


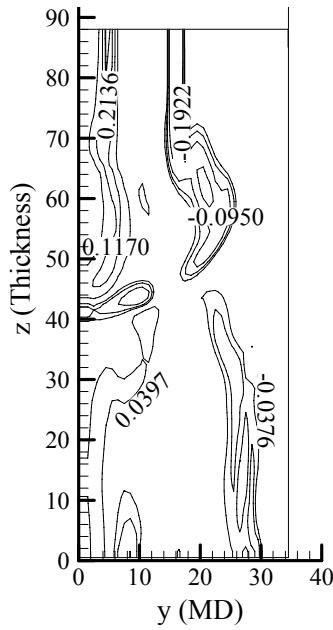
Figure 2.10 Vorticity distributions for type B forming surface (25% open area).



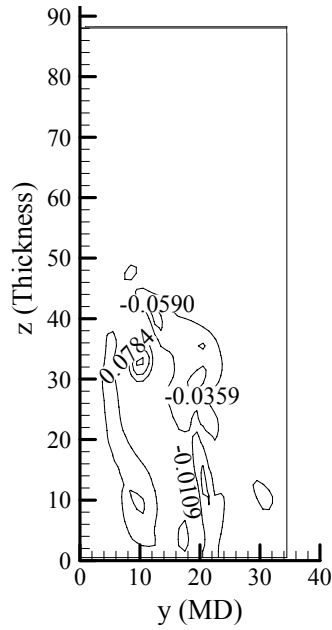
(a) MD & CD plane, $z=60$



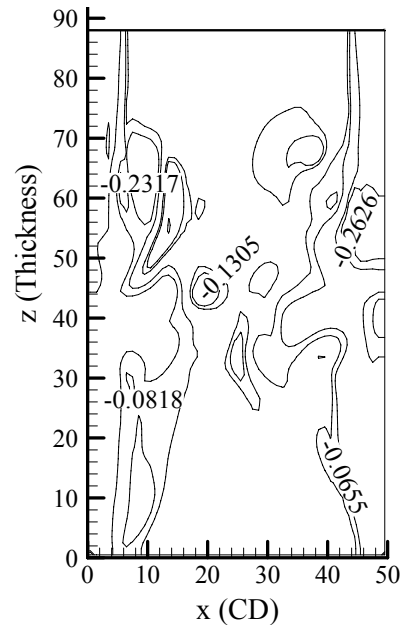
(b) MD & CD plane, $z=40$



(c) MD & thickness cross-section at $x=4$

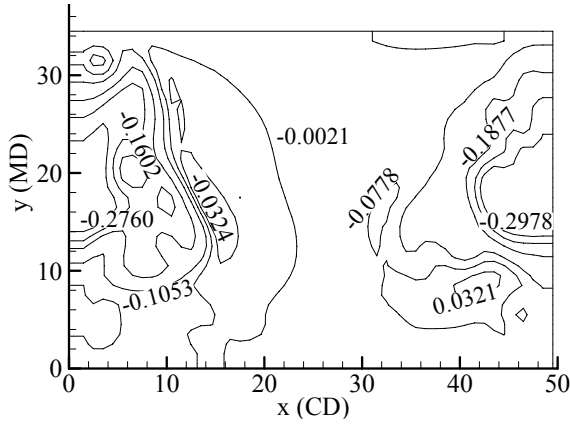


(d) MD & thickness cross-section at $x=18$

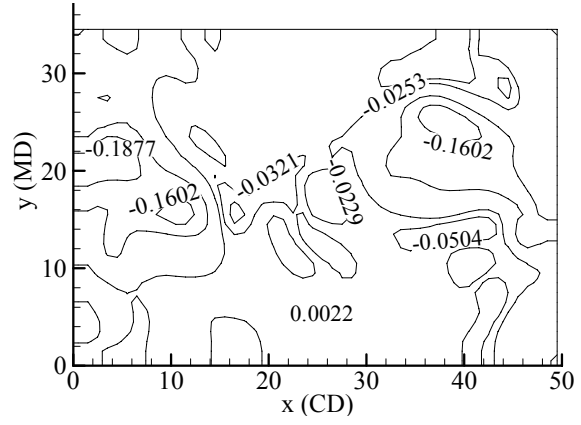


(e) CD & thickness cross-section at $y=20$

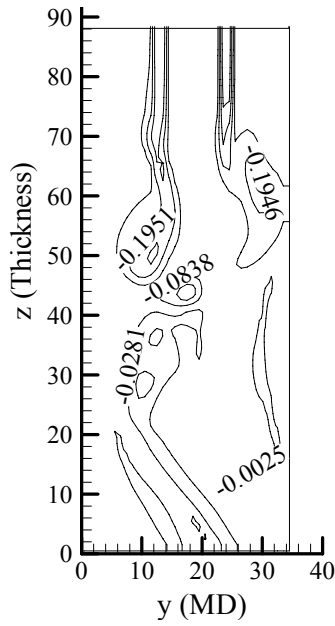
Figure 2.11 Vorticity distributions for type C forming surface (29% open area).



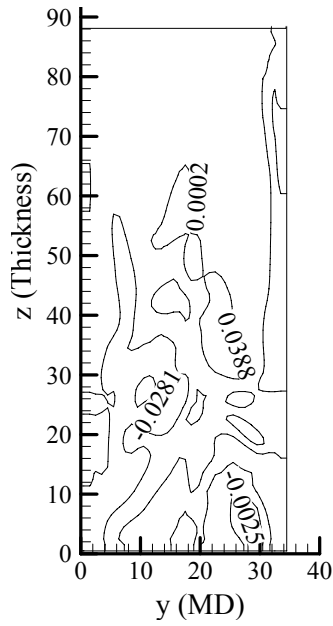
(a) MD & CD plane, $z=60$



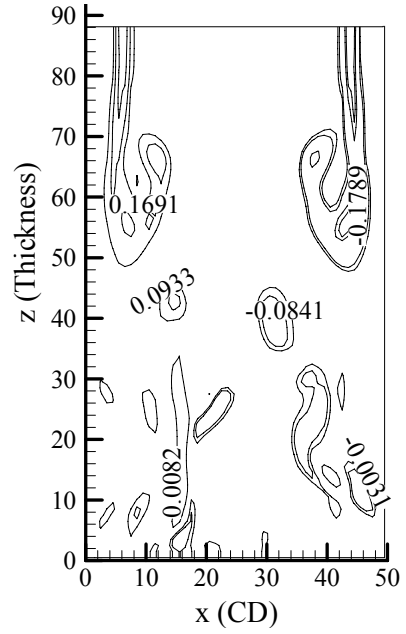
(b) MD & CD plane, $z=40$



(c) MD & thickness cross-section at $x=4$

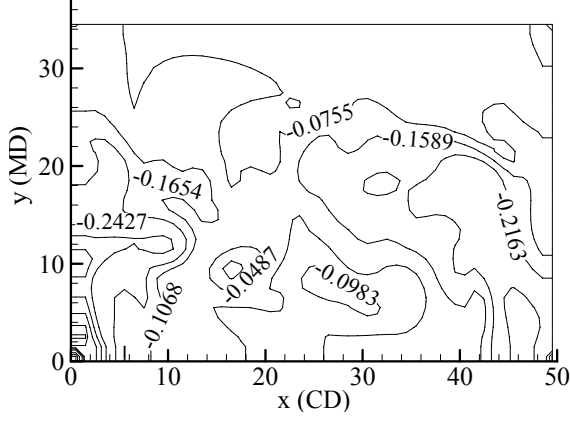


(d) MD & thickness cross-section at $x=18$

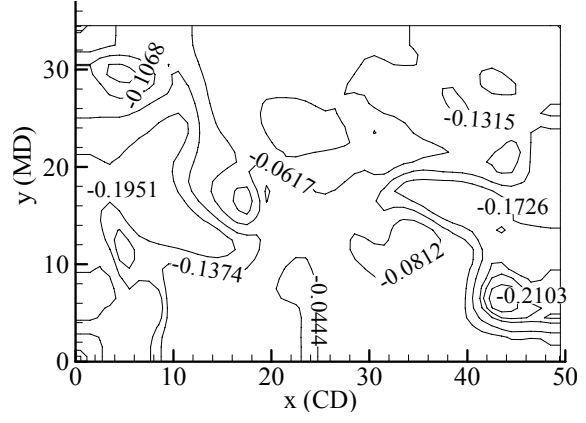


(e) CD & thickness cross-section at $y=20$

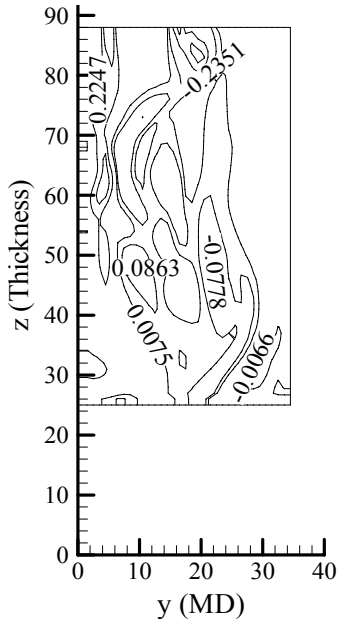
Figure 2.12 Vorticity distributions for type D forming surface (35% open area).



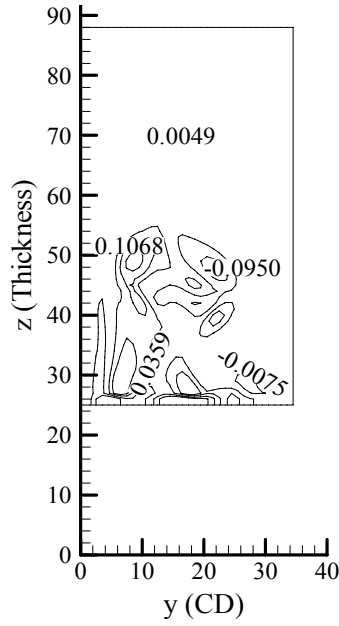
(a) MD & CD plane, $z=60$



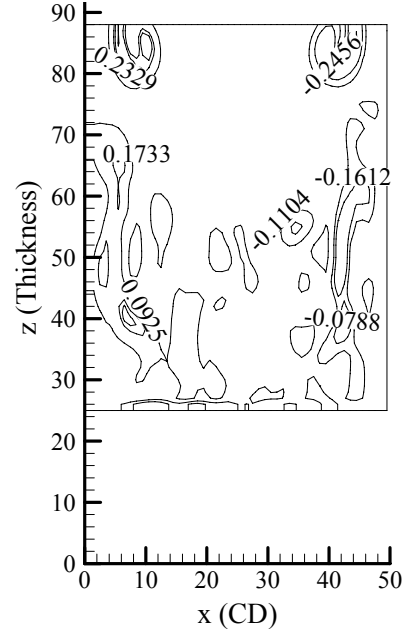
(b) MD & CD plane, $z=40$



(c) MD & thickness cross-section at $x=4$



(d) MD & thickness cross-section at $x=18$



(e) CD & thickness cross-section at $y=20$

Figure 2.13 Vorticity distributions for type E forming surface (solid: 0% open area).

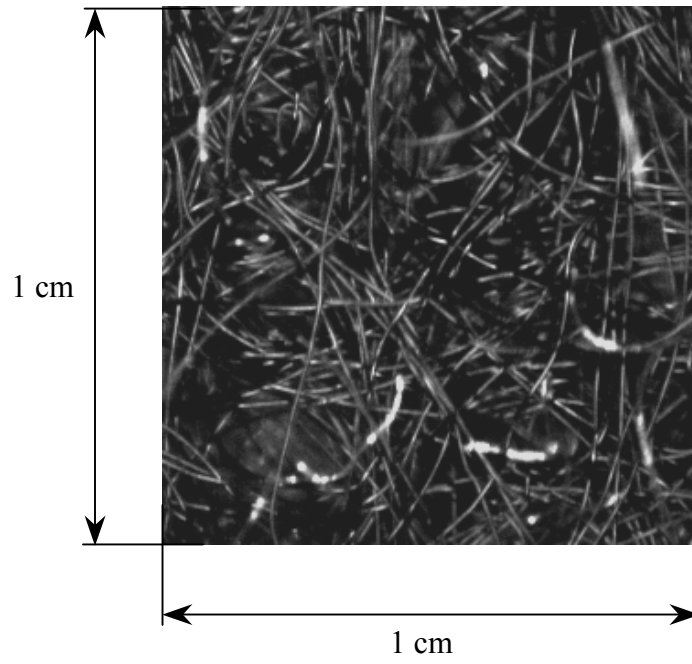


Figure 2.14 Representative fiberweb sample for calculating web porosity.

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3 A POROUS MEDIUM MODEL OF THE HYDROENTNAGLEMENT PROCESS

ABSTRACT

In this chapter, a theoretical model of the hydroentanglement process is developed. The fiberweb is modeled as a porous layer, which is supported by a periodic net of forming wires. The model is based on the assumption that the degree of fiber entanglement and, consequently, the strength of the fabric are proportional to the average water vorticity in the fiberweb. The model accounts for the water ricochet by the wires, so there is a thin fluid layer above the porous fiberweb layer due to the water reflection. Numerical simulations are performed to study the water flow field and the vorticity in the fiberweb. The effects of the thickness of the porous fiberweb layer, its permeability, and the inlet water jet velocity on the degree of fiber entanglement are investigated. Simulations show that most of the fibers are entangled in the MD-CD plane. There is a critical fiberweb thickness for a given jet pressure, and a critical jet velocity for a given fiberweb thickness. If the fiberweb thickness or jet velocity is larger than critical, the process is not efficient.

Nomenclature

A	area of the outflow boundary, m^2
b_0	reference length used in simulations (10% of the empirical inlet water jet diameter), m
c_F	Forchheimer coefficient

C_s	empirical modeling constant for Large Eddy Simulation (LES) computations
D_j	water jet diameter, m
DM	Darcy modification in the turbulence model
FMA	Forchheimer Modification A term in the k - ε turbulence model
FMB	Forchheimer Modification B term in the k - ε turbulence model
h_1	thickness of the fluid layer above the fiberweb, m
h_2	thickness of the porous medium layer (fiberweb), m
h_3	thickness of the layer composed by forming wires, m
J	ratio of the effective viscosity of the porous medium to the fluid dynamic viscosity, μ_{eff} / μ
JL model	modified k - ε turbulence model proposed by Jones and Launder [14]
K	permeability of the fiberweb layer, m^2
p	water jet pressure, Pa
Q^+	volume flow rate, m^3/s
Re	Reynolds number of water jets = $\rho U_0 D_j / \mu$
Ri	Ricochet parameter
$\bar{S}_{ij}$	strain-rate tensor of filtered velocity field in LES
t	time, s
T	total computational time, s
U_0	inlet water jet velocity, m/s
u, v, w	water velocity components in the x -, y -, and z -directions (within the fiberweb understood as components of the filtration velocity), m/s

$\mathbf{v}$	water velocity vector, m/s
V	volume of a small square prism around a forming wire (the averaging domain for computing the average vorticity around the forming wire), m ³
x, y, z	Cartesian coordinates
X_L, Y_L, Z_L	length of the computational domain in the x -, y -, and z -directions, m

Greek symbols

ε	dissipation rate of turbulence kinetic energy [m ² /s ³]
k	turbulence kinetic energy [m ² /s ²]
μ	dynamic viscosity of water [kg/(m·s)]
μ_{eff}	effective viscosity of the porous medium
μ_t	turbulent viscosity [kg/(m·s)]
ν	kinematic viscosity of water, m ² /s
ν_T	subgrid-scale eddy viscosity in LES computations
ρ	water density, kg/m ³
ϕ	porosity of the fiberweb
φ	open area of the forming wires
Δ	Δ filter width in LES

Superscripts

*	dimensionless variable
---	------------------------

Subscripts

0 inlet

3.1 INTRODUCTION

In the hydroentanglement process, high-pressure fine water jets are directed toward a web of loose fibers (fiberweb) that is supported by forming wires (see Figure 3.1a). As a result of the impact of the jets, the fibers entangle forming an integrated web where fibers are held together by friction forces. The resulting fabric strength depends on the fiberweb properties (basis weight, thickness, etc.), fiber parameters (fiber diameter, bending modulus, etc.), forming wires geometry, and jet parameters.

Although hydroentanglement is the fastest growing nonwoven fabric bonding technology, most research in this area has been focused on experimental studies. Berkalp et al. [1] experimentally examined the development of texture during this process as a function of water jets specific energy, which in turn depends on the water jet diameter, jet pressure, number of jets per unit length, and the basis weight of the fiberweb. Experimental research of Pourdeyhimi et al. [2] developed structure-process-property relations for hydroentangled nonwovens. Unfortunately, experimental studies of the hydroentanglement process are costly and elaborate because there are a large number of parameters affecting this process and it is difficult to control all these parameters in real-life experiments.

Numerical analysis can be used to investigate how, as a result of the impact of water jets, the fiberweb transforms into a fabric as the degree of fiber entanglement

grows. This chapter is aimed at developing a hydroentanglement model, which is then used to establish the effect of hydroentanglement process parameters (such as the forming surface geometry, process speed, jet pressure, and vacuum pressure) on fabric strength and the efficiency of entanglement. Empirical data are used to estimate how entanglement is translated into tensile strength. The model is used to investigate the effect of the fiberweb thickness and permeability on the efficiency of the process.

Since the flow induced by impinging water jets is turbulent, the numerical model relies on turbulent flow model in partly porous configurations. Bejan [3] reviewed fundamentals of free turbulent flows and turbulent flows in porous media. Prakash et al. [4] performed experiments and 2D simulations of a turbulent flow in porous media. They compared two different turbulence models for investigating the effect of the porous layer on flow in the overlying turbulent clear fluid layer. A review by Lage et al. [5] describes different macroscopic turbulence models in porous media.

This chapter continues the research of the last chapter (also see Xiang et al. [6]), in which the fiberweb and forming wires are modeled as two different layers of porous medium with uniform permeabilities. The present chapter takes a step forward in modeling the hydroentanglement process by considering a realistic geometry of forming wires. This results in a spatially highly non-uniform flow through the fiberweb. It is the hydrodynamics of this flow that determines the dynamics of fiber entanglement and final strength of the fabric. The ricochet of water by forming wires is accounted for, which results in a thin fluid layer above the porous fiberweb. 3D simulations of water jets passing through the porous fiberweb and forming wires are performed. The effects of the

fiberweb thickness, fiberweb permeability, and the inlet water jet velocity on the degree of fiber entanglement are investigated.

3.2 MATHEMATICAL MODEL

This chapter uses the approach to partly porous configurations and geometries with porous inserts developed in Huang and Vafai [7-9] and Vafai and Huang [10]. There are two length scales characterizing porous structures in this problem. One length scale is associated with a fiber diameter in the fiberweb while the second length scale is associated with the diameter of forming wires. Since the fiber diameter is much smaller than that of the forming wires, two different models are utilized for the fiberweb and the supporting layer (forming wires). The fiberweb is simulated as a porous layer with uniform porosity ϕ . The layer of forming wires is simulated as an anisotropic layer, part of which is occupied by the wires and part is occupied by the empty space between the wires (see Figure 3.1b).

3.2.1 MODEL GEOMETRY

Figure 3.1a displays the schematic diagram of the hydroentanglement process and the computational domain. The x -axis is directed in the cross machine direction (CD), the y -axis is in the machine direction (MD), and the z -axis is directed across the thickness of the porous fiberweb and the forming wires. The highly pressurized water jets impinging on the fiberweb have a typical diameter of 0.127mm. It is assumed that the diameter of the water jet remains constant until the jet hits the fiberweb; this is because the breakup length of the water jet is much larger than a typical distance between the jet nozzle and

the fiberweb in the hydroentanglement process (Tafreshi and Pourdeyhimi [11]). For this reason, there is no interaction between the jets before they hit the fiberweb.

Since part of the water splashes back after it hits the forming wires, it is assumed that there is a thin fluid layer over the fiberweb. The portion of the injected water that is not splashed back flows through the fluid layer (the upper layer in Figure 3.1a, of thickness h_1), the porous fiberweb layer (the middle layer in Figure 3.1a, of thickness h_2), and the layer composed by forming wires (the lower layer in Figure 3.1a, of thickness h_3). The process is continuous, and the forming wires layer is moving at 1m/s in the MD (in the y -direction).

Since the impinging jets induce vortices within the fluid region, the fiberweb, and the voids between the forming wires, and the distance between water jets is small (0.635mm), the vortices caused by two neighboring water jets interact with each other and fibers in the fiberweb and cause fiber entanglement (see Figure 3.2) due to the rotational effect of the water flow. The rotational effect of the fluid flow on a solid particle or a fiber is determined by flow vorticity, for example, Shahcheraghi and Dwyer [12] evaluated the rotation rate of a sphere in a flow field by one-half of the local flow vorticity at the sphere-center position.

In this chapter, it is assumed that the degree of fiber entanglement is proportional to the accumulated average vorticity in the fiberweb region. To validate this assumption, Figure 3.3 shows a correlation between accumulated average vorticity computed using the model presented in section 3.2.2 of this chapter and experimentally measured tensile strength (Zheng, [13]) in the x (CD) and y (MD) directions at different water jet pressures for Fiberweb of Type 1 and Forming Wires of Type A (properties of the fiberweb and

forming wires are given in Tables 3.1 and 3.2, respectively). The horizontal axis in Figure 3.3 corresponds to the computed accumulated average vorticity in the fiberweb, and the vertical axis represents the fabric's tensile strength experimentally measured by Zheng [13]. It is found that the correlation coefficients of the linear fit lines are very close to unity (higher than 0.99). Since the tensile strength is a measure of fiber entanglement, it follows from Figure 3.3 that the accumulated average vorticity in the fiberweb is linearly correlated with the degree of fiber entanglement.

Since the impinging jet velocity is very high (usually about 200 m/s), the flow in the fluid layer, porous fiberweb layer, and in the voids between the forming wires (see Figure 3.1a) is turbulent. A turbulent flow model is used to simulate 3D flow in all three layers.

3.2.2 GOVERNING EQUATIONS AND BOUNDARY EQUATIONS

Governing equations with modifications to account for turbulence effects within the porous medium [4] are given below. These equations describe the water flow through the porous medium (the fiberweb layer) in Cartesian coordinates. This form of equations is similar to equations governing the flow in the clear fluid region; the momentum equation (Equation (3.2)) for the flow in the porous fiberweb layer becomes identical to the momentum equation in the top fluid layer and in the empty space between the forming wires when the Darcy and Forchheimer terms are dropped and the porosity, ϕ , is set equal to unity.

In simulations, the modified k - ϵ turbulence model proposed by Jones and Launder [14] (the JL model) is used for the porous medium (the fiberweb layer). In this model, the Darcy modification (DM) is the additional Darcy damping term, and the Forchheimer

term is split into two parts, namely, the Forchheimer Modification A (FMA) and Forchheimer Modification B (FMB) terms. The k (turbulence kinetic energy) and ε (dissipation rate) equations reduce to the familiar k and ε equations in the top fluid layer and in the voids between the forming wires when the Darcy Modification (DM) and Forchheimer Modification A/B (FMA/FMB) terms are dropped from these equations and ϕ is set to unity. The governing equations are:

Continuity equation:

$$\phi \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (3.1)$$

Momentum equation:

$$\rho \frac{\partial u_i}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial u_i}{\partial x_j} = -\nabla p + \frac{\partial}{\partial x_j} \left[(\mu J + \mu_t) \left(\frac{\partial u_i}{\partial x_j} \right) \right] - \frac{\mu \phi u_i}{K} - \rho \frac{c_F \phi u_i Q}{\sqrt{K}} \quad (3.2)$$

where ρ is the water density, $\mathbf{v}$ is the water velocity (understood as filtration velocity in the porous fiberweb), t is the time, x_i ($i = 1, 2, 3$) are the Cartesian coordinates, p is the pressure, ϕ is the porosity of the fiberweb, and c_F is the dimensionless Forchheimer coefficient [15]. J is the viscosity ratio, μ_{eff} / μ , where μ_{eff} is the effective viscosity of the porous medium and μ is the dynamic viscosity of water. In computations, the value of J is set to unity as, for example, in [16]. K is the permeability of the porous medium and μ_t is the turbulent viscosity which is obtained from the following turbulence model (the JL model):

k equation (for turbulence kinetic energy):

$$\begin{aligned}
\rho \frac{\partial k}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial k}{\partial x_j} &= \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho J \varepsilon + \rho D \\
&\quad - \frac{2\mu\phi k}{K} - \frac{8}{3} \frac{\rho c_F \phi (2Q)k}{\sqrt{K}} + \frac{2c_F \phi \mu_t}{\sqrt{K}} \left(\frac{2}{Q} \right) \left(u_i u_j \frac{\partial u_j}{\partial x_i} \right)
\end{aligned} \tag{3.3}$$

Darcy modification (DM) Forchheimer modification A (FMA) Forchheimer modification B (FMB)

ε equation (for dissipation rate of turbulence kinetic energy):

$$\begin{aligned}
\rho \frac{\partial \varepsilon}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial \varepsilon}{\partial x_j} &= \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + (C_{\varepsilon 1} f_1 P_k - \rho J C_{\varepsilon 2} f_2) \frac{\varepsilon}{k} \\
&\quad + \rho E - \frac{4\mu\phi\varepsilon}{K} - \frac{2c_F \phi}{\sqrt{K}} \left\{ \frac{4}{3} (2Q) \rho \varepsilon + \frac{5\mu}{6} \left(2 \frac{\partial k}{\partial x_j} \frac{\partial Q}{\partial x_j} \right) \right\}
\end{aligned} \tag{3.4}$$

Darcy modification (DM) Forchheimer modification A (FMA)

where

$$\begin{aligned}
\mu_t &= \rho c_\mu f_\mu \frac{k^2}{\varepsilon}, & \nu_t^* &= c_\mu^* \frac{k^2}{\varepsilon}, & \text{Re}_t &= k^2 / \nu \varepsilon \\
P_k &= \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2, & Q &= \sqrt{u_i u_i}, & f_\mu &= \exp \left(\frac{-2.5}{1 + \text{Re}_t / 50} \right) \\
f_1 &= 1.0, & f_2 &= 1 - 0.3 \exp(-\text{Re}_t^2), & D &= 0, & E &= 0 \\
c_\mu &= 0.09, & c_{\varepsilon 1} &= 1.44, & c_{\varepsilon 2} &= 1.92, & \sigma_k &= 1.0, & \sigma_\varepsilon &= 1.3
\end{aligned}$$

In computations, the above governing equations are solved in their dimensionless form, obtained by defining the following dimensionless variables:

$$u^* = \frac{u}{U_0}, \quad v^* = \frac{v}{U_0}, \quad w^* = \frac{w}{U_0}, \quad t^* = \frac{t}{b_0 / U_0}$$

$$x^* = \frac{x}{b_0}, \quad y^* = \frac{y}{b_0}, \quad z^* = \frac{z}{b_0}, \quad \rho^* = 1, \quad p^* = \frac{p}{\rho_0 U_0^2}$$

$$Re = \frac{\rho_0 b_0 U_0}{\mu}, \quad \mu^* = \frac{\mu}{\rho_0 b_0 U_0}, \quad k^* = \frac{k}{U_0^2}, \quad \varepsilon^* = \frac{\varepsilon}{U_0^4}$$

where U_0 is the inlet water jet velocity; $b_0 = 12.7 \times 10^{-6}$ m, which is ten percent of the inlet water jets diameter; and ρ is the water density.

The numerical approach used in the research in this chapter is based on unsteady Reynolds-averaged Navier-Stokes (URANS) equations. Breuer et al. [17] found that URANS equations reliably and efficiently predict flows consisting of regions with thin attached boundary layers but cannot simulate reliably boundary layer flows with separation. Schwarze [18] found that for the oscillating mould flow, the mean values, amplitudes, and frequencies which are deduced from solving URANS equations are in agreement with corresponding experimental observations and data obtained from LES simulations. Since the geometry simulated in this chapter does not include any boundary layers, it is expected that solving URANS equations reasonably reproduces the unsteady characteristics of the flow field. To validate this assumption, a comparison between URANS and LES computations for a 2D case is given below in section 3.3.1.

The following inlet, outflow, and symmetry boundary conditions are utilized:

Inlet section ($0 \leq x \leq X_L$, $0 \leq y \leq Y_L$, $z=0$):

A portion of the impinging water is splashed back by the forming wires, and some of it is reflected and leaves the computational domain through the top and side boundaries. Once the water evacuation effect under the forming wires and the water reflection effect by the wires are balanced, the thickness of the upper fluid layer becomes

constant. Since the flow is turbulent, some amount of turbulence needs to be introduced into the system at the inlet, which is achieved by specifying values of k and ε within the water jet impact areas at the upper surface of the fiberweb (Graham and Bremhorst, [19]). Outside the water jet impact areas at the upper surface of the fiberweb, the free surface interface conditions are utilized. The boundary conditions can be expressed as follows:

$$\begin{cases} k_0 = 0.001U_0^2, & \varepsilon_0 = 0.1643(k_0^{1.5}/0.35D_j) & \text{within the water jets} \\ \partial k/\partial z = 0, & \partial \varepsilon/\partial z = 0 & \text{outside the water jets} \end{cases} \quad (3.5)$$

Symmetry plane ($x=0$ or $x=X_L$, $0 \leq y \leq Y_L$, $0 \leq z \leq Z_L$):

$$\frac{\partial u_i}{\partial x} = \frac{\partial u_i}{\partial y} = 0, \quad \frac{\partial k}{\partial y} = \frac{\partial \varepsilon}{\partial y} = 0, \quad \frac{\partial k}{\partial x} = \frac{\partial \varepsilon}{\partial x} = 0 \quad (3.6)$$

Outflow section ($0 \leq x \leq X_L$, $0 \leq y \leq Y_L$, $z=Z_L$):

A uniform suction boundary condition is used in the outflow section.

$$u_x = u_y = 0, \quad u_z = \begin{cases} Q(1-Ri)/A & \text{at the empty space between the wires} \\ 0 & \text{at the wires} \end{cases} \quad (3.7)$$

$$\frac{\partial k}{\partial z} = \frac{\partial \varepsilon}{\partial z} \quad (3.8)$$

In the outflow boundary condition, Q^+ is the volume flow rate, which is calculated from the given inlet mean velocity of the water jet flow, Ri is the ricochet parameter, which is the reflected portion of water brought into the system by water jets, and A is the area of the voids between the wires at the outflow boundary.

There is no need for explicit imposing of any boundary conditions at the porous/fluid interface since the momentum equation as well as k and ε equations are uniformly valid in both porous and fluid regions, only additional damping terms are

introduced in the turbulence transport equations in the porous layer (the fiberweb). Thus, the fluid filtration velocity as well as the k and ε functions are automatically continuous across the interface.

3.2.3 NUMERICAL METHOD AND GRID SYSTEMS

For the discretization of governing equations, the second-order upwind finite-difference scheme is used for the convection terms, whereas the diffusion terms are discretized using the second-order central finite-difference scheme. The SIMPLE algorithm described in Patankar [20] is utilized to solve the discretized partial differential equations. To avoid divergence, an under-relaxation factor of 0.5 is used for the velocities and pressure, whereas for the turbulent quantities, k and ε , the under-relaxation factor is set to 0.3. All equations are solved in their dimensionless form.

Computations are performed on a uniform staggered grid of $35 \times 50 \times 102$ nodes in the machine direction (MD, y -direction), cross machine direction (CD, x -direction), and streamwise direction (z -direction), respectively. A typical CPU time on a single 2.8 GHz Intel Xeon processor for a 3D simulation is 36 hours.

3.3 RESULTS AND DISCUSSIONS

The parameters of the water jets used in numerical simulations are listed in Table 3.3. Three different fiberwebs are investigated, whose parameters are listed in Table 3.1. The fiberweb parameters are representative of polyester fibers with density of 1.39 g/cm^3 and average fiber diameter of $1.227 \times 10^{-5} \text{ m}$.

Three different forming wire geometries are investigated whose parameters are listed in Table 3.2. The water ricochet by the forming wires is accounted for. It is

estimated that 16% of the water that impinges on the forming wires is reflected back. The ricochet parameter, which represents the reflected portion of the water brought into the computational domain by the jets, is calculated as $Ri = 0.16 \times (1 - \phi)$, where ϕ is the open area of the forming wires, which depends on the geometry of forming wires (see Table 3.2). In simulations, the thickness of the forming wires layer is determined by the largest diameter of the MD and CD wires (see Figure 1b). The Reynolds number of the water jet flow is $Re = \rho U_0 D_j / \mu = 25400$, where D_j is the water jet diameter.

3.3.1 COMPARISON BETWEEN FLOW FIELDS COMPUTED USING URANS AND LES MODELS

To validate the URANS model (described in section 3.2.2), a comparison with the predictions of a Large Eddy Simulation (LES) model for a 2D case is performed. Since no LES model currently exists for a homogenized porous medium, a comparison is carried out for the high-porosity limit of the fiberweb ($\phi \rightarrow 1$) when it can be treated as clear fluid region. LES computations are performed for the same geometry as URANS computations (see Figure 1a) for Forming wires of Type A, the subgrid scale (SGS) is obtained using Smagorinsky model [21]:

$$\nu_T \triangleq (C_S \Delta)^2 |\bar{S}| = (C_S \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} \quad (2.9)$$

where ν_T is the subgrid-scale eddy viscosity, Δ is the filter width, $\Delta = (\Delta x \cdot \Delta y)^{1/2}$, $\bar{S}_{ij}$ is the strain-rate tensor of the filtered velocity field, and C_S is the empirical modeling constant, which is set to 0.025 in the present computations.

Figure 3.4 compares time-averaged dimensionless vorticity distributions in the plane perpendicular to the MD obtained by URANS and LES simulations at $t^* = 400$.

Computations are two-dimensional, and the MD length is set to unity. It is found that LES predicts a larger number of small vortices in the fiberweb than URANS. However, the overall structure of the flow field is similar: there are two large vortices in the upper portion of the fiberweb, and some smaller vortices near the forming wires. Predicted average parameters of the flow field in the fiberweb, such as the accumulated average vorticity in the fiberweb, are very close for these two methods. In 3D simulations, the accumulated average vorticity in three different directions in the porous fiberweb layer is

computed as $\frac{1}{T} \int \left[\iiint_V |(\nabla \times \mathbf{v})_i| dV / V \right] dt$, where $\nabla \times \mathbf{v}$ is the vorticity vector, $|(\nabla \times \mathbf{v})_i|$ is

the absolute value of the i^{th} ($i=x, y, z$) component of the vorticity vector, V is the volume of the fiberweb within the computational domain, and T is the total computational time, which is $114.2 \mu\text{s}$ ($T^* = 1800$). In 2D simulations displayed in Figure 4, there is just one component of accumulated average vorticity, in the x - z plane. URANS predicts the dimensionless accumulated average vorticity to be 1.002×10^{-2} while the LES prediction is 1.001×10^{-2} . The difference is thus less than 0.1%. Since the primary objective of this research is to investigate fiber entanglement, which is assumed to be proportional to the accumulated average vorticity in the fiberweb, it is concluded that URANS results are sufficiently accurate for this purpose.

From the analysis of turbulent jets (White, [22]), if a turbulent round jet impinges into the same (as the jet) ambient fluid, the jet grows at a half-angle of 9.7° , independent of the Reynolds number. The half-angle is the angle between the centerline of the jet and its edge; the edge of the jet is defined as the location where the fluid velocity drops to half the centerline velocity. Computational results indicate that in the water saturated

fiberweb, for the case when porosity is very large ($\phi \rightarrow 1$), the water jet grows at a half-angle of 8.5° . This means that computational results are within 12% of the theoretical value given in [22]. The difference can be explained by different turbulence models used in this chapter and in [22].

3.3.2 INFLUENCE OF THE WATER RICOCHET ON THE FLOW FIELDS

Parameters of Fiberweb of Type 1 (Table 3.1) and Forming Wires of Type A (Table 3.2) are used to obtain computational results in this section.

The flow field is visualized by dimensionless velocity and vorticity distributions, which are displayed in Figure 3.5a. The streamlines are strongly curved in the regions containing vortices; therefore, as the vortex comes through the fiberweb, the fibers located within the vortex swirl along the streamlines and entangle with other fibers located in this region. It is also found that there are small backflow regions near the forming wires, especially near the middle forming wire (see the boxed region in Figure 3.5a), in which water is reflected back by the wires. The water reflection by the wires enhances interaction between the water and the fibers because water flows through the same region of the fiberweb twice, which causes more vortices and results in a better fiber entanglement.

The calculated dimensionless accumulated average vorticity in the x - y plane (in the z -direction) is 4.174×10^{-2} , which is much larger than that in the other two planes (1.069×10^{-2} in the y - z plane and 1.002×10^{-2} in the x - z plane, respectively). This indicates that most of the rotational effect of the turbulent flow in the fiberweb is in the x - y plane, which suggests that most of the fibers in the fiberweb are entangled in the x - y plane (the MD-CD plane). This result is consistent with industry observations (Holmes, [23]).

3.3.3 EFFECT OF THE POROUS LAYER AND ITS PERMEABILITY

The effect of permeability of the porous fiberweb on hydrodynamics of water flow is investigated. Three fiberwebs with different permeabilities, whose parameters are listed in Table 3.1, are considered. These computations are performed for Forming Wires of Type A.

Figures 3.5a-c compare velocity and vorticity distributions in the flow field in the plane perpendicular to the MD at $y^* = 18$ for the three fiberwebs that have different porosities and permeabilities at $t^* = 900$. The permeability of Fiberweb of Type 1 is the largest, while that of Fiberweb of Type 3 is the smallest. From Figures 3.5a-c, it is evident that the permeability of the fiberweb has a significant impact on the flow pattern in the fiberweb. In the computational domain, there are two large vortices that develop in the upper portion of the fiberweb layer; these vortices break down into a few smaller vortices as they move through the fiberweb. When the fiberweb permeability is decreased, the two large vortices that develop at the upper boundary of the fiberweb increase in size and break down into smaller vortices at a lower position. This happens because the momentum of water is larger for the fiberweb with a higher permeability, so the water pressure fluctuations occur at a higher frequency, which makes it easier for the vortex to break down [24, 25]. Therefore, in Fiberweb of Type 1, the upper two vortices break down before they had a chance to grow large. This explains why a porous medium with a smaller permeability can sustain a larger vortex moving through it. When the permeability is increased, the large vortex breaks down into smaller vortices before it has grown. From vorticity contour lines, it is also evident that vorticity in the fiberweb

decreases with the decrease of the fiberweb permeability. Therefore, it is expected that more densely packed fiberwebs entangle less efficiently than loose fiberwebs.

As mentioned earlier in this chapter, it is assumed that the degree of fiber entanglement is proportional to the accumulated average vorticity in the fiberweb. Dimensionless average vorticities in Fiberwebs 1 through 3 are compared in Table 3.4. It is evident that the accumulated average vorticity in Fiberwebs 1 through 3 in different planes in the fiberweb decreases with the decrease of fiberweb permeability, meaning that Fiberweb of Type 1 would produce the best fabric at the same input energy.

3.3.4 EFFECT OF THE FIBERWEB THICKNESS

To investigate the effect of the fiberweb thickness on the flow pattern and fiber entanglement in the hydroentanglement process, simulations are performed for eight different porous fiberweb thicknesses ranging from 0.40 to 2.50 mm. The permeability of all fiberwebs is the same and corresponds to permeability of Fiberweb of Type 1.

Figure 3.6 depicts the dimensionless accumulated average vorticity in the fiberweb versus dimensionless fiberweb thickness (10% of the water jet diameter is used as a reference length) for Forming Wires of Types A, B, and C, which are characterized by different wire diameters and open areas (see Table 3.2). The results are shown in the MD, CD, and fiberweb thickness directions. It is evident that for all three types of forming wires, the average vorticities in the fiberweb in all three directions decrease with the increase of the fiberweb thickness. This means that for a single manifold the degree of fiber entanglement is the largest for the fiberweb of the smallest thickness. The results also suggest that the accumulated average vorticity in the fiberweb attains an asymptotic limit as the fiberweb thickness increases. Indeed, when the fiberweb thickness is larger

than 1.50 mm (dimensionless fiberweb thickness is larger than 118), the accumulated average vorticity in the fiberweb remains almost unchanged. This is because for a large fiberweb thickness, the kinetic energy of the water jets completely dissipates in the upper portion of the fiberweb, causing almost no entanglement in its lower portion. This means there is a maximum fiberweb thickness up to which the process is efficient.

Comparing the results for the three different forming wires, it is evident that the accumulated average vorticity in the fiberweb for Forming Wires of Type B is the largest in each direction. This is because the ricochet parameter for Forming Wires of Type B, $Ri_B=14.40$, is much larger than for the other two forming wires, which causes more interaction between the water flow and the fibers, hence a better fiber entanglement. The accumulated average vorticity in the fiberweb for Forming Wires of Type C is smaller than that for Type A despite a larger ricochet parameter. This is because the ricochet parameters for Forming Wires of Type A and C are pretty close ($Ri_A=11.36$ and $Ri_C=12.00$, see Table 3.2); however, Forming Wires of Type A are much finer, and the reflected water flow by these wires generates a larger number of small vortices in the fiberweb resulting in larger accumulated average vorticity. This suggests that the degree of fiber entanglement is larger and the process is more efficient for the forming wires with finer wires providing the wires have close ricochet parameters.

3.3.5 EFFECT OF THE INLET WATER JET VELOCITY

The effect of the inlet water jet velocity on fiber entanglement is investigated. Simulations are performed for eight different inlet water jet velocities that range from 100 to 300 m/s. Parameters of Fiberweb of Type 1 are used.

Figure 3.7 shows the dimensionless accumulated average vorticity in the fiberweb versus the inlet water jet velocity for different forming wires. It is evident that for all three types of forming wires, the accumulated average vorticity in the fiberweb in all three directions increase almost linearly with the increase of the inlet jet velocity up to 250 m/sec. Increasing the jet velocity beyond 250 m/sec did not cause appreciable increase in vorticity in all three directions. This means that for a single manifold the degree of fiber entanglement is larger when the inlet jet has a higher velocity. Since providing a higher jet velocity in this process requires high energy, the results of the model suggest that very high jet velocities (higher than 250 m/s for cases addressed in this chapter) should be avoided since the improvement of entangling efficiency at such high inlet velocities is not that significant. There is an optimal inlet jet velocity at which there is a good balance between the energy consumption and the degree of fiber entanglement. According to the results presented in Figure 3.7, this optimal jet velocity is about 250 m/s for the cases studied in this chapter.

Similar to the results presented in section 3.3.4, it is found that in each direction the accumulated average vorticity in the fiberweb for Forming Wires of Type B is the largest, while that for Forming Wires of Type C is the smallest

3.4 CONCLUSIONS

3D simulation results of the water flow through the fiberweb and forming wires show water reflection regions near the wires. By analyzing the accumulated average vorticity in the fiberweb, it is found that most of the fibers are entangled in the MD-CD plane.

With the decrease of the fiberweb permeability, two large vortices that are generated at the upper boundary of the fiberweb increase in size; they break down to smaller vortices at a lower position. The results suggest that a fiberweb with a smaller permeability can sustain a larger vortex passing through it; the vortex would break down earlier into smaller vortices in a fiberweb of larger permeability. The average water vorticity in the fiberweb decreases with the decrease of the fiberweb permeability, which decreases the degree of fiber entanglement and the quality of the fabric.

It is also established that the accumulated average vorticity in the fiberweb decreases with the increase of the fiberweb thickness. The results indicate that the accumulated average vorticity attains an asymptotic limit as the fiberweb thickness increases. This is because for a large fiberweb thickness, the energy of the water jets completely dissipates in the upper portion of the fiberweb, causing almost no entanglement in its lower portion. This suggests there is a maximum fiberweb thickness up to which the process remains efficient. Additionally, it is found that the degree of fiber entanglement increases almost linearly with the increase of the inlet jet velocity up to a jet velocity of 250 m/s for the cases studied; after that the increase in vorticity (or fiber entanglement) is not appreciable.

By investigating the effect of the fiberweb thickness and inlet jet velocity, it is found that the ricochet parameter for the forming wires has a major effect on the degree of fiber entanglement. The use of a finer mesh forming surface leads to a higher degree of fiber entanglement if ricochet parameters of the fine and coarse forming surfaces are close.

Table 3.1 Geometrical parameters of fiberwebs.

Fiberweb	Permeability (m ²)	Porosity (%)	Thickness, h_2 (mm)
1	2.915×10^{-10}	95	0.711
2	2.320×10^{-11}	85	0.711
3	5.737×10^{-12}	75	0.711

Table 3.2 Geometrical parameters of forming wires.

Forming wires	Count (/inch)	MD wire Diameter (mm)	CD wire Diameter (mm)	Open Area (%)	Ricochet parameter Ri (%)
A	100×90	0.11	0.14	29	11.36
B	84×72	0.22	0.22	10	14.40
C	36×27	0.40	0.40	25	12.00

Table 3.3 Water jet and fluid layer parameters.

Jet diameter	Distance between centerline of two jets	Jet pressure	Jet velocity	Thickness of fluid layer, h_l
0.127 mm	0.635 mm	20 MPa	200 m/s	0.0254 mm

Table 3.4 Dimensionless accumulated average vorticity in the fiberweb for fiberwebs with different permeabilities.

	x - y Plane	y - z Plane	x - z Plane
Fiberweb 1	4.174×10^{-2}	1.069×10^{-2}	1.002×10^{-2}
Fiberweb 2	3.683×10^{-2}	0.972×10^{-2}	0.898×10^{-2}
Fiberweb 3	3.452×10^{-2}	0.908×10^{-2}	0.823×10^{-2}

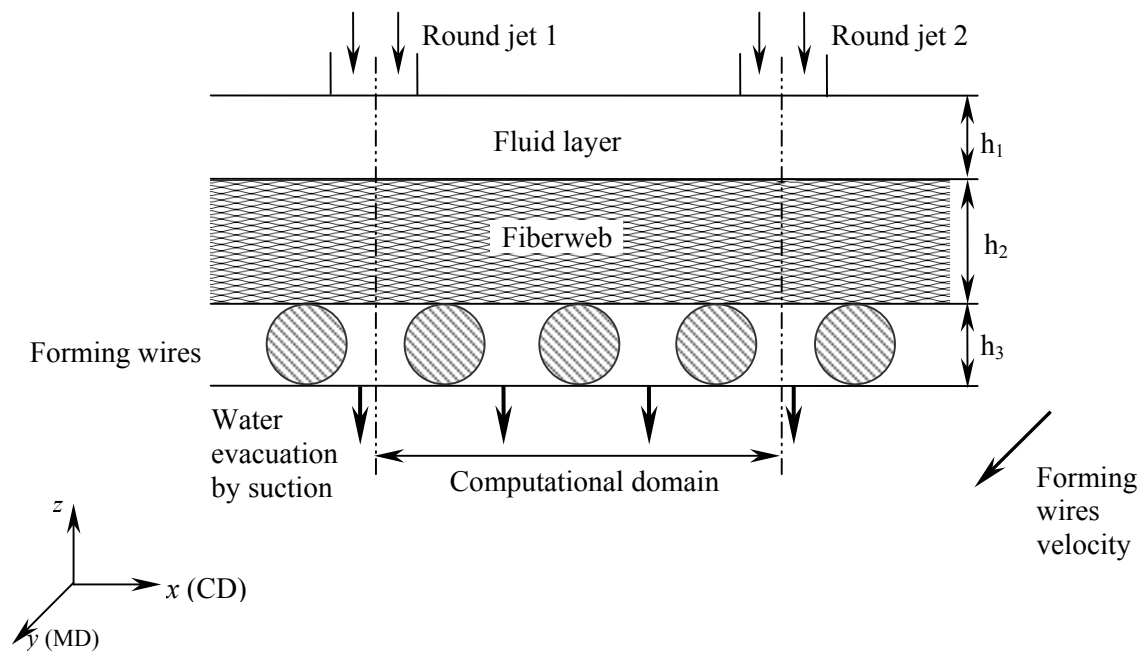


Figure 3.1a Schematic diagram of the problem and the computational domain.

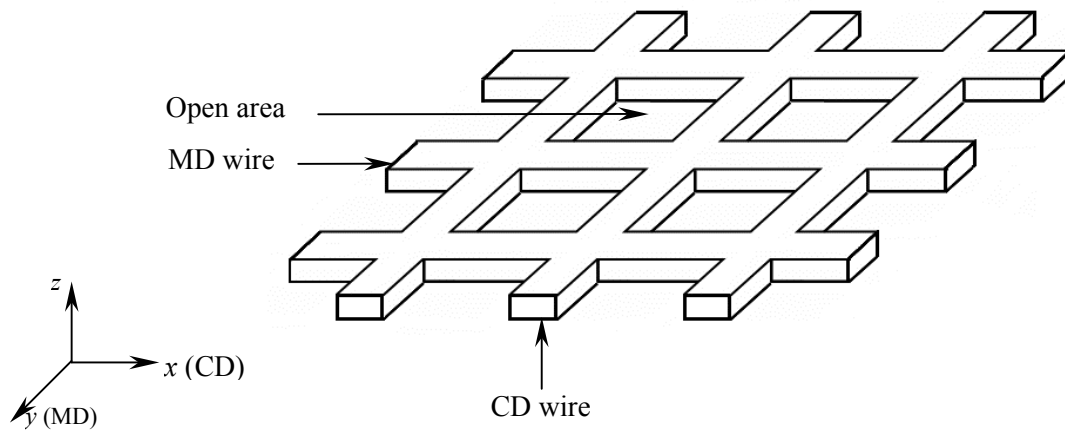


Figure 3.1b Typical geometry of the forming wires.

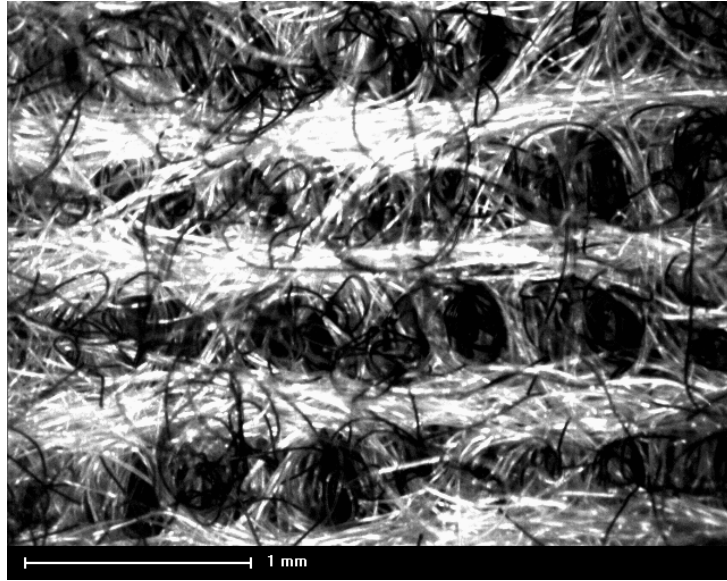
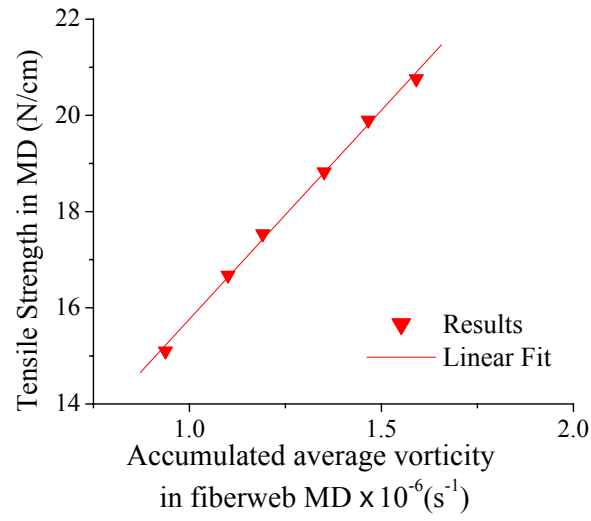
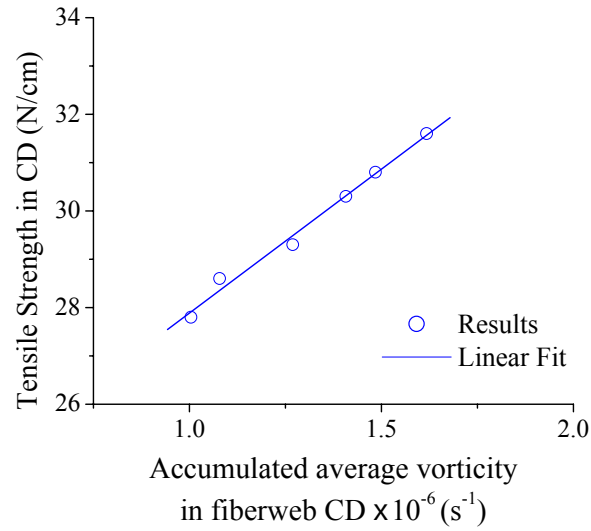


Figure 3.2 Entangled fibers in the fiberweb.

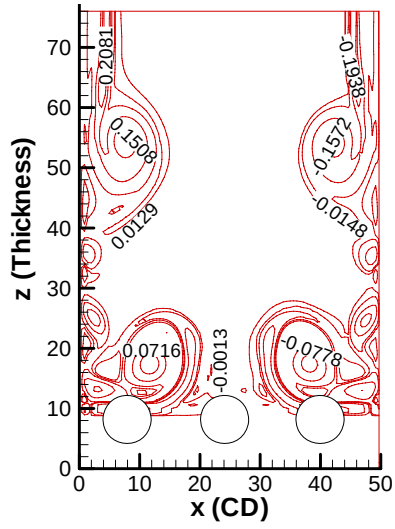


(a) Results in y(MD) direction (Correlation coefficient $R=0.99864$)

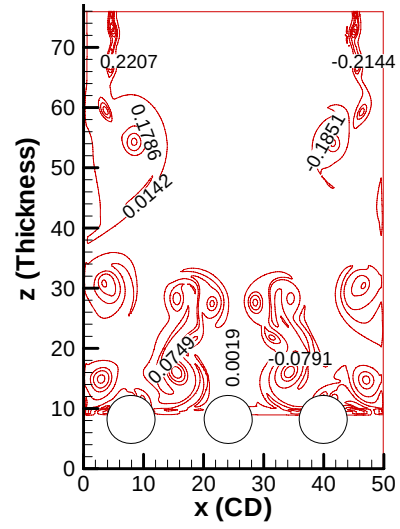


(b) Results in x(CD) direction (Correlation coefficient $R=0.99458$)

Figure 3.3 Calculated accumulated average vorticity versus experimentally measured tensile strength.

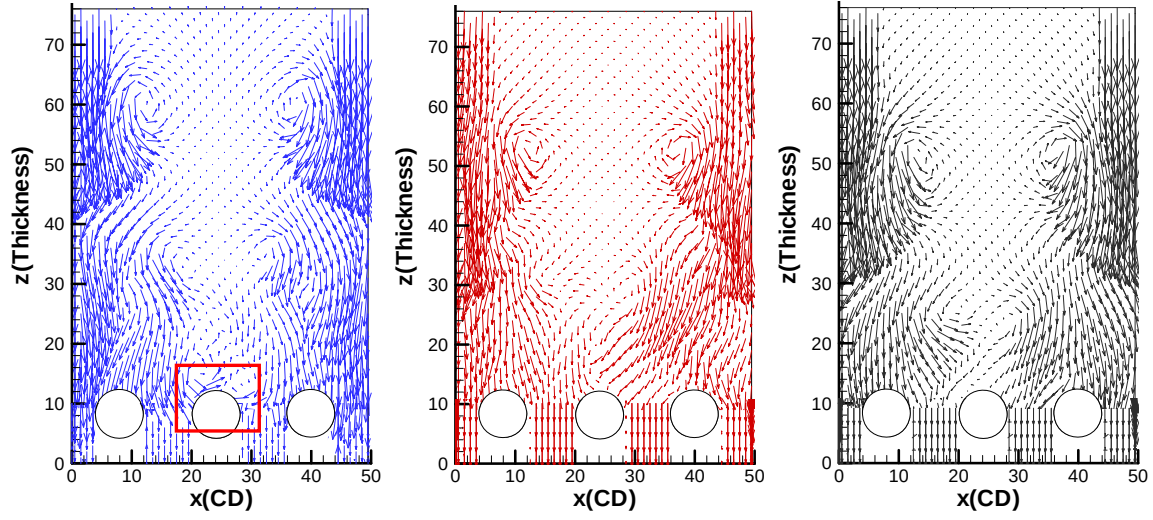


(a) URANS

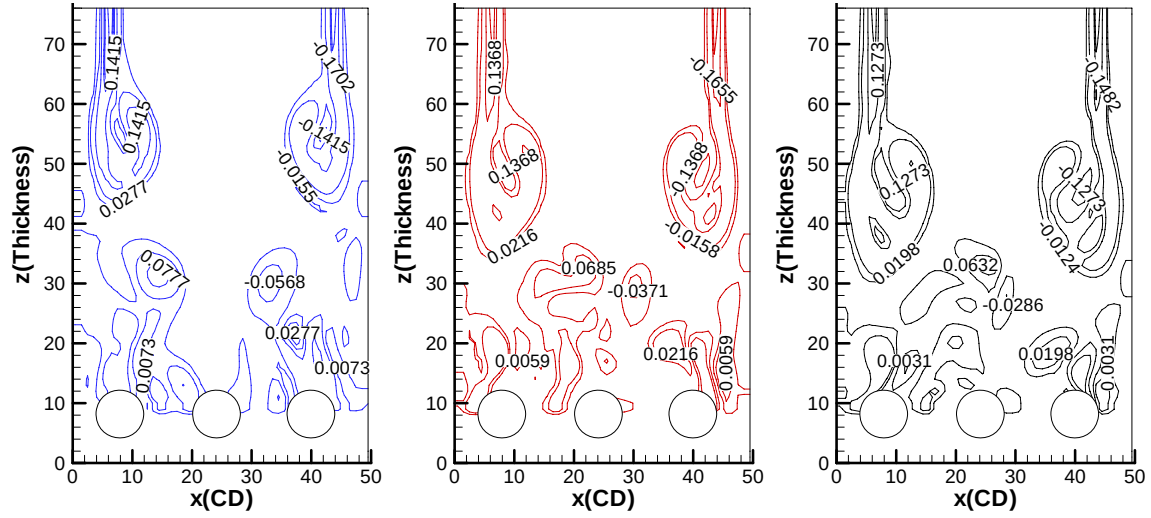


(b) LES

Figure 3.4 Comparison of dimensionless vorticity distributions at $t^* = 400$ predicted by URANS (a) and LES (b) models.



Velocity vector plots



Vorticity distributions

(a) Fiberweb of Type 1

(b) Fiberweb of Type 2

(c) Fiberweb of Type 3

Figure 3.5 Velocity and vorticity distributions for fiberwebs with different permeabilities.

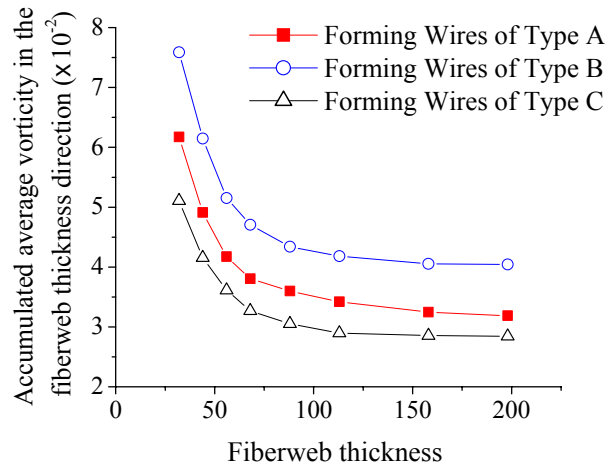
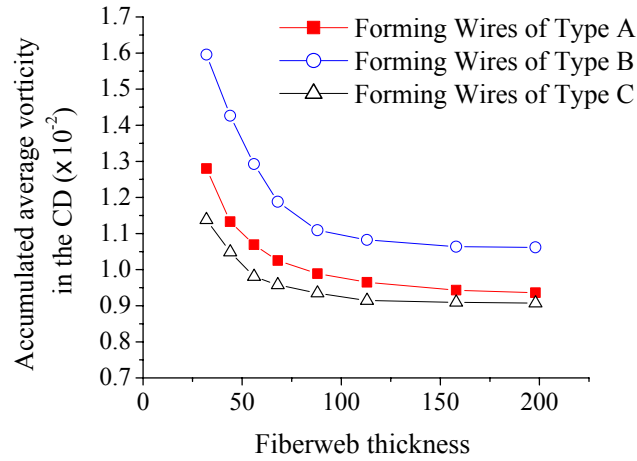
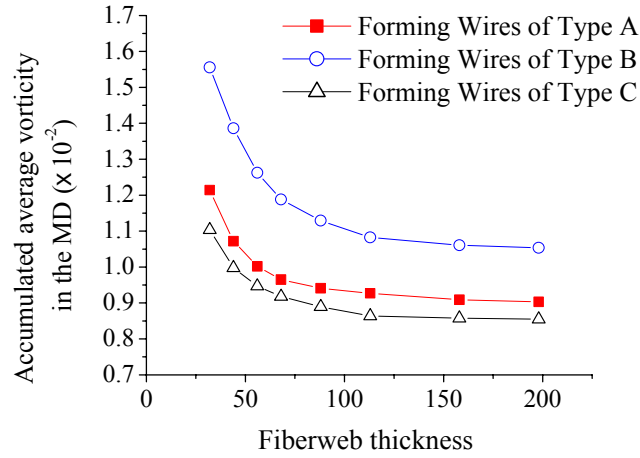


Figure 3.6 Dimensionless accumulated average vorticity in the fiberweb versus dimensionless fiberweb thickness for different forming wire geometries.

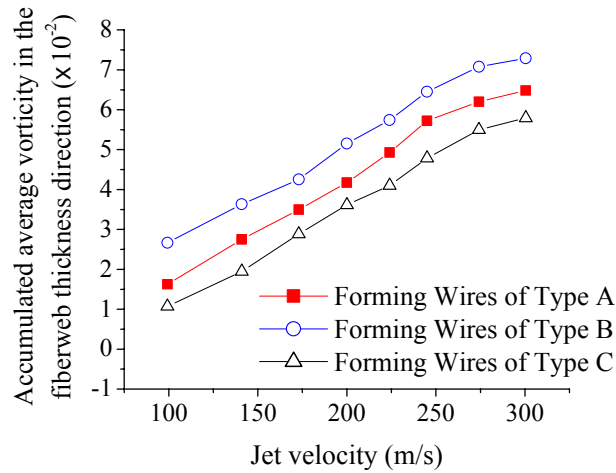
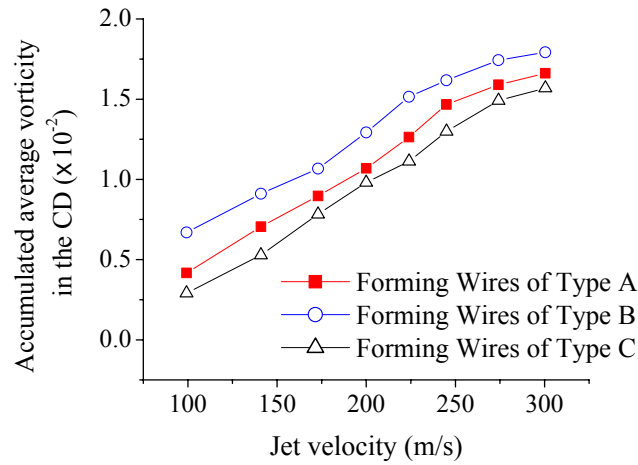
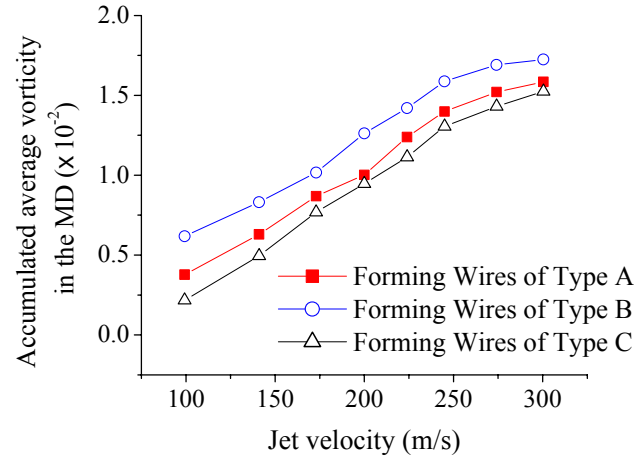


Figure 3.7 Dimensionless accumulated average vorticity in the fiberweb versus inlet water jet velocity for different forming wire geometries.

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4 COMBINED NUMERICAL AND EXPERIMENTAL INVESTIGATION ON THE EFFECT OF JET PRESSURE AND FORMING BELT GEOMETRY ON THE HYDROENTANGLEMENT PROCESS

ABSTRACT

This chapter presents the results of combined experimental and numerical investigation on the effects of the jet pressure and forming belt geometry on fiber entanglement. Extensive comparisons of simulations with experimental data are reported and analyzed to give a clear understanding of the effect of fiberweb and forming belt properties on the critical jet pressure. The modeling results are in good correlation with experimental data for a wide range of jet pressures. The effect of the jet count per unit length on the degree of fiber entanglement is also investigated.

4.1 INTRODUCTION

Hydroentanglement is the fastest growing technology for manufacturing nonwoven fabrics with texture and appearance that resemble woven and knitted fabrics. In the hydroentanglement process, a fiberweb composed of initially loose fibers, which is supported by forming surface, continuously passes under several manifolds of multiple highly pressurized fine water jets. Jet impingement causes multiple vortices as water passes through the fiberweb. Since fibers follow water streamlines and engage in a swirling motion as a result of the impact of water jets, they rotate around other fibers that surround them. This leads to fiber twisting and entangling around neighboring fibers and thus the produced fabric is held together by fiber-to-fiber friction.

A considerable amount of research was conducted to better understand hydroentanglement products and process parameters. In [1] and [2], experimental and numerical investigations of the effect of the nozzle geometry on the water jet breakup and impact force in the hydroentanglement process were performed. In [3], experiments were performed to investigate effects of the initial fiberweb geometry and pressure distribution between different manifolds of water jets on properties of hydroentangled fabrics. The experimental investigation in [4] dealt with the effect of fiberweb and fiber properties on the energy consumption and critical water jet pressure, at which the fabric tensile strength reaches its maximum value.

Experimental studies reported in [5] developed the preliminary structure-process-property relationships for hydroentangled nonwovens. In [6], the authors took two-dimensional SEM images of hydroentangled fabrics, evaluated the fiber orientation and fiber length distribution, and analyzed the relationships between microstructural variables and fabric mechanical properties (strength and modulus), which were used to estimate the degree of entanglement in hydroentangled fabrics.

Experimental studies also shown that utilizing the hydroentanglement process, fiberwebs from cotton [7], or a hybrid of mixed fibers [8] can be entangled to attain high tensile strength and tear resistance, where the latter show possible synergistic improvements in fabric properties.

The energy consumption in the hydroentanglement process was also an important issue in research and development work. In [9], the development of texture during hydroentangling is examined as a function of hydroentangling energy. To reduce energy consumption in the hydroentanglement process, many techniques can be used, such as

improving the water jet injector, designing improved piping and vacuum system as well as developing an efficient high pressure pumping system, better fiber composition and web forming method [10]. Hydroentanglement can also be combined with other bonding processes, such as chemical, thermal or hydrogen, to improve fabric properties and reduce the amount of hydraulic energy required [11].

Despite these extensive experimental studies, there is very few modeling work on the hydroentanglement process. Mao and Russell [12] defined the hydroentanglement intensity as the sum of the deflection depths of all fiber segments subjected to the impinging water jet impact. 2D analysis was performed to investigate the effect of fiber rigidity on the hydroentanglement intensity. Seyam et al. [13] experimentally measured tensile strength and specific energy at low jet pressures, and correlated the results with jet drag forces, which were derived from a 2D geometrical model based on a unit cell of forming wire. The published theoretical models did not deal with prediction of the effect of process speed, fiberweb thickness, jet pressure, and jet count on the performance of the resultant hydroentangled fabrics. In [14, 15] the authors developed a comprehensive numerical model of this process, which showed how the fiberweb structure is modified as water jets pass through the fiberweb and forming surface and revealed, by correlating simulation results with experiments, that the degree of fiber entanglement is proportional to the average vorticity in the fiberweb. However, experimental data used in [14, 15] to correlate with simulations are for low jet pressures that are currently not practiced by industry (lower than 9 MPa). The aim of this chapter is to perform experimental studies at high jet pressures and compare those with simulations to show the usefulness of the

model at high jet pressures. The effect of jet count per unit length is also numerically investigated in this chapter.

4.2 EXPERIMENTAL SETUP

Samples of hydroentangled fabric are produced using Fleissner's hydroentanglement machine with three jet manifolds available at the facilities of Nonwoven Cooperative Research Center (NCRC), NC State University. Three carded and crosslapped webs from polyester fibers of different basis weights (50 g/m^2 , 75 g/m^2 , and 100 g/m^2) were produced. The polyester fiber used is of linear density of 0.168 g/km (1.68 dtex) and average fiber length of 38 mm . Three woven forming belts (see Table 4.1) provided by Albany International were used as forming surfaces. The fiberweb and forming belt speed were kept constant at 30 m/min .

The highly pressurized water jets impinging on the fiberweb have the diameter of 0.127 mm , and density of 15.8 jets/cm (40 jets/inch). Table 4.2 shows the jet pressure levels of the three manifolds. The low jet pressure of the first manifold was kept constant at 4 MPa to prewet the fiberwebs. A total of 54 hydroentangled fabrics were produced (three basis weights $\times$ six pressure levels $\times$ 3 belts). Each trial (fabric) was replicated three times.

After the hydroentanglement process, rectangular samples of a size of $25 \text{ mm} \times 150 \text{ mm}$ were cut from each fabric; five samples in the machine direction and five in the cross machine direction. The fabric thickness was measured at 10 different locations on each sample and an average was calculated.

The ASTM standard method D5035-95 was used to measure the breaking force and modulus of each fabric sample. In conjunction with an average sample thickness and width values, the average tensile strength and modulus for each set of five samples in the machine direction (MD) and cross-machine direction (CD) were calculated using the measured load values.

4.3 MATHEMATICAL MODEL

The modeling approach in this chapter is the same as that in the previous chapter (see section 3.2, also see Xiang et al. [14, 15]). The fiberweb is modeled as a layer of a porous medium with uniform porosity; to investigate the effect of different forming belts the realistic geometry of the forming wires under the fiberweb is modeled. The model also accounts for the part of water that is splashed back by the forming wires. Figure 4.1 depicts the cross-section of the computational domain by a plane perpendicular to the machine direction. The x -axis is directed in the CD, the y -axis is in the MD, and the z -axis is perpendicular to the x - y plane (thickness direction the fiberweb and the forming wires). The highly pressurized water jets impinging on the fiberweb have a typical diameter of 0.127 mm. It is assumed that the diameter of the water jet remains constant until the jet hits the fiberweb, and there is no interaction between the jets before they hit the fiberweb. This is because the breakup length of the water jet is much larger than a typical distance between the jet nozzle and the fiberweb in the hydroentanglement process [1].

Three-dimensional turbulent flow in the thin water layer on top of the fiberweb, porous fiberweb layer, and in the voids between the forming wires is simulated numerically using the method developed in [14].

4.4 RESULTS AND DISCUSSION

4.4.1 EXPERIMENTAL RESULTS

For the three fiberwebs with different basis weights, Figures 4.2 through 4.4 show the measured tensile strength and modulus properties of the hydroentangled fabrics in the MD and CD for different forming belts. It is evident that when other process parameters are the same, the tensile strength and modulus in the CD are larger than those in the MD for a given fiberweb. This is because tensile strength of hydroentangled fabrics is anisotropic; the direction with greater strength is determined by the initial fiber orientation. The fiberwebs used in experiments were carded and cross-laid. The fiber orientation in such fiberwebs is mostly in CD and this explains the reason behind the why the tensile strength in CD is higher than in MD.

It is also found that for a given fiberweb, the tensile strength and modulus for the finest forming belt (100 mesh) are the highest in MD and CD, while those for the coarsest forming belt (10 mesh) are the lowest.

From results obtained for the 50 g/m² fiberweb (see Figure 4.2), it is evident that there is a critical jet pressure for this fiberweb, which is around 14 MPa. Increasing the pressure from 14 MPa to 17 MPa reduces the tensile strength and modulus of the fabrics in both MD and CD. The critical jet pressures for the 75 g/m² and 100 g/m² fiberwebs are about 17 MPa (Figure 4.3) and 20 MPa (Figure 4.4), respectively. Since providing a

higher jet pressure in this process requires higher energy input into the process, these experimental results suggest that jet pressures higher than critical should be avoided since the process efficiency declines.

4.4.2 SIMULATION RESULTS

The effect of the inlet water jet pressure on fiber entanglement was also investigated numerically. Simulations were performed for nine different inlet water jet pressures that range from 5 to 35 MPa (Table 4.3). In simulations, three carded and cross-lapped fiberwebs with 50 g/m², 75 g/m², and 100 g/m² basis weights were used, which are the same as those used in experiments. The line speed was fixed at 30 m/min.

The average vorticity in the fiberweb is used in simulations to evaluate the fabric tensile strength (the degree of fabric entanglement). Figure 4.5 shows the average vorticity in the fiberweb versus the water jet pressure for different forming wires of Table 4.1 for the 50 g/m² fiberweb. It is evident that for all three types of forming wires, the average vorticity in the fiberweb in all three directions increases almost linearly with the increase in the jet pressure up to 14 MPa. Increasing the jet pressure beyond 14 MPa does not cause any appreciable increase in vorticity in all three directions. Additionally, the vorticity in the fiberweb slightly decreases when the input jet pressure is larger than 14 MPa, which means that for the fiberweb with the basis weight of 50 g/m², the fiber entanglement does not improve when the jet pressure exceeds 14 MPa. Thus the simulation results predict that the critical jet pressure for the fiberweb of 50 g/m² is 14 MPa, which is consistent with experimental data (see section 4.4.1). The modeling results also revealed that the finer is the mesh, the larger the tensile strength and modulus are, which is also consistent with experimental results.

Figure 4.6 shows the average vorticity in the fiberweb versus the water jet pressure for different forming wires for the 75 g/m² fiberweb. The critical pressure of 17 MPa is predicted for the fiberweb with the basis weight of 75 g/m². For this fiberweb, when the jet pressure is less than the critical pressure (17 MPa), the degree of fiber entanglement increases with jet pressure, while the improvement of fiber entanglement is insignificant when the jet pressure increases beyond 17 MPa. Figure 4.7 shows the average vorticity in the fiberweb versus the water jet pressure for different forming belts for the 100 g/m² fiberweb. The critical jet pressure for this fiberweb is predicted to be 20 Mpa.

4.4.3 CORRELATION BETWEEN EXPERIMENTS AND SIMULATIONS

Figure 4.8 shows the correlation between simulations and experiments for the 50 g/m² fiberweb. The horizontal axis represents the simulated average vorticity in the fiberweb (Figure 4.5) at different jet pressures, and the vertical axis represents the experimentally measured tensile strength and modulus (Figure 4.2) at the same jet pressures. It is found that the tensile strength and modulus of this fiberweb in the MD are both linearly correlated with the average vorticity in the fiberweb in MD. However, linear correlation between tensile strength and modulus versus average vorticity in the CD for this fiberweb does not work that well. This is because the fiberweb with the basis weight of 50 g/m² is very thin, and its tensile strength and modulus in the CD are affected very negatively when the jet pressure is above the critical pressure (14 MPa), but the simulation of water flow alone cannot predict the fabric properties well for thin fiberwebs. So the simulation can be improved by accounting for the variation of fiberweb porosity at different jet pressures.

Figure 4.9 correlates the simulation results of Figure 4.6 with experimental data of Figure 4.3 for the 75 g/m² fiberweb. Figure 4.10 correlates the simulation results of Figure 4.7 with experimental data of Figure 4.4 for the 100 g/m² fiberweb. It is found that for these two fiberwebs, the measured tensile strength and modulus in the MD or CD are linearly correlated with the simulated average vorticity in the fiberweb in MD or CD, respectively.

In summary, the suggested modeling approach works well not only at low jet pressures considered in [14, 15], but also at high jet pressures. The correlations between simulations and experiments at a wide range of jet pressures show that both the tensile strength and the modulus exhibit an approximately linear correlation with the average vorticity in the MD or CD. This makes it possible to predict the optimal process parameters for a given fiberweb and forming belt without performing extensive experiments.

There is room for further improvement of the developed model. The conducted experiments show for the investigated fiberweb, fabric tensile strength and modulus in the CD is much higher than those in the MD, while simulations predict only a slightly higher average vorticity in the CD than that in the MD. This is because the fiberweb is modeled as a layer of isotropic porous medium in this chapter. The improved version of the model must account for anisotropic properties of fiberweb; the effect of anisotropy becomes more pronounced at high jet pressures.

4.4.4 MODEL PREDICTION: EFFECT OF DISTANCE BETWEEN TWO NEIGHBORING WATER JETS IN A MANIFOLD ON FIBER ENTANGLEMENT

A typical geometry of nozzles used in the hydroentanglement process is shown in Figure 4.11, where D is the distance between the two neighboring water jets. Six different jet counts, listed in Table 4.4, are investigated. The investigated fiberweb has a basis weight of 50 g/m^2 , and is carded and crosslapped with polyester fibers, which have the density of 1.39 g/cm^3 and average fiber diameter of $1.227 \times 10^{-5} \text{ m}$. The results presented in this section are for the forming wire of 100 mesh and line speed of 30 m/min.

From the discussion in Section 4.4.2, it follows that the critical pressure for the fiberweb with the basis weight of 50 g/m^2 is about 14 Mpa. The impact of a single manifold of the jets is considered, and three different jet pressures are simulated, those are 5, 8.5, and 12 MPa.

Figure 4.12(a) shows the specific energy at different jet counts, and Figures 4.12(b), (c) and (d) depict the average vorticity in the fiberweb versus jet count per unit length in the MD-CD plane, MD-fiberweb thickness direction (TD) plane, and CD-TD plane at different jet pressures. The specific energy increases linearly with the jet count. It is evident that at the jet pressure of 5 MPa, the fiber entanglement increases almost linearly with the increase of jet count. At the jet pressure of 8.5 MPa, the fiber entanglement still increases with the increase of the jet count in a manifold, but the rate of the increase of fiber entanglement with increase in the jet count becomes lower. When the jet pressure is increased to 12 MPa, the fiber entanglement improves only as long as jet count increases up to 15.8 jets/cm (40 jets/inch). Increasing the number of jets beyond 15.8 jets/cm (40 jets/inch) does not cause appreciable increase in fiber entanglement.

It is also found in Figure 4.12 that when the other processing parameters are the same, to obtain a given degree of fiber entanglement (a given average vorticity in the fiberweb), the process can be run at a lower jet pressure by using a higher jet count. This indicates that to attain the maximum fabric tensile strength, one could run the process at a jet pressure lower than the critical pressure (obtained in sections 4.4.1 and 4.4.2) by increasing the jet count per unit length in a manifold beyond 15.8 jets/cm. This makes it possible to reduce energy consumption in the hydroentanglement process.

4.5 CONCLUSIONS

Experimental measurements of the tensile strength and modulus of hydroentangled fabrics produced from polyester fiberwebs with different basis weights are presented. The results show that the tensile strength and modulus in the CD are higher than those in the MD for a given fiberweb because fiber orientation is mostly in CD. It is also evident that the tensile strength and modulus in the MD and CD directions are larger when a finer mesh forming belt is used. Using the model and the corresponding experimental data, we verified the well known established fact that there is a critical jet pressure for a given fiberweb. Tensile strength of hydroentangled fabrics increases with jet pressure when the jet pressure is smaller than the critical pressure; it reaches its maximum at the critical pressure and subsequently levels off (or even decreases slightly) as the jet pressure continues to increase. The critical jet pressure increases with the fiberweb basis weight.

Simulation results correctly reproduce the effect of the water jet pressure and forming belt geometry on fiber entanglement. Comparisons of numerical results with

experimental data show that both the tensile strength and the modulus are linearly correlated with the average vorticity in the fiberweb in the MD and CD. The model thus provides a tool for revealing the optimal parameters to manufacture fabrics with high degree of entanglement and performance while minimizing the energy consumption.

The investigation of the effect of jet count on fiber entanglement indicates that for a given fiberweb and forming belt, it is desirable to run the hydroentanglement process at a lower jet pressure than the critical pressure by increasing the jet count higher than 15.8 jets/cm (which is traditionally practiced). This makes it possible to produce the fabric with its maximum strength as well as saving the energy consumption.

Table 4.1 Geometrical parameters of the forming wires.

Forming wires	Count (/cm) [/inch]	MD wire diameter (mm)	CD wire diameter (mm)	Open area (%)	Wire cross-section shape	Thickness (mm)
100 mesh	40.0×35.4 [100×90]	0.11	0.14	29	Round	1.6510
36 mesh	14.2×10.6 [36×27]	0.40	0.40	25	Round	0.3586
10 mesh	4.3×4.3 [11×11]	0.89	1.00	35	Round	0.2794

Table 4.2 Jet pressure levels at different manifolds.

Pressure (MPa)		
Manifold No. 1	Manifold No. 2	Manifold No. 3
4	5	5
4	9	9
4	14	14
4	17	17
4	20	20
4	22.5	22.5

Table 4.3 Jet pressure levels used in simulations.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9
Manifold 1 (MPa)	4	4	4	4	4	4	4	4	4
Manifold 2 (MPa)	5	9	14	17	20	24	28	32	35
Manifold 3 (MPa)	5	9	14	17	20	24	28	32	35

Table 4.4 Jet counts used in simulations.

Jet count (jets/cm) [jets/inch]	7.9 [20]	11.8 [30]	15.8 [40]	19.7 [50]	23.6 [60]	37.6 [70]
Distance between two neighboring jets, D (mm)	1.270	0.847	0.635	0.508	0.423	0.363

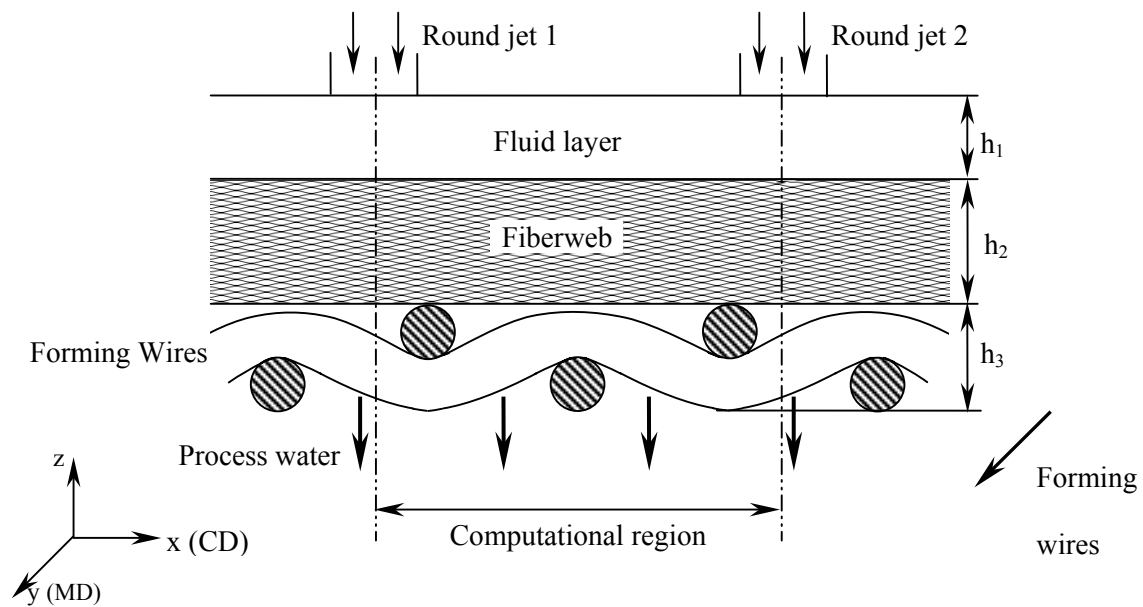


Figure 4.1 Schematic diagram of the problem and computational domain.

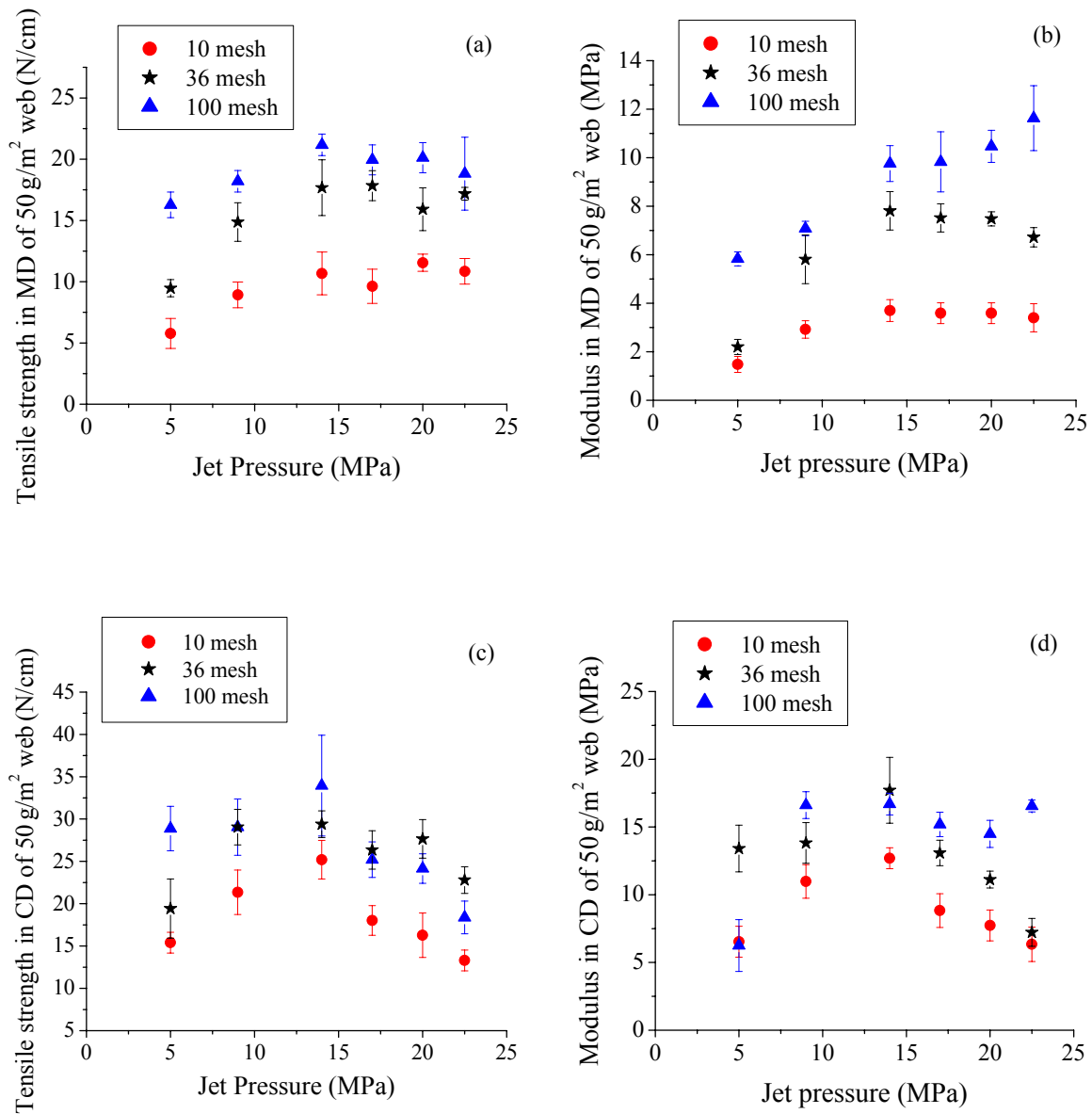


Figure 4.2 Experimental tensile strength and modulus results for 50 g/m² web:
(a) strength-pressure in the MD; (b) modulus-pressure in the MD; (c) strength-pressure in the CD; (d) modulus-final pressure in the CD.

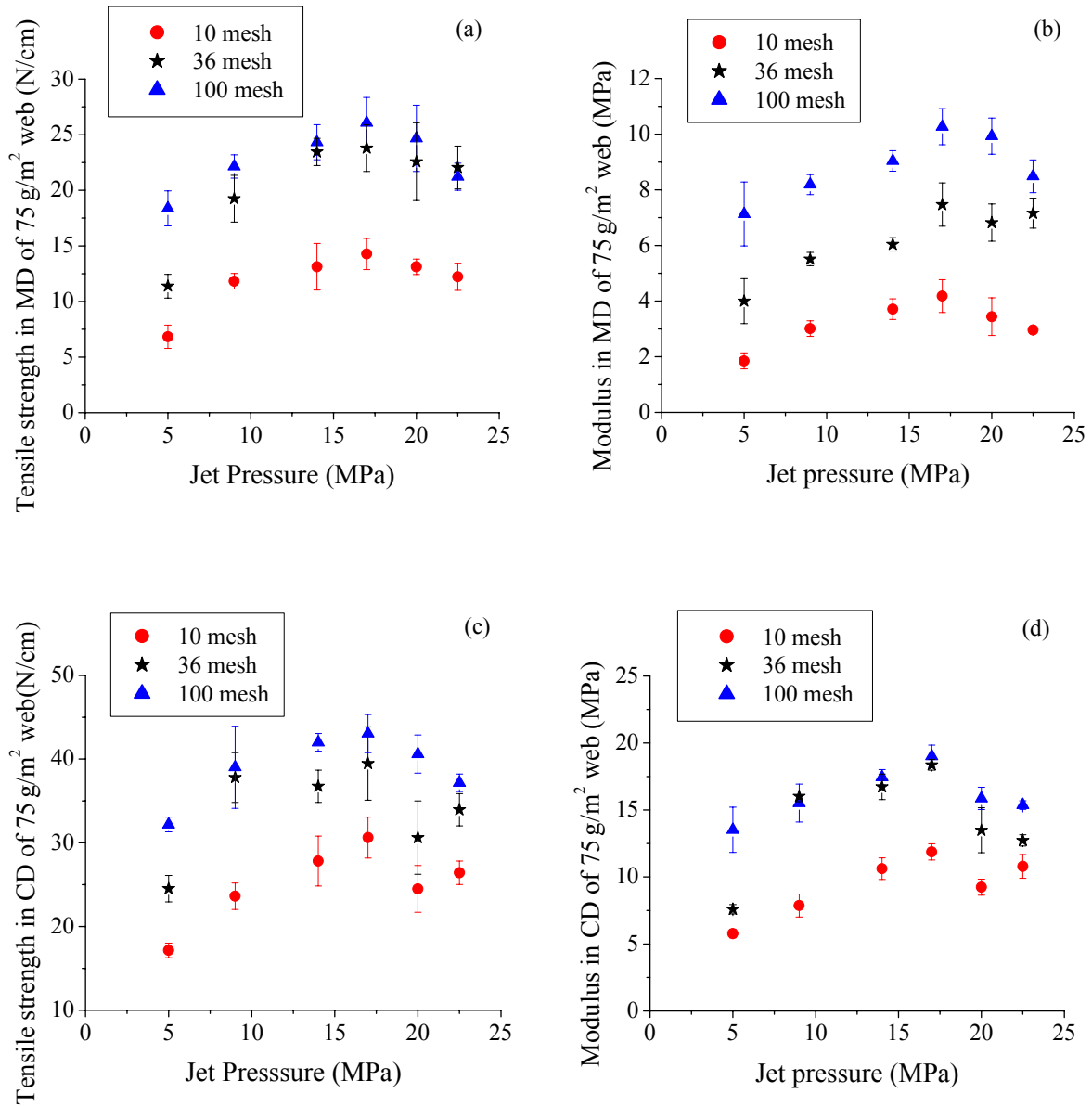


Figure 4.3 Experimental tensile strength and modulus results for 75 g/m² web:
(a) strength-pressure in the MD; (b) modulus-pressure in the MD; (c) strength-pressure in the CD; (d) modulus-pressure in the CD.

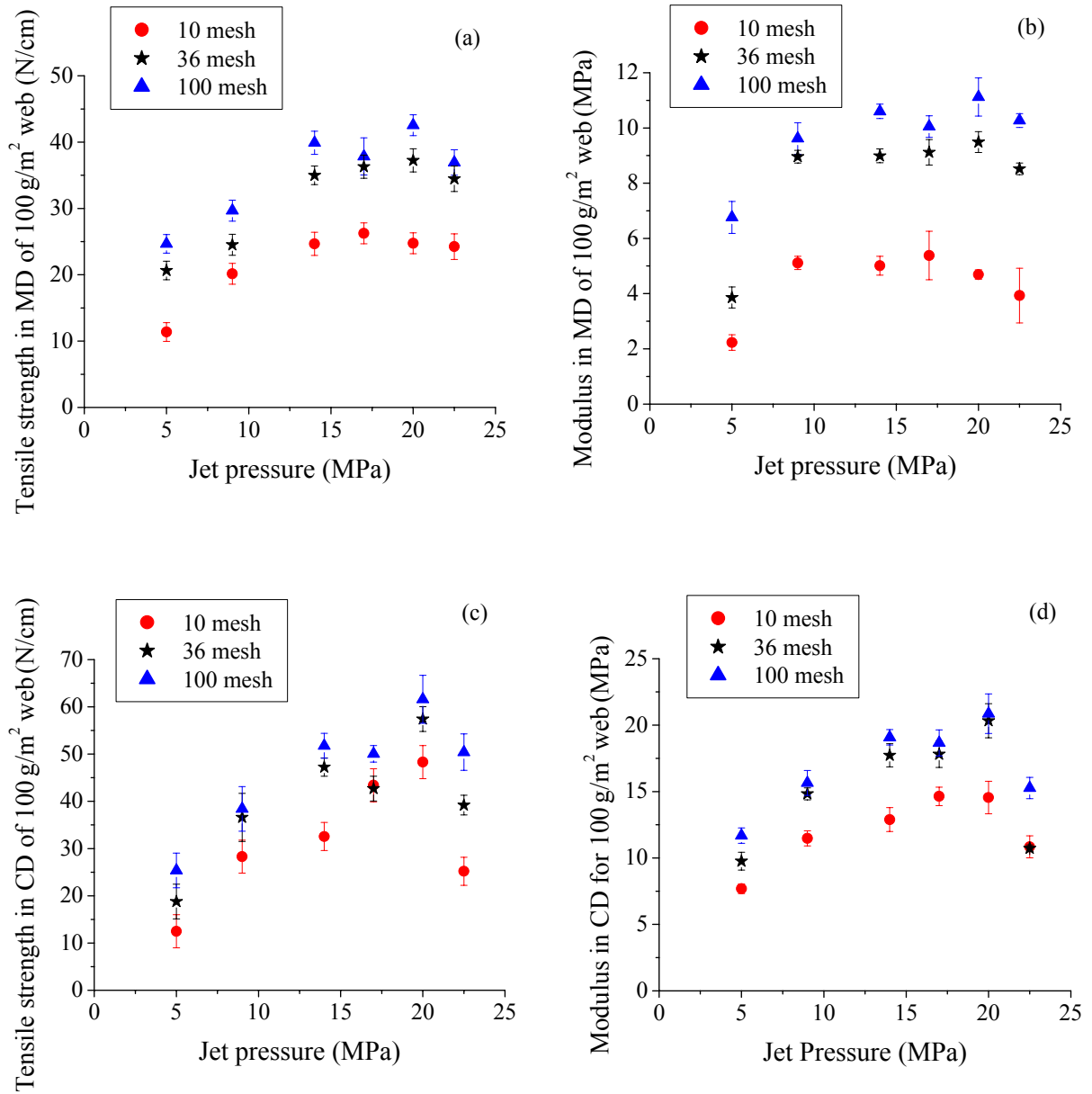


Figure 4.4 Experimental tensile strength and modulus results for 100 g/m² web:
(a) strength-pressure in the MD; (b) modulus-pressure in the MD; (c) strength-pressure in the CD; (d) modulus-pressure in the CD.

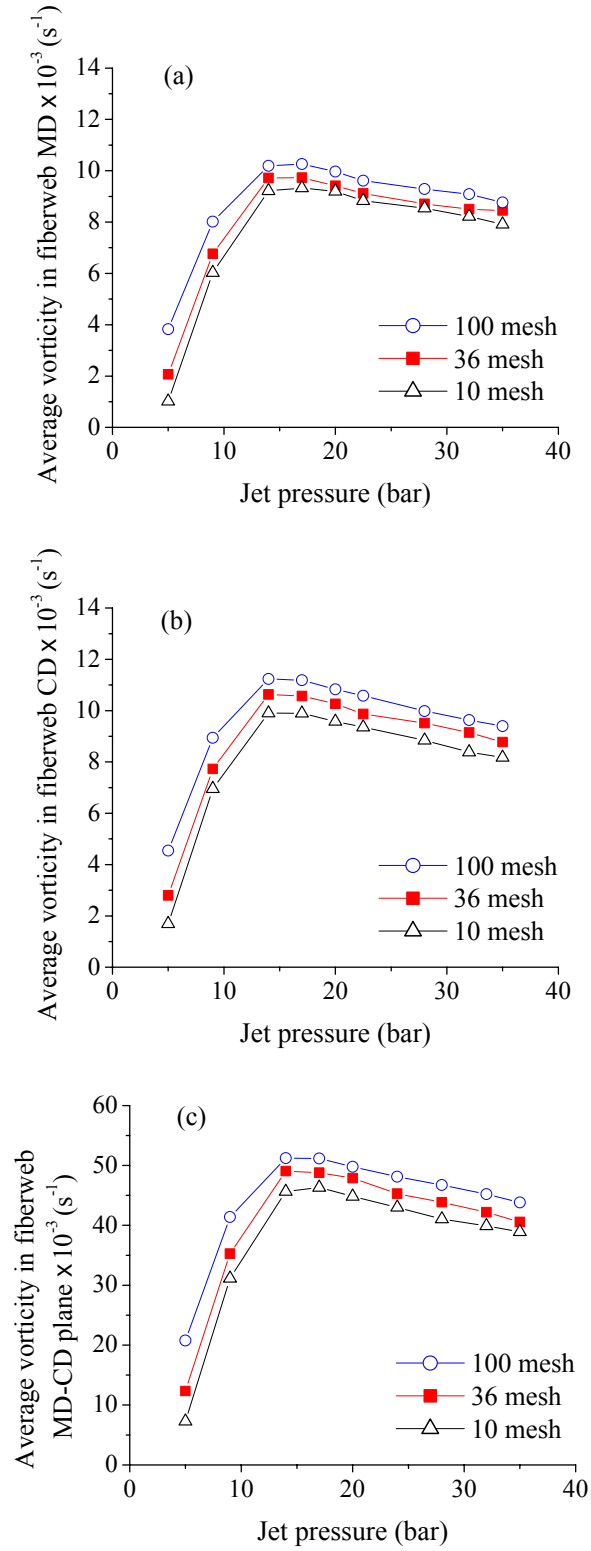


Figure 4.5 Effect of jet pressure/specific energy on fiber entanglement for 50 g/m² fiberweb: (a) in fiberweb MD; (b) in fiberweb CD; (c) in fiberweb MD-CD plane.

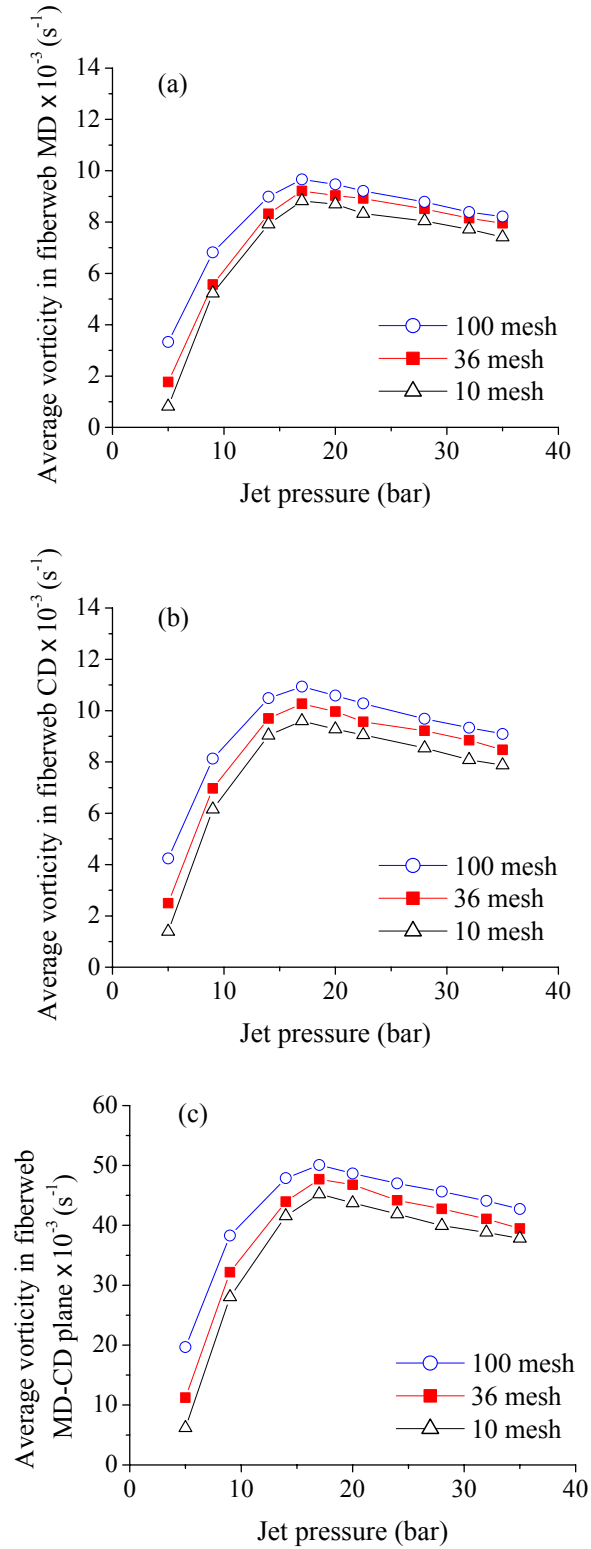


Figure 4.6 Effect of jet pressure/specific energy on fiber entanglement for 75 g/m² fiberweb: (a) in fiberweb MD; (b) in fiberweb CD; (c) in fiberweb MD-CD plane.

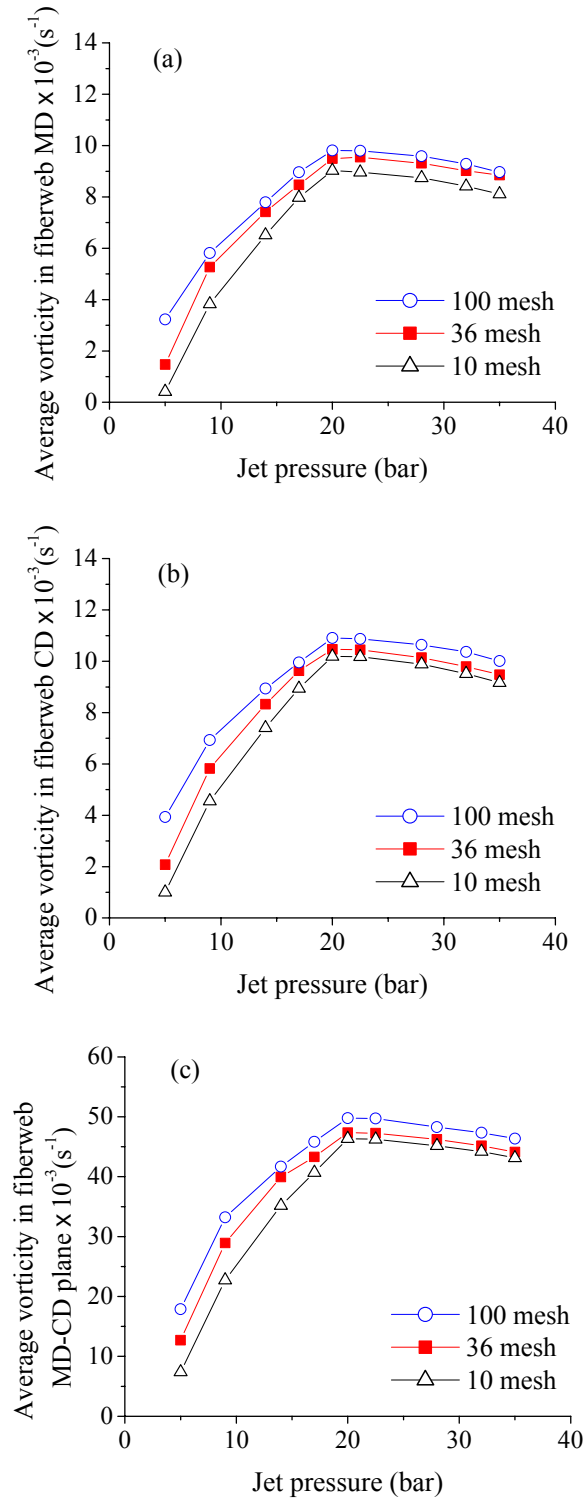


Figure 4.7 Effect of jet pressure/specific energy on fiber entanglement for 100 g/m² fiberweb: (a) in fiberweb MD; (b) in fiberweb CD; (c) in fiberweb MD-CD plane.

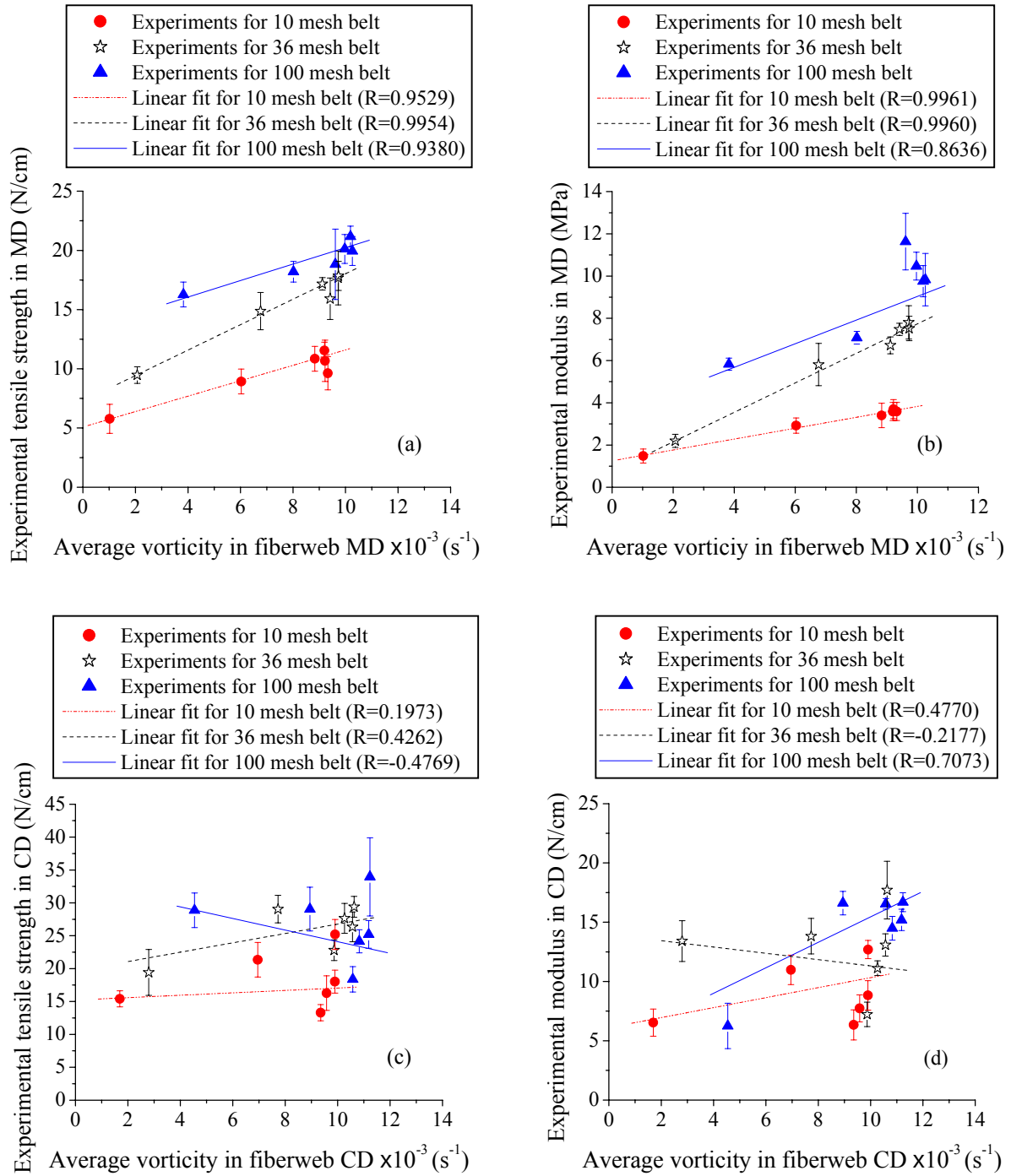


Figure 4.8 Correlation between experiments and simulations for the 50 g/m² fiberweb: (a) tensile strength versus average vorticity in the MD; (b) modulus versus average vorticity in the MD; (c) tensile strength versus average vorticity in the CD; (d) modulus versus average vorticity in the CD.

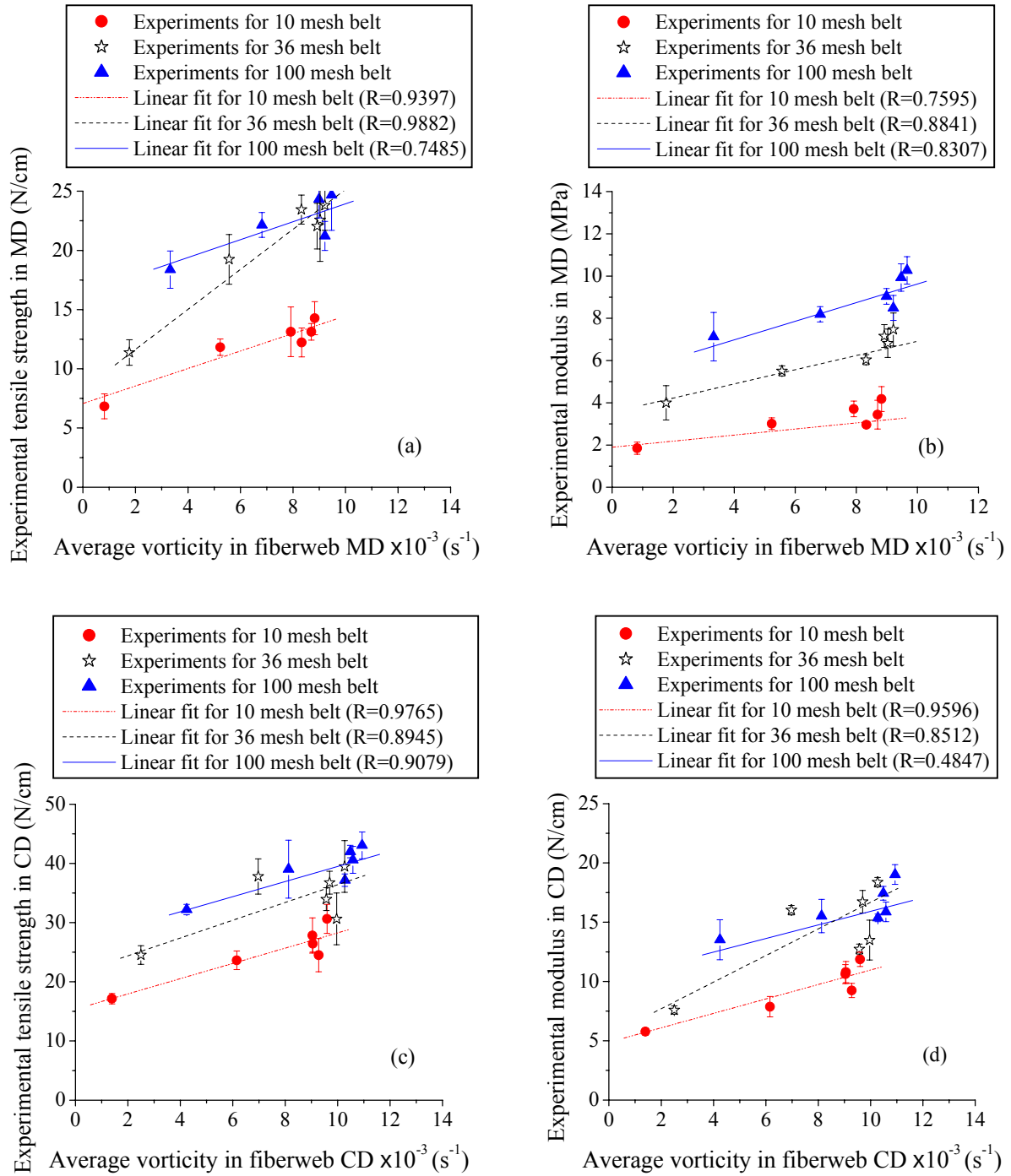


Figure 4.9 Correlation between experiments and simulations for the 75 g/m² fiberweb: (a) tensile strength versus average vorticity in the MD; (b) modulus versus average vorticity in the MD; (c) tensile strength versus average vorticity in the CD; (d) modulus versus average vorticity in the CD.

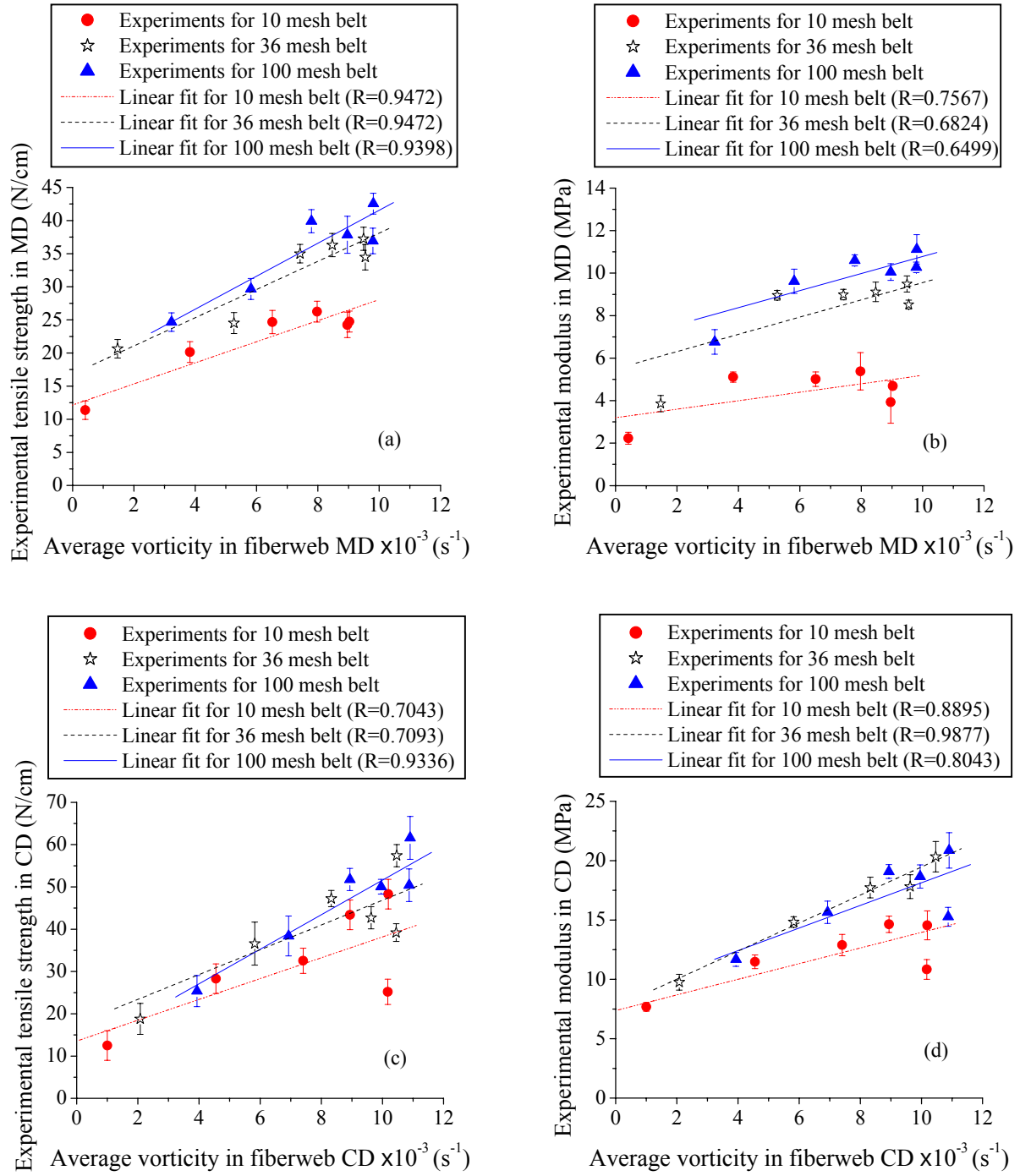


Figure 4.10 Correlation between experiments and simulations for a 100 g/m² fiberweb: (a) tensile strength versus average vorticity in the MD; (b) modulus versus average vorticity in the MD; (c) tensile strength versus average vorticity in the CD; (d) modulus versus average vorticity in the CD.

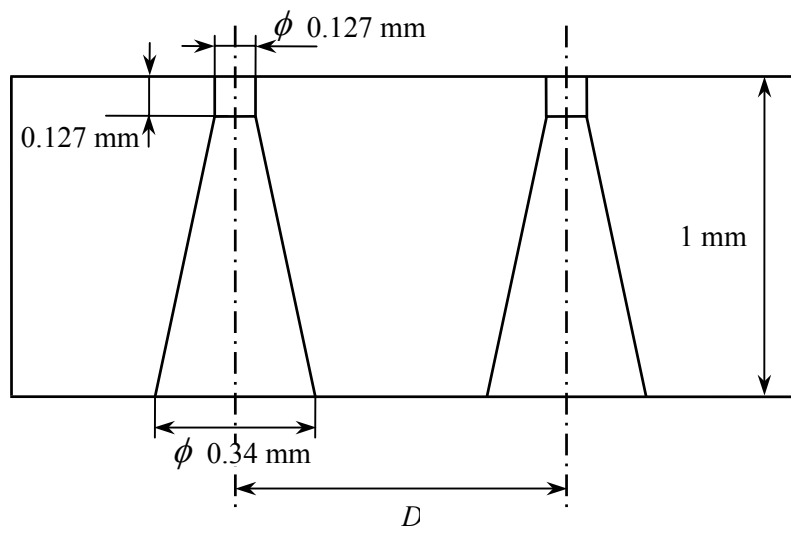


Figure 4.11 Schematic of the nozzles (cone-down) in the hydroentangling process.

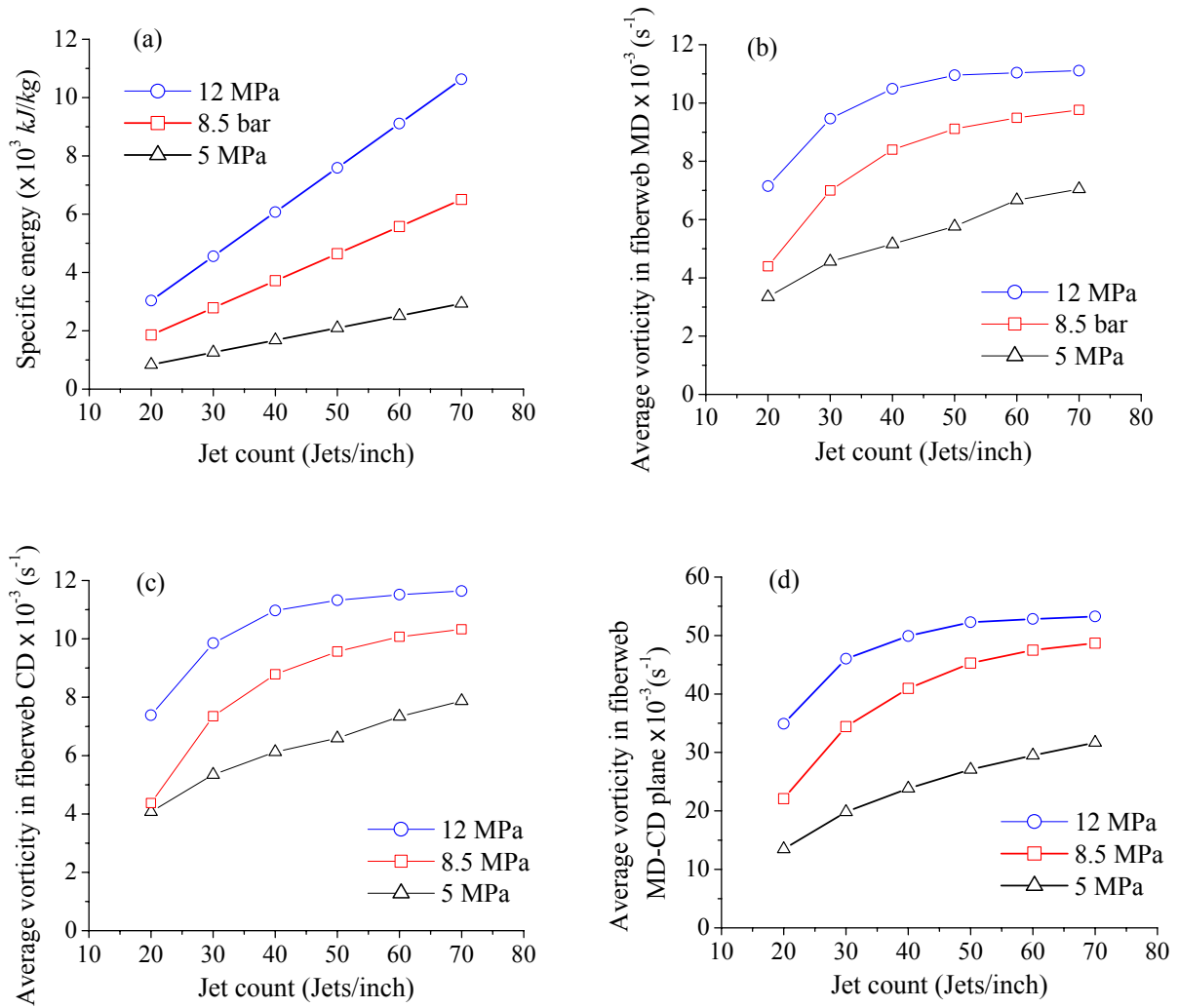


Figure 4.12 Effect jet count per unit length on fiber entanglement for a 100 mesh forming belt: (a) specific energy versus jet count; (b) vorticity in CD-TD plane versus jet count; (c) vorticity in MD-TD plane versus jet count; (d) vorticity in MD-CD plane versus jet count.

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5 EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE PEELING FORCE REQUIRED FOR THE DETACHMENT OF FABRIC FROM THE FORMING BELT IN THE HYDROENTANGLEMENT PROCESS

ABSTRACT

In the hydroentanglement process, multiple highly pressurized fine water jets are directed toward a fiberweb composed of initially loose fibers, which is supported by the forming belt. The impact of the jets causes fiber entanglement in the fiberweb and produces an integrated fabric with desired aesthetics. It is important that at the end of the process the fiberweb could be easily separated from the forming wires. In this chapter, the peeling force required for separating the hydroentangled fabric from the forming belt is measured experimentally. Numerical simulations of the hydroentanglement process are also carried out to predict the probability of fibers to be pushed in the knuckles of the forming wires. The fibers that get caught in the knuckles are mainly responsible for the peeling force of the fabric from the forming wires. The fiberweb is modeled as a porous layer which is supported by forming wires. By correlating experimental results with simulations, a mathematical model, which is based on simulating average vorticity around the forming wires, is developed to predict the peeling force. The effect of the thickness of the fiberweb layer on the peeling force is investigated.

Nomenclature

A	area of the outflow boundary, m^2
b_0	reference length used in simulations (10% of the empirical inlet water jet

	diameter), m
c_F	Forchheimer coefficient
D_a	distance between the forming wire and the peripheral face of the square prism around the wire (the peripheral face of the averaging domain, see Figures. 5.5a and 5.5b), m
D_j	water jet diameter, m
D_w	forming wire diameter, m
d_{MD}	Diameter of the MD wire, m
d_{CD}	Diameter of the CD wire, m
F_p	peeling force per unit width of the fabric, N/cm
h_1	thickness of the fluid layer above the fiberweb, m
h_2	thickness of the porous medium layer (fiberweb), m
h_3	thickness of the layer composed by forming wires, m
K	permeability of the fiberweb layer, m ²
$N_{Knuckles}$	portion of the fabric/forming wires interface occupied by knuckles
P	water jet pressure, Pa
$P_{Knuckle}$	probability of fibers to be pushed into a knuckle
p_{MD}	distance between two successive MD wires, m
p_{CD}	distance between two successive CD wires, m
Q^+	volume flow rate, m ³ /s
Ri	Ricochet parameter
t	time, s

T	total computational time, s
U_0	inlet water jet velocity, m/s
u, v, w	water velocity components in the x -, y -, and z -directions (within the fiberweb understood as components of the filtration velocity), m/s
$\mathbf{v}$	water velocity vector, m/s
V	volume of a small square prism around a forming wire (the averaging domain for computing the average vorticity around the forming wire, see Figure 5.7), m ³
x, y, z	Cartesian coordinates
X_L, Y_L, Z_L	length of the computational domain in the x -, y -, and z -directions, m

Greek symbols

ε	dissipation rate of the turbulence kinetic energy, m ² /s ³
k	turbulence kinetic energy, m ² /s ²
μ	dynamic viscosity of water, kg/(m·s)
μ_t	turbulent viscosity, kg/(m·s)
ν	kinematic viscosity of water, m ² /s
ρ	water density, kg/m ³
ϕ	porosity of the fiberweb
Ω	average vorticity in the machine direction around the forming wires

Superscripts

*	dimensionless variable
---	------------------------

Subscripts

0 inlet

5.1 INTRODUCTION

Hydroentanglement is the fastest growing technology for manufacturing nonwoven fabrics. In a typical hydroentanglement process, loose fibers are supported by forming wires and highly pressurized, fine, closely spaced water jets impinge on the fiberweb (Figure 5.1). Jet impingement causes multiple vortices as water passes through the fiberweb, and since the fibers follow water streamlines and engage in a swirling motion, they entangle with surrounding fibers. The produced fabric is held together by the fiber-to-fiber friction force. For fibers located in the lower portion of the fiberweb close to the forming wires, it is quite usual to be pushed into the knuckles (fibers are pushed into the cross-over area of MD and CD wires) of the forming wire (Figure 5.6). This creates difficulty in separating the fabric from the forming wires; if the required peeling force is large, the structure and properties of the fabric may be negatively impacted during fabric separation from the forming wires.

Extensive experimental research has been conducted in an attempt to better understand the hydroentanglement process and products. The effect of the fiberweb and fiber properties on the critical water jet pressure and energy consumption was investigated experimentally [1] and experimental investigation [2] addressed the effect of pressure distribution between different manifolds of water jets and initial fiberweb geometry on properties of hydroentangled fabric. The structure-process-property relationships for hydroentangled nonwovens were developed experimentally in [3]. A 2D

mechanical cell model was developed in [4], which is validated by correlating the jet drag force with the measured fabric tensile strength and specific energy at low jet pressures. Utilizing the hydroentanglement process, fiberwebs from cotton (experimental study reported in [5]), and a hybrid of mixed fibers (experimental study reported in [6]) can be entangled to attain strong tensile strength and excellent tear resistance, where the latter show possible synergistic improvements in fabric properties.

Despite the significant effect of the peeling force on the final fabric properties, no research addressing the peeling force required to separate the fabric from the forming wires in the hydroentanglement process. This chapter takes the first step in addressing this important issue. The chapter is based on Chapters 3 and 4 (also see [7, 8]) and takes a step forward in order to investigate the fiber entanglement around the forming wires, the probability of fibers to be caught in the knuckles, and predict the peeling force required to separate fabric from the forming belt. Three-dimensional (3D) simulations of water jets passing through the porous fiberweb and forming wires are performed to predict fibers behavior close to the forming surface. Experimental measurements of the peeling force are also performed, based on which a mathematical model for the peeling force prediction is developed. The effect of the fiberweb thickness on the entanglement of fibers around the forming wires and their entrapment in the knuckles is investigated.

5.2 EXPERIMENTAL METHODS AND IMPLEMENTATION

5.2.1 HYDROENTANGLEMENT PROCESS

Carded and crosslapped webs from polyester fibers of two different basis weights (50 g/m² and 100 g/m²) were hydroentangled using three different jet pressures and four

different forming wires. In total 24 samples were produced. The polyester fiber used is of linear density of 1.68 dtex (0.168 g/km) and average fiber length of 38 mm. The webs were processed using Fleissner's hydroentanglement machine (available at NCRC facilities) and four woven belts provided by Albany International. Table 5.1 summarizes the details of processing conditions and Table 5.2 depicts the geometrical parameters of the forming wires. The jet pressures in different tests (see Table 5.1) are different. In each test, the fiberweb is processed by three different manifolds, where the first manifold is used for the pre-wetting of the fiberweb only. The jet pressure given later in this chapter refers to the jet pressure of the final manifold.

5.2.2 *PEELING FORCE TEST PROCEDURE*

Carded and crosslapped webs from polyester fibers of two different basis weights (50 g/m² and 100 g/m²) were hydroentangled using three different jet pressures and four different forming wires. In total 24 samples were produced. The polyester fiber used is of linear density of 1.68 dtex (0.168 g/km) and average fiber length of 38 mm. The webs were processed using Fleissner's hydroentanglement machine (available at NCRC facilities) and four woven belts provided by Albany International. Table 5.1 summarizes the details of processing conditions and Table 5.2 depicts the geometrical parameters of the forming wires. The jet pressures in different tests (see Table 5.1) are different. In each test, the fiberweb is processed by three different manifolds, where the first manifold is used for the pre-wetting of the fiberweb only. The jet pressure given later in the chapter refers to the jet pressure of the final manifold.

5.3 SIMULATION METHOD

The main reason why a force is required to separate the fabric from the forming belt is fiber entrapment in the knuckles of the forming wires. This is caused by the entangling effect of the water jets, which, in addition to entangling the fibers, also push some of the fibers into the spaces between the forming wires, conform the fibers around the forming wires, and push fibers into the knuckles. The simulation approach in this chapter estimates the peeling force evaluating the probability of fibers which are located at the bottom of the fiberweb to be pushed into the knuckles of the forming wires and simulating the water vorticity around forming wires.

5.3.1 MODEL GEOMETRY

In the hydroentanglement process, a manifold of high pressure water jets is directed toward the fibers. All water jets are identical, and the water flow fields induced by them are also identical; therefore, a unit cell including only two jets is considered in this model. Figure 5.4 depicts the computational domain. There is a thin fluid layer over the fiberweb because part of water splashes back after it hits the forming wires. The portion of the injected water that is not splashed back flows through the fluid layer (the upper layer in Figure 5.4, of thickness h_1), the fiberweb layer (the middle layer in Figure 5.4, of thickness h_2), and the layer composed by forming wires (the lower layer in Figure 5.4, of thickness h_3).

Two different models are utilized for the fiberweb and the supporting layer of forming wires. The fiberweb is simulated as a porous layer with uniform porosity ϕ . The layer of forming wires is simulated as an anisotropic layer, part of which is occupied by the wires and part is occupied by the space between the wires (see Figure 5.5). This is

because there are two length scales characterizing geometrical structures in this problem: one length scale is associated with the fiber diameter in the fiberweb while the second length scale is associated with the diameter of forming wires; the fiber diameter is much smaller than that of the forming wires (ratio of wire diameter to fiber diameter in this chapter ranges from 9.0 to 81.5).

The process is continuous, and the fiberweb and forming belt are moving at a controlled speed (taken here to be 30 m/min) in the y -direction (commonly known as the machine direction, MD). The x -axis is directed in the cross machine direction (CD), in which the row of water jets is lined up. The highly pressurized water jets impinging on the fiberweb have a diameter of 0.127 mm, and there are 15.8 jets/cm (40 jets/ inch). The z -axis is directed upward in the fiberweb and the forming wires thickness direction.

Since the impinging jet velocity is very high (above 50 m/s), the flow in the fluid layer, porous fiberweb layer, and in the voids between the forming wires is turbulent. A turbulent flow model is therefore used to simulate the 3D flow in all three layers.

5.3.2 GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

Governing equations describing the water flow through the clear fluid layer, voids between forming wires, and the porous fiberweb layer are given below. Governing equations are modified to account for turbulence effects within the porous medium [9], and describe the water flow through the porous fiberweb layer. The same governing equations are used to compute the flow in the clear fluid region. This is possible because the momentum equation (Equation (5.2)) that describes the flow in the fiberweb layer reduces to the momentum equation in the top fluid layer and in the spaces between the

forming wires when the D'Arcy and Forchheimer terms are dropped and the porosity, ϕ , is set equal to unity.

For the flow in the porous fiberweb layer, the modified k - ε turbulence model proposed by Jones and Launder [10] (the JL model) is used. In this model, the Darcy modification (DM) is the additional Darcy damping term, and the Forchheimer term is split into two parts, namely, the Forchheimer Modification A (FMA) and Forchheimer Modification B (FMB) terms. This turbulence model can also be used for the water flow in the top fluid layer and in the voids between the forming wires because the k (turbulence kinetic energy) and ε (dissipation rate) equations reduce to the familiar k and ε equations when the Darcy Modification (DM) and Forchheimer Modification A/B (FMA/FMB) terms are dropped from these equations and ϕ is set equal to unity.

The governing equations are given below.

Continuity equation:

$$\phi \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (5.1)$$

Momentum equation:

$$\rho \frac{\partial u_i}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial u_i}{\partial x_j} = -\nabla p + \frac{\partial}{\partial x_j} \left[(\mu J + \mu_t) \left(\frac{\partial u_i}{\partial x_j} \right) \right] - \frac{\mu \phi u_i}{K} - \rho \frac{c_F \phi u_i Q}{\sqrt{K}} \quad (5.2)$$

where ϕ is the porosity of the fiberweb, t is the time, ρ is the water density, $\mathbf{v}$ is the water velocity (understood as the filtration velocity in the porous fiberweb), x_i ($i=1,2,3$) are the Cartesian coordinates, and p is the pressure. The coefficient K is the permeability of the porous medium and c_F is the dimensionless Forchheimer coefficient [11]. μ is the

dynamic viscosity of water and μ_t is the turbulent viscosity which is obtained from the following turbulence model (the JL model):

k equation (for the turbulence kinetic energy):

$$\rho \frac{\partial k}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho J \varepsilon + \rho D$$

$$- \frac{2\mu\phi k}{K} - \frac{8}{3} \frac{\rho c_F \phi (2Q)k}{\sqrt{K}} + \frac{2c_F \phi \mu_t}{\sqrt{K}} \left(\frac{2}{Q} \right) \left(u_i u_j \frac{\partial u_j}{\partial x_i} \right)$$

Darcy modification
(DM)

Forchheimer modification A
(FMA)

Forchheimer modification B (FMB)

(5.3)

ε equation (for the dissipation rate of turbulence kinetic energy):

$$\rho \frac{\partial \varepsilon}{\partial t} + \frac{\rho u_j}{\phi} \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu J + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + (C_{\varepsilon 1} f_1 P_k - \rho J C_{\varepsilon 2} f_2) \frac{\varepsilon}{k}$$

$$+ \rho E - \frac{4\mu\phi\varepsilon}{K} - \frac{2c_F\phi}{\sqrt{K}} \left\{ \frac{4}{3} (2Q) \rho \varepsilon + \frac{5\mu}{6} \left(2 \frac{\partial k}{\partial x_j} \frac{\partial Q}{\partial x_j} \right) \right\}$$

Darcy modification (DM)

Forchheimer modification A (FMA)

(5.4)

where

$$\mu_t = \rho c_\mu f_\mu \frac{k^2}{\varepsilon}, \quad \nu_t^* = c_\mu^* \frac{k^2}{\varepsilon}, \quad \text{Re}_t = k^2 / \nu \varepsilon$$

$$P_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2, \quad Q = \sqrt{u_i u_i}, \quad f_\mu = \exp \left(\frac{-2.5}{1 + \text{Re}_t / 50} \right)$$

$$f_1 = 1.0, \quad f_2 = 1 - 0.3 \exp(-\text{Re}_t^2), \quad D = 0, \quad E = 0$$

$$c_\mu = 0.09, \quad c_{\varepsilon 1} = 1.44, \quad c_{\varepsilon 2} = 1.92, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3$$

In computations, the above governing equations are solved in their dimensionless form, obtained by defining the following dimensionless variables:

$$\begin{aligned} u^* &= \frac{u}{U_0}, & v^* &= \frac{v}{U_0}, & w^* &= \frac{w}{U_0}, & t^* &= \frac{t}{b_0/U_0} \\ x^* &= \frac{x}{b_0}, & y^* &= \frac{y}{b_0}, & z^* &= \frac{z}{b_0}, & \rho^* &= 1, & p^* &= \frac{p}{\rho_0 U_0^2} \\ Re &= \frac{\rho_0 b_0 U_0}{\mu}, & \mu^* &= \frac{\mu}{\rho_0 b_0 U_0}, & k^* &= \frac{k}{U_0^2}, & \varepsilon^* &= \frac{\varepsilon}{U_0^4} \end{aligned}$$

where U_0 is the inlet water jet velocity; $b_0 = 0.0127\text{mm}$, which is ten percent of the inlet water jets diameter; and ρ_0 is the water density.

The following inlet, outflow, and symmetry boundary conditions are utilized:

Inlet section ($0 \leq x \leq X_L, 0 \leq y \leq Y_L, z=0$):

A portion of the impinging water is splashed back by the forming wires, and some of it leaves the computational domain through the top and side boundaries. Once the water evacuation effect under the forming wires and the water reflection effect by the wires are balanced, the thickness of the upper fluid layer becomes constant, and the boundary conditions are expressed as follows:

$$\begin{cases} k_0 = 0.001 U_0^2, & \varepsilon_0 = 0.1643 (k_0^{1.5} / 0.35 D_j) & \text{within the water jets} \\ \partial k / \partial z = 0, & \partial \varepsilon / \partial z = 0 & \text{outside the water jets} \end{cases} \quad (5.5)$$

Symmetry plane ($x=0$ or $x=X_L, 0 \leq y \leq Y_L, 0 \leq z \leq Z_L$):

$$\frac{\partial u_i}{\partial x} = \frac{\partial u_i}{\partial y} = 0, \quad \frac{\partial k}{\partial y} = \frac{\partial \varepsilon}{\partial y} = 0, \quad \frac{\partial k}{\partial x} = \frac{\partial \varepsilon}{\partial x} = 0 \quad (5.6)$$

Outflow section ($0 \leq x \leq X_L, 0 \leq y \leq Y_L, z=Z_L$):

$$u_x = u_y = 0, \quad u_z = \begin{cases} Q(1 - Ri) / A & \text{at the empty space between the wires} \\ 0 & \text{at the wires} \end{cases} \quad (5.7)$$

$$\frac{\partial k}{\partial z} = \frac{\partial \varepsilon}{\partial z} \quad (5.8)$$

(a uniform suction boundary condition).

In the outflow boundary condition, Q^+ is the volume flow rate, which is calculated from the given inlet mean velocity of the water jet flow, A is the area of voids between the wires at the outflow boundary, and Ri is the Ricochet parameter, which is defined as the reflected portion of water brought into the system by water jets; this parameter is proportional to unity minus the portion of the forming belt area occupied by the open space. The Ricochet parameter accounts for the effect of water reflection by the forming wires.

Across the interface of any two different layers, the fluid filtration velocities as well as the k and ε functions are automatically continuous. This is because the momentum equation as well as k and ε equations are uniformly valid in both the porous and clear fluid regions, only additional damping terms are introduced in the turbulence transport equations in the porous layer (the fiberweb). Thus, there is no need for explicit imposing of any boundary conditions at the porous/fluid interface.

5.3.3 NUMERICAL METHOD AND GRID SYSTEM

All equations are solved in their dimensionless form. The convection terms are discretized using the second-order upwind finite-difference scheme, whereas the second-order central finite-difference scheme is used for the diffusion terms. The SIMPLE algorithm described in [12] is utilized to solve the discretized partial differential

equations. An under-relaxation factor of 0.5 is used for the velocities and pressure to avoid divergence, whereas for the turbulent quantities, k and ε , the under-relaxation factor is set to 0.3.

Computations are performed on a uniform staggered grid of $50 \times 35 \times 102$ nodes in the x -direction, y -direction, and streamwise direction (z -direction), respectively. A typical CPU time on a single 2.8 GHz Intel Xeon processor for a single 3D simulation is 36 hours.

5.3.4 PEELING FORCE MODEL

The research in Chapters 2 through 4 (also see [7, 8]) illuminated the mechanism of fiber entanglement in the hydroentanglement process. In this process, the impinging water induces vortices as it passes through the fiberweb and the voids between the forming wires. The streamlines are strongly curved in the region occupied by a vortex. Since the distance between two neighboring water jets is very small (0.635mm), the vortices caused by these water jets interact with the neighboring vortices and fibers in the fiberweb, and cause fiber entanglement due to the rotational effect of the water flow. The rotational effect of the fluid flow on a solid particle or a fiber is determined by flow vorticity (in [13], for example, the rotation rate of a sphere in a flow field is evaluated by one-half of the local flow vorticity at the sphere-center position).

Near the forming surface, water vorticity results in fibers swirling around the forming wires and entangling around the wires. Once the fibers are entangled around the wires, they can slide along the wire toward the knuckle due to fluid forces and then be pushed into the knuckle (the crossover points of the forming wires, see Figure 5.6) As a

result, most fibers entangled around the forming wires are caught in the wires at knuckles; this leads to the difficulty in separating the fiberweb from the forming wires.

It is hypothesized that the peeling force per unit width of the fabric has a direct relationship with the degree of fiber entanglement around the forming wires. The research in Chapters 2 through 4 (also see [7, 8]) validated the assumption that the average vorticity in the fiberweb is linearly correlated with the degree of fiber entanglement. In this chapter the average vorticity is computed over a small representative region around each forming wire (including the volume occupied by the knuckle) to estimate the peeling force. The average vorticity in three different directions around the forming wires is computed as $\frac{1}{T} \int \left[\iiint_V |(\nabla \times \mathbf{v})_i| dV / V \right] dt$, where $\nabla \times \mathbf{v}$ is the vorticity vector, $|(\nabla \times \mathbf{v})_i|$ is the absolute value of the i^{th} ($i=x, y, z$) component of the vorticity vector, V is of the volume of a small square prism around the wire (see Figure 5.7), and T is the total computational time (averaging is performed both spatially and temporarily).

Since the fabric is usually separated from the forming wires in the MD, only the average value of vorticity vector component in the MD is computed as described above to evaluate the degree of local fiber entanglement around the forming wires. Figure 5.7 shows the averaging domain around a forming wire, where $D_a = D_w / 4$.

5.4 EXPERIMENTAL RESULTS

Figures 5.8 and 5.9 show the experimentally determined peeling force versus jet

pressure for different fiberwebs. It is evident that for the same forming belt, when the water jet pressures are the same, the fabric with a larger basis weight exhibits a smaller peeling force (compare the results in Figure 5.8 with those in Figure 5.9 at any given pressure and given type of the forming belt). This is because the kinetic energy of the water jets dissipates as water filtrates through the fiberweb. A fabric with a larger basis weight has a larger thickness; therefore, more kinetic energy dissipates in the upper portion of the fiberweb, causing less entanglement (less number of fibers caught in the knuckles as it can be seen from Figure 5.6) around the forming wires, which results in a smaller peeling force of the fabric from the forming belt.

It is also found that for the same forming belt and given fiberweb basis weight, the peeling force increases with the increase of the jet pressure (compare the results of Figure 5.8 (or Figure 5.9) for any given type of a forming belt). This is because at a higher jet pressure, water jets produce a larger impact force and provide more energy inducing more intense vortices in the fiberweb. These more intense vortices cause a larger degree of fiber entanglement in the fiberweb as well as around the forming wires, which causes a larger peeling force.

The results also illuminate that when the other process parameters are the same, the peeling force for a coarser mesh forming belt is larger than that for a finer mesh forming belt. This is because on a coarser mesh forming belt the fibers entangle much easier around the wires and are more easily pushed into the knuckles. More fiber ends are in a given space between wires in case of a coarse mesh than fine mesh. In case of coarse mesh a fiber supported by a wire and protruding to the space between two wires is longer

and such fibers will wrap around the wire and thus provide high degree of entanglement in fiberweb and around the wires.

The microscopic structures of the forming belts after the fabrics have been removed are taken (see Figure 5.10). To make the fibers and forming wires readable, the magnifications for different forming belts are different. It is evident that for the coarsest 10 mesh forming belt (Figure 5.10a), there are more fibers entangled around the forming wires and left caught in the knuckles. As the forming belt gets finer, the number of fibers left caught by the forming wires gets fewer (Figures 5.10b and 5.10c). This is especially visible for the 100 mesh forming belt (Figure 5.10d), in which case very few fibers are left caught in the knuckles. The results give evidence why the peeling force is larger for a coarser mesh forming belt.

5.5 RESULTS OF COMPUTER SIMULATION

The same cases studied experimentally are investigated numerically. The calculated average vorticity in the MD around the forming wires, which is used to estimate the peeling force, is depicted in Figures 5.11 and 5.12. For given structure of forming wires it is evident that the average vorticity follows the same trends as the experimentally measured peeling force when the water jet pressure and the web basis weight are varied. This suggests that the larger the calculated average vorticity around the forming wires, the larger the peeling force is.

However, the average vorticity around the forming wires alone cannot correctly predict the effect of the size of the forming wires. Simulations show that for a coarser mesh forming belt, the average vorticity in the MD around wires is smaller, while

experimental results indicate that the peeling force for a coarser mesh forming belt is larger. To resolve this contradiction a model estimating the probability of fibers getting caught in the knuckles of the forming wires is developed.

5.6 MATHEMATICAL MODEL CORRELATING PROBABILITY OF FIBERS GETTING CAUGHT IN THE KNUCKLES WITH THE KNUCKLES WITH THE MESH SIZE

Since the peeling force of the fabric from the forming wires is due mainly to the fibers that are caught in the wires in the knuckles, the effect of the forming wires on the peeling force is related to the portion of the fabric/forming wires interface occupied by knuckles, which is estimated as:

$$N_{knuckles} = \frac{d_{MD} \cdot d_{CD}}{p_{MD} \cdot p_{CD}} \times 100\% \quad (5.9)$$

where d_{MD} is the MD wire diameter, d_{CD} is the CD wire diameter, p_{MD} is the distance between two successive MD wires, and p_{CD} is the distance between two successive CD wires, as displayed in Figure 5.5.

Since the experimental investigation shows that the peeling force on a coarser mesh forming belt is larger, this suggests that the probability for fibers to be pushed into a knuckle is related to the mesh size. To develop the model for the probability, it is assumed that if the area of a knuckle is larger than 100 mm^2 , the probability is equal to unity (meaning that all fibers entangled around forming wires end up sliding into the knuckles). If a knuckle occupies the area smaller than 100 mm^2 , the probability is defined as:

$$P_{knuckle} = \left(\frac{A \text{ knuckle area}}{100 \text{ mm}^2} \right)^{1/3} \quad (5.10)$$

where the exponent 1/3 is used to best fit the experimental results, and a knuckle area is equal to $d_{MD} \times d_{CD}$. The value of 100 mm² in Eq. (5.10) is in fact a reference value, which is used for defining the dimensionless area occupied by a knuckle.

By correlating simulations with experiments, it is found that experimentally determined peeling force correlates best with the simulated average vorticity in the MD around the wires if the following mathematical model is used:

$$F_p = 6.2(N \cdot s / cm) \times N_{Knuckles} \times P_{knuckle} \times (\Omega / 10^3) \quad (5.11)$$

where F_p is the peeling force per unit width of the fabric [N/cm] and Ω is the average vorticity in the MD around forming wires [s⁻¹], The mathematical model in Eq. (5.11) is an empirical model, which is developed to best fit the calculated average vorticity with experimental data. The constant 6.2 in Eq. (5.11) is a best fit parameter. Changing the reference area of 100 mm² in Eq. (5.10) to something else will not change the model; the only effect will be adjusting the value of the best fit constant 6.2 in Eq. (5.11).

Figure 5.13 shows a comparison between experimental results (shown by successive data points) and model predictions obtained using computed average vorticity in the MD around the forming wires, Ω , and Eq. (5.11) (the model predictions are shown by straight lines). Results are presented for four different forming belts. The parameters required for using Eq. (5.11) to predict the peeling force are given in Table 5.4 along with correlation coefficients of experimentally measured peeling force and that predicted by

Eq. (5.11). It is evident that the mathematical model given by Eq. (5.11) results in excellent correlation between experimental results and numerical predictions.

5.7 MODEL PREDICTIONS: EFFECT OF FIBERWEB THICKNESS

Numerical simulations are performed for eleven different fiberweb thicknesses ranging from 0.40 to 4.40 mm to investigate the effect of the fiberweb thickness on the strength of fabric attachment to the forming wires. All of the fiberwebs (see Table 5.3) whose thicknesses are linear with their basis weights are made of polyester fibers. The fiberwebs with 50 g/m² and 100 gm² basis weights are the realistic and the others are hypothetical webs with calculated thickness assuming linear thickness-basis weight relationship. The water jets pressure of the final manifold is 20 MPa, and the line speed is 30 m/min.

The average vorticity in the MD around wires is computed. Figure 5.14 depicts the average vorticity in the MD around forming wires versus fiberweb thickness for 10 mesh and 100 mesh forming belts. Then using the mathematical model given by Eq. (5.11), the peeling force of the fabric from the forming belt is computed and depicted in Figure 5.15. It is evident that for each forming belt, both the average vorticity in the MD around the wires and the peeling force of the fabric from the forming belt decrease with the increase of the fiberweb thickness. This is because most of the kinetic energy of the water jets dissipates in the upper portion of the fiberweb, and if the fiberweb is thick, only a few fibers are entangled around the wires and pushed into the knuckles, which results in a small peeling force.

It is also shown that when other processing parameters are the same, the calculated average vorticity values for the finer mesh forming belt are larger (Figure 5.14). However, the utilization of Eq. (5.11) to predict the peeling force leads to a correct prediction that the peeling force from the finer mesh forming belt is smaller (Figure 5.15).

5.8 CONCLUSIONS

The force required to separate the hydroentangled fabric from the forming belt is measured experimentally for fiberwebs with different basis weights formed with range of jet pressure and forming belts. It is found that the peeling force gets higher as the fiberweb basis weight gets lower, the final manifold jet pressure gets higher, and the forming belt count gets lower. The above conclusions have been drawn based on experiments with polyester fibers, further studies are needed to uncover the effect of entangling different types of fibers and their blends.

3D simulations of water jets impinging on the forming wires are performed. A mathematical model based on the simulated average vorticity in the MD around wires is developed. The model predictions are in excellent agreement with experimental results. Using the modeling approach, it is established that the peeling force of the fabric from the forming belt decreases with the increase of the web thickness. In addition, it is found that the use of a coarser mesh forming belt leads to more fibers caught in the wires in the knuckles, hence a larger peeling force.

The modeling described in this chapter provides a tool for designing forming surfaces and selecting the correct blend of fiber, fiberweb, and jet pressure to

manufacture fabrics with high degree of entanglement and performance while minimizing the peeling force required separating the fabric from the forming belt.

Table 5.1 Processing conditions.

Test No.	Pressure (MPa)			Machine speed (m/min)
	Manifold No. 1	Manifold No. 2	Manifold No. 3	
1	4	9	9	30
2	4	14	14	30
3	4	20	20	30

Table 5.2 Geometrical parameters of the forming wires.

Forming wires	Count (/cm) [/inch]	MD wire diameter (mm)	CD wire diameter (mm)	Open area (%)	Wire cross-section shape	Thickness (mm)
100 mesh	40.0×35.4 [100×90]	0.11	0.14	29	Round	1.6510
75 mesh	30.0×24.4 [75×62]	0.15	0.22	26	Round	0.6858
36 mesh	14.2×10.6 [36×27]	0.40	0.40	25	Round	0.3586
10 mesh	4.3×4.3 [11×11]	0.89	1.00	35	Round	0.2794

Table 5.3 Fiberwebs used for investigation of web thickness effects.

Web thickness (mm)	0.40	0.56	0.71	0.86	1.12	1.42	2.00	2.51	2.95	3.65	4.40
Basis weight (g/m ²)	28.2	39.4	50.0	60.5	78.9	100.0	140.8	176.8	207.7	257.0	309.9

Table 5.4 Parameters required for using Eq. (5.11) to predict the peeling force and correlation coefficients of experimentally measured peeling force and that predicted by Eq. (5.11).

Forming belt	Portion of knuckles, $N_{Knuckles}$	Probability that fibers are pushed into knuckles, $P_{Knuckle}$	Correlation coefficient
10 mesh	16.692 %	0.20724	0.92060
36 mesh	24.106 %	0.11696	0.97332
75 mesh	23.785 %	0.069104	0.96062
100 mesh	21.483 %	0.053601	0.95007

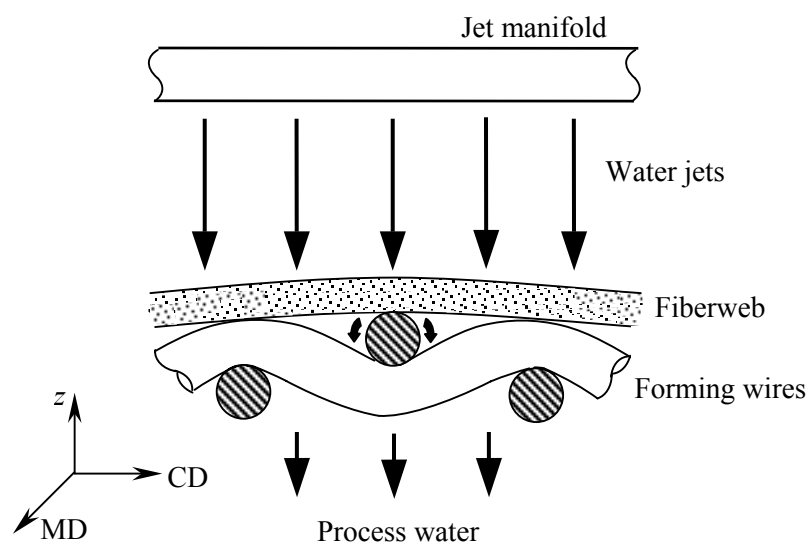


Figure 5.1 Typical cross-section of a hydroentanglement unit.

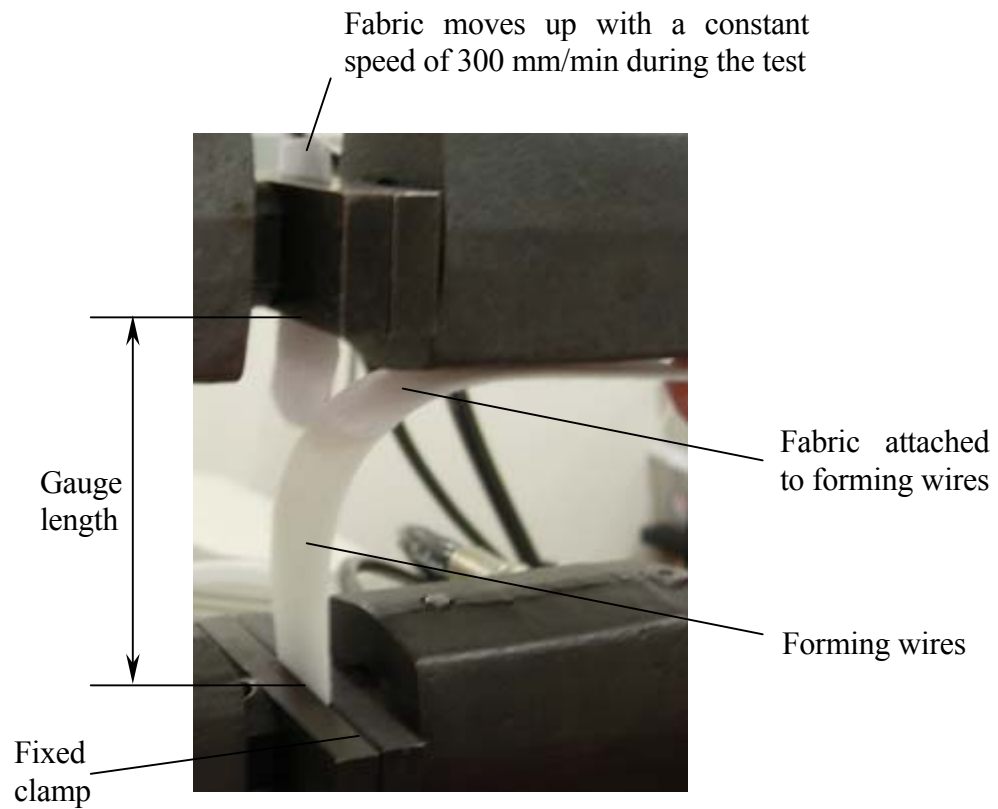


Figure 5.2 Initial state of the fabric partly separated from the forming wires before testing in the Sintech tester.

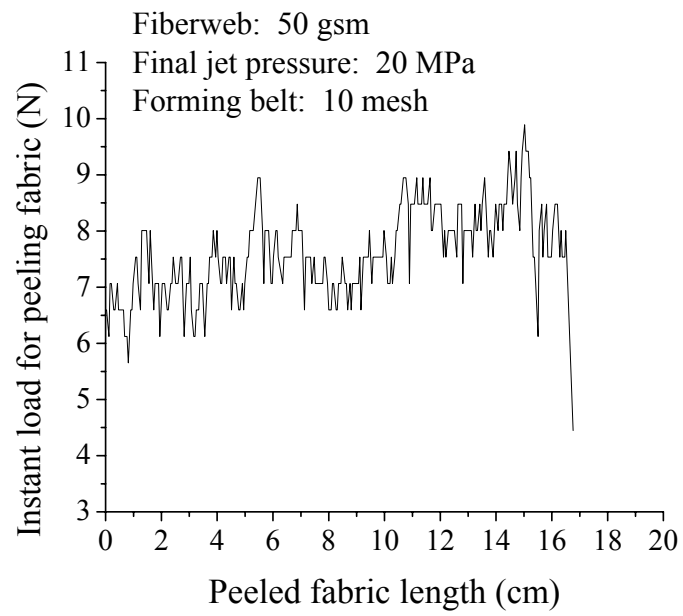


Figure 5.3 A typical graph obtained from the tensile tester.

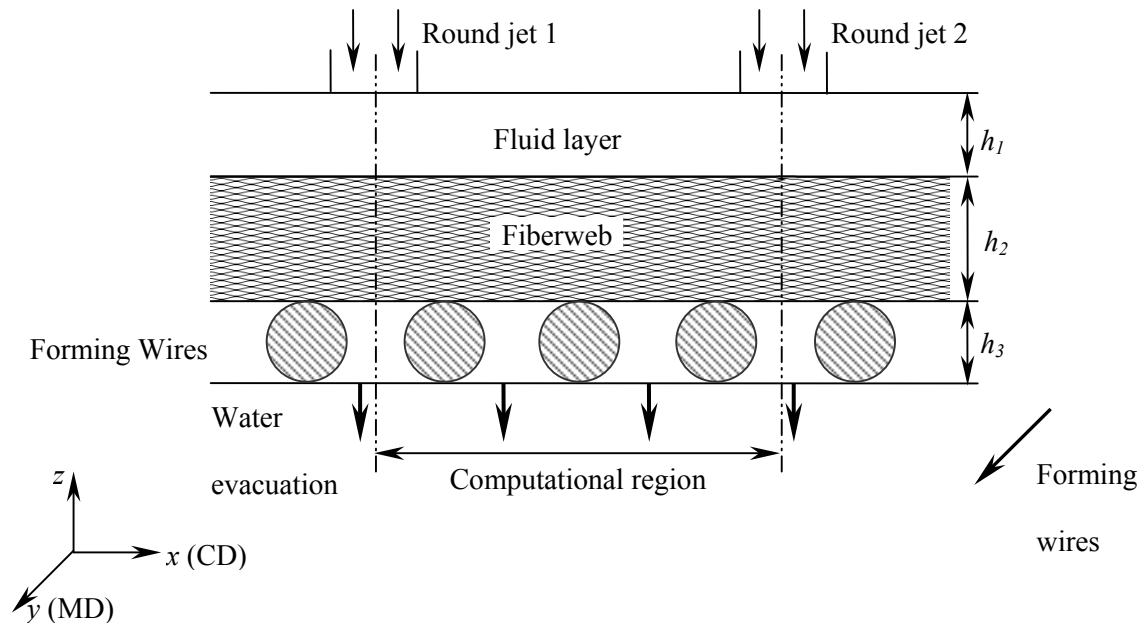


Figure 5.4 Schematic diagram of the problem and computational domain.

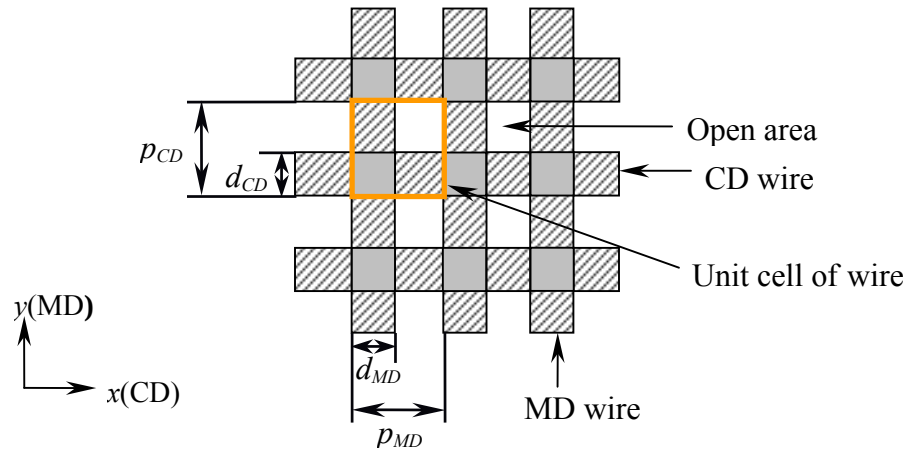


Figure 5.5 Typical geometry of forming wires (in all computed cases the forming wires have circular cross-section; rectangular cross-section is shown here to simplify the diagram).

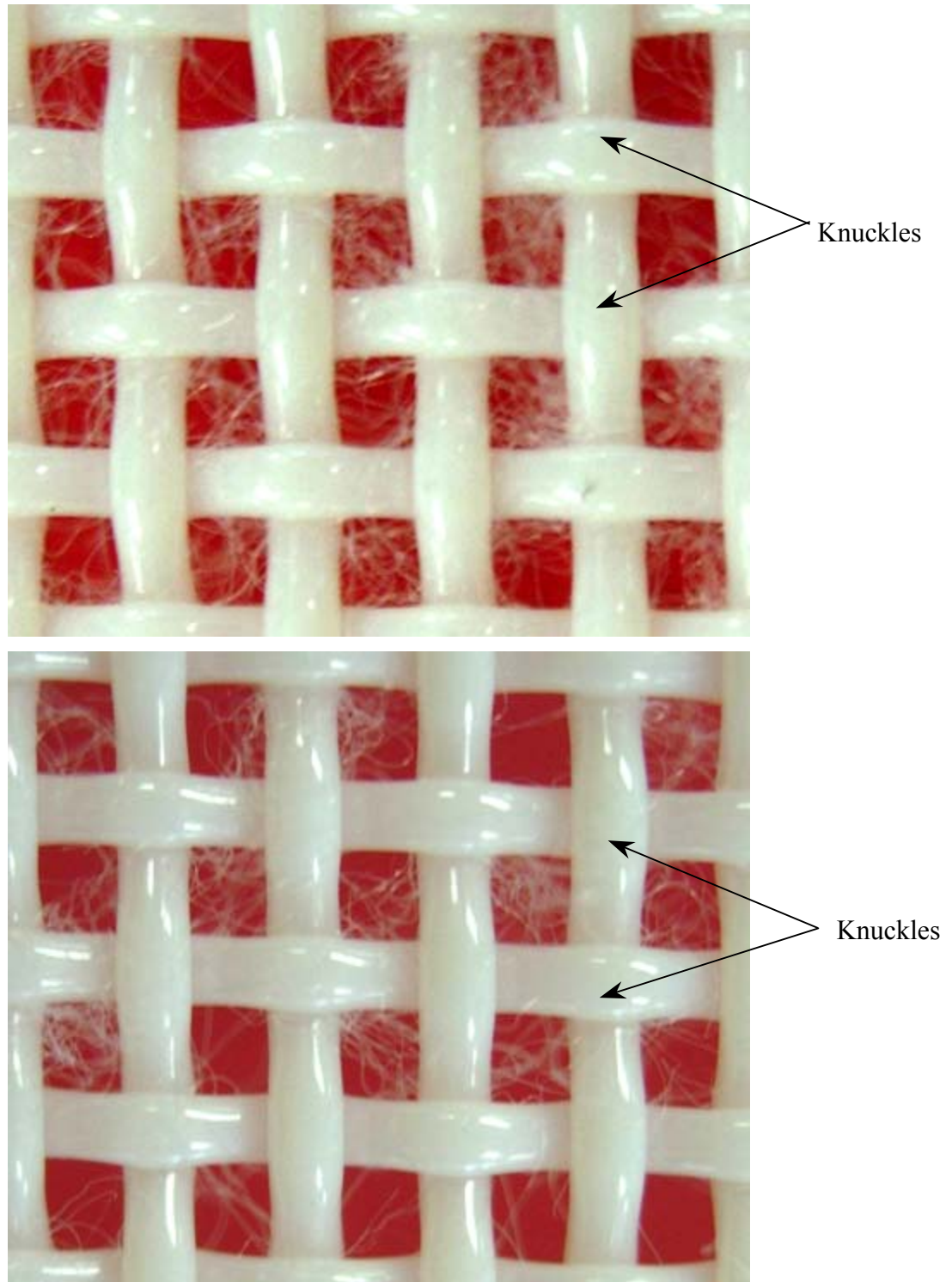


Figure 5.6 Fibers remained caught in the knuckles after peeling tests (10 mesh forming belt) (Top: 20 MPa pressure, 50 g/m²; Bottom: 20 MPa pressure, 100 g/m²).

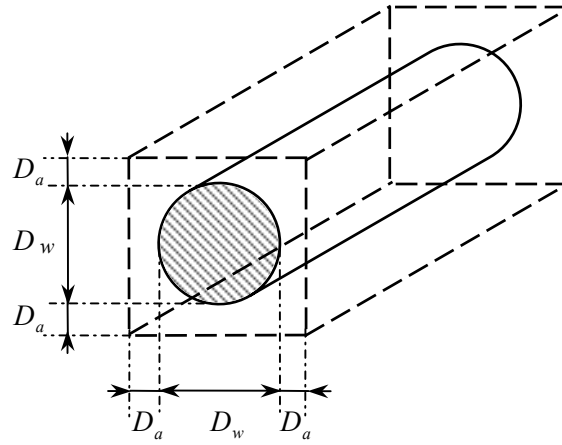


Figure 5.7 Small square prism around a forming wire for average vorticity calculations
 $(D_a = D_w / 4)$.

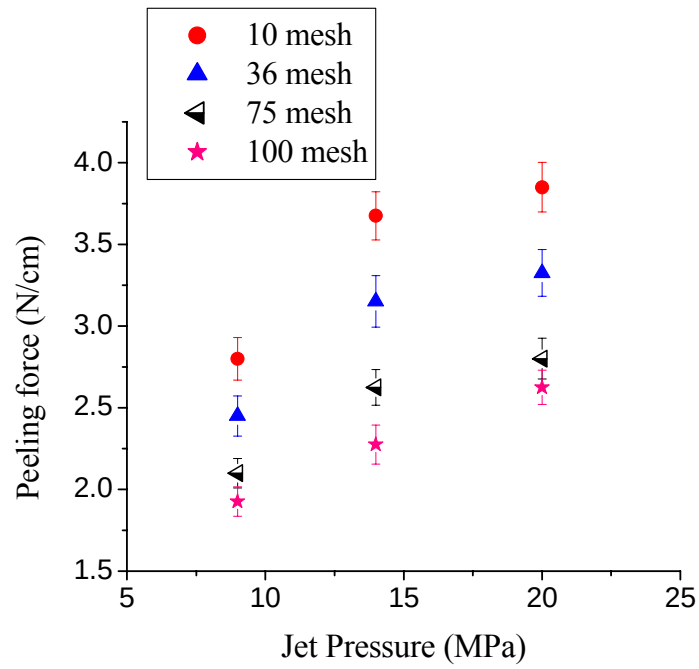


Figure 5.8 Experimental measurements of the peeling force versus jet pressure for 50 g/m² fiberweb (the variation of the peeling force between the five measurements is shown by the interval, the data point in the middle shows the mean value).

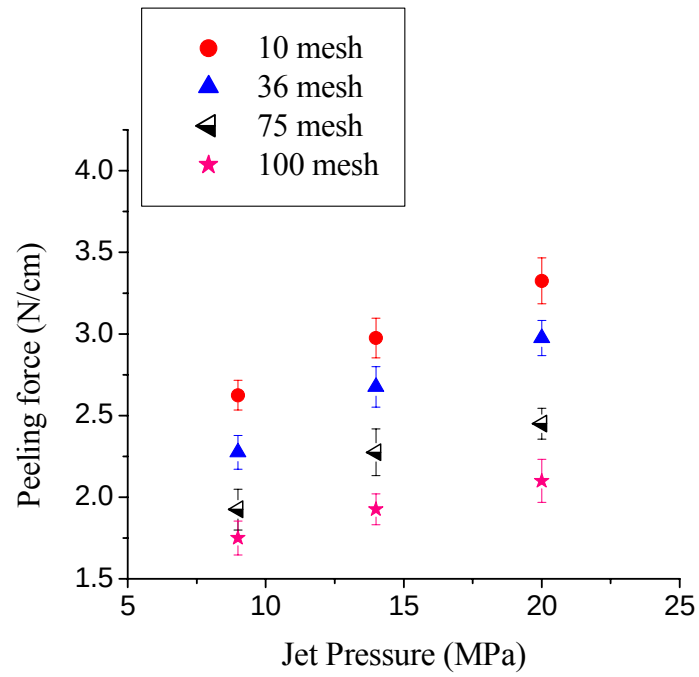
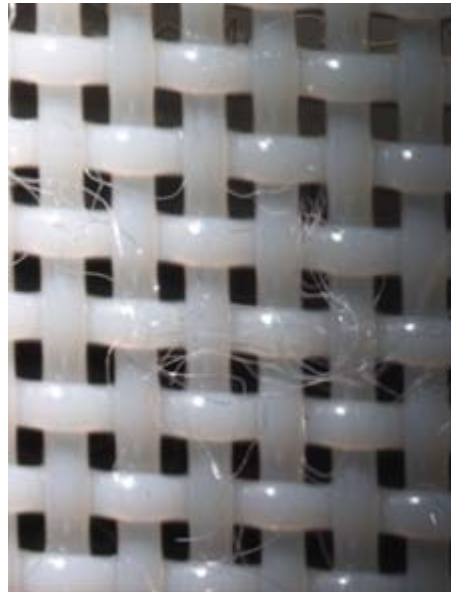


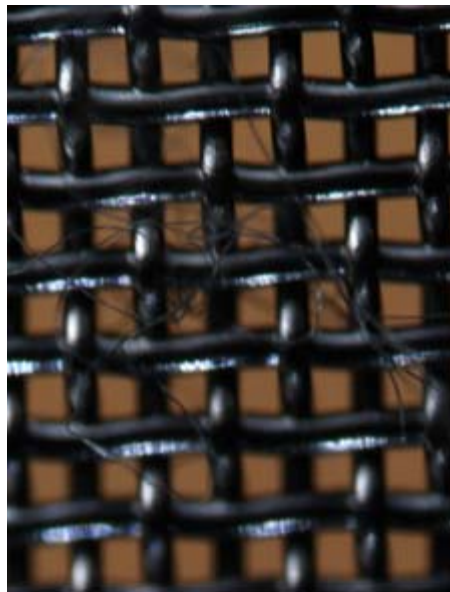
Figure 5.9 Experimental measurements of the peeling force versus jet pressure for 100 g/m² fiberweb (the variation of the peeling force between the five measurements is shown by the interval, the data point in the middle shows the mean value).



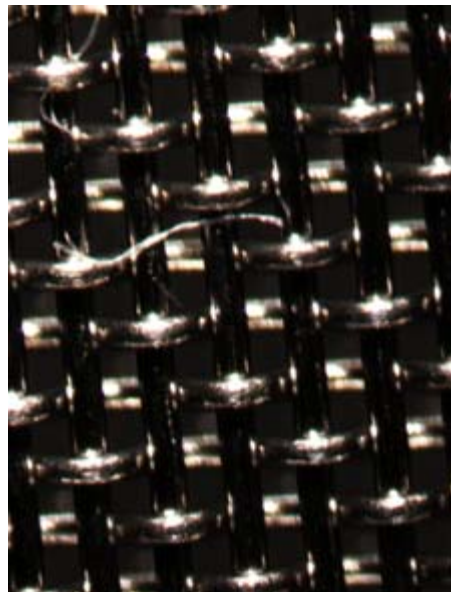
(a)



(b)



(c)



(d)

Figure 5.10 Forming belts after fabrics have been peeled off:
(a) 10 mesh; (b) 36 mesh; (c) 75 mesh; (d) 100 mesh.

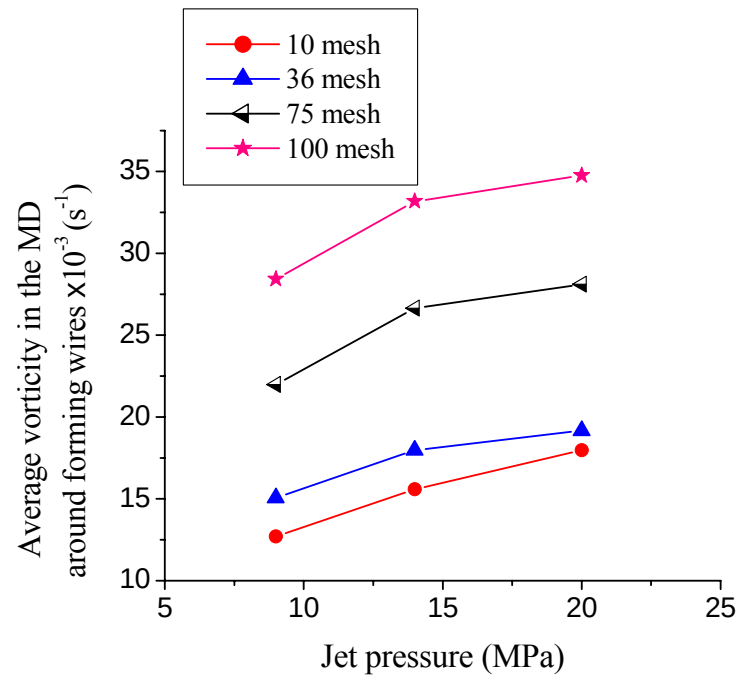


Figure 5.11 Simulated average vorticity in the MD around forming wires versus jet pressure for 50 g/m² fiberweb.

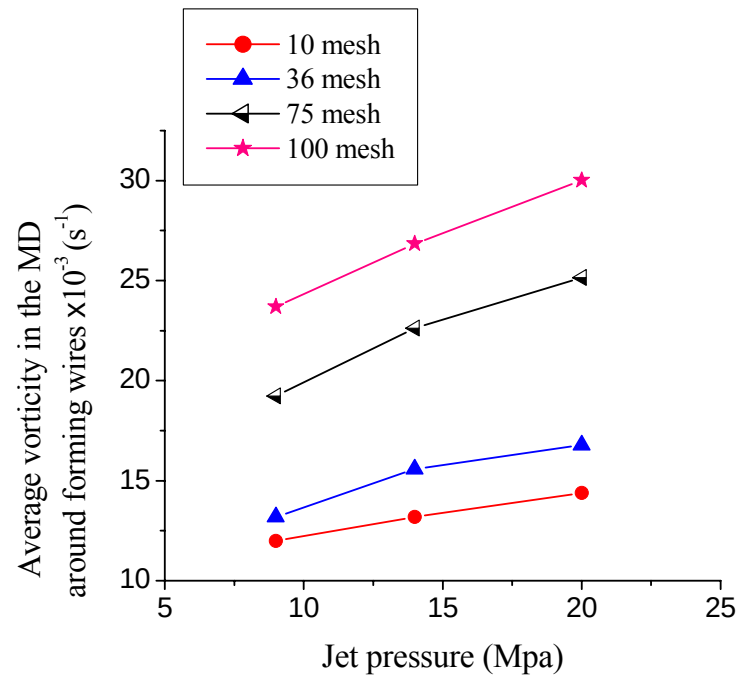


Figure 5.12 Simulated average vorticity in the MD around forming wires versus jet pressure for 100 g/m² fiberweb.

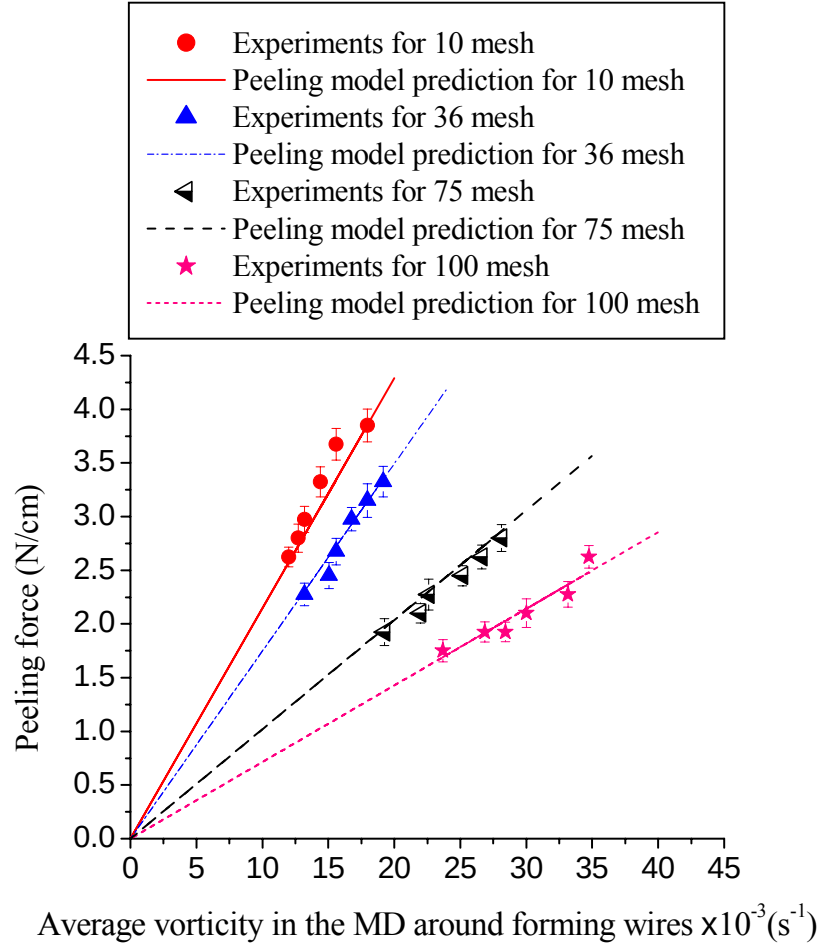


Figure 5.13 Correlation between simulated average vorticity and experimentally measured peeling force (the variation of the peeling force between the five measurements is shown by the interval, the data point in the middle shows the mean value).

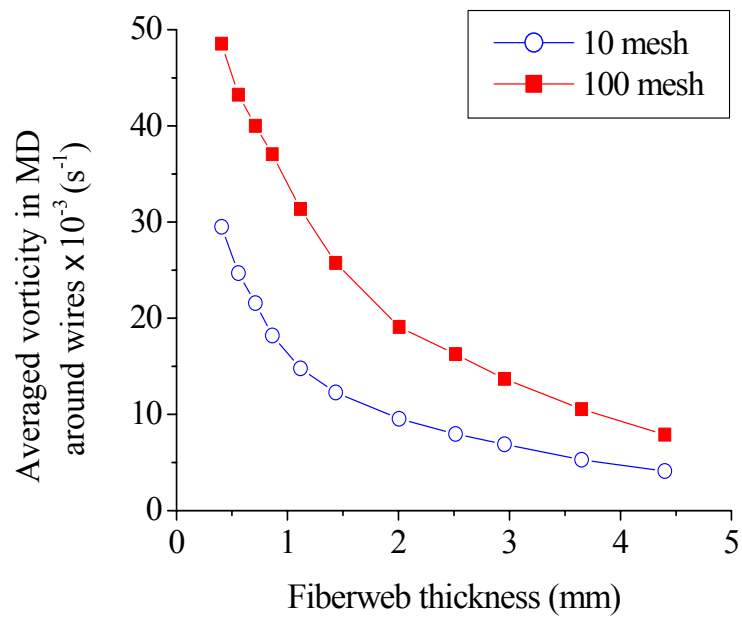


Figure 5.14 Average vorticity in the MD around wires versus fiberweb thickness for different forming belts.

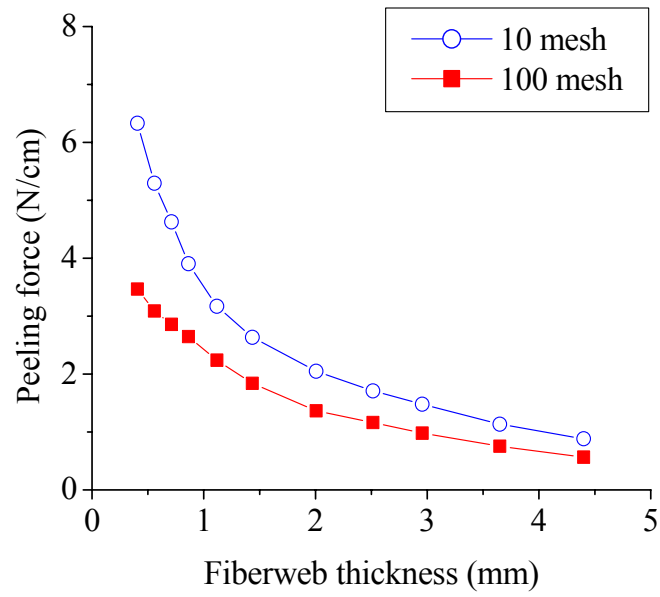


Figure 5.15 Predicted peeling force (using Eq. (5.11)) versus fiberweb thicknesses for different forming belts.

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6 CONCLUSIONS

This dissertation investigated the hydroentanglement process in which water jets penetrating through the fiberweb as well as the forming belt. Numerical simulations and experiments are both performed to investigate the effect of process parameters on the degree of fiber entanglement and the peeling force required to separate hydroentangled fabrics from forming belt. Mathematical modeling, numerical results, and experimental data are presented.

6.1 REMARKS ON DEGREE OF FIBER ENTANGLEMENT IN THE HYDRO-ENTANGLEMENT PROCESS

A model for one manifold of the hydroentanglement process is developed. 3D simulation results of the water jets through the fiberweb and forming wires show water reflection regions near the wires. The time-dependent development of the water flow field shows that vortices are induced by the water jets and the streamlines in the vortices are strongly curved. The mechanism of fiber entanglement is such that the fiber gets involved in a vortex and entangles around neighboring fibers.

The comparison of simulation results with experimental data validates this model's major assumption that the degree of the fiber entanglement is linearly proportional to the average vorticity in the fiberweb. The model thus provides a tool for revealing the optimal parameters to manufacture fabrics with high degree of entanglement and performance while minimizing the energy consumption.

By analyzing the accumulated average vorticity in the fiberweb, it is found that most of the fibers are entangled in the MD-CD plane.

Obtained computational results provide evidence that the degree of entanglement in the hydroentanglement process, which is measured by the average vorticity in the fiberweb layer, is influenced by the jet pressure and jet diameter. It is found that 0.127 mm jet diameter is the optimal parameter, which is widely used in industry.

Simulation results and the corresponding experimental data verified that there is a critical jet pressure for a given fiberweb, which is the well known established fact. Tensile strength of hydroentangled fabrics increases with jet pressure when the jet pressure is smaller than the critical pressure; it reaches its maximum at the critical pressure and subsequently levels off (or even decreases slightly) as the jet pressure continues to increase. The critical jet pressure increases with the fiberweb basis weight.

It is established that with the decrease of the fiberweb permeability, the degree of fiber entanglement and the quality of the fabric decrease. It is also established that the accumulated average vorticity in the fiberweb decreases with the increase of the fiberweb thickness. The results indicate that the accumulated average vorticity attains an asymptotic limit as the fiberweb thickness increases. This suggests there is a maximum fiberweb thickness up to which the process remains efficient.

It is found that the ricochet parameter for the forming wires has a major effect on the degree of fiber entanglement. The use of a finer mesh forming surface leads to a higher degree of fiber entanglement if ricochet parameters of the fine and coarse forming surfaces are close. For the forming belts used in this dissertation, it is found that the tensile strength and modulus in the MD and CD directions are larger when a finer mesh forming belt is used.

The investigation of the effect of jet count on fiber entanglement indicates that for a given fiberweb and forming belt, it is applicable to run the hydroentanglement process at a lower jet pressure than the critical pressure for 15.8 jets/cm jet count by increasing the jet count higher than 15.8 jets/cm (which is traditionally practiced). This makes it possible to produce the fabric with its maximum strength as well as saving the energy consumption.

6.2 REMARKS ON THE PEELING FORCE REQUIRED FOR SEPARATING HYDROENTANGLED FABRICS FROM FORMING BELT

Experimental investigation of the peeling force required to separate the hydroentangled fabric from the forming belt. The peeling force is measured for fiberwebs with different basis weights formed with range of jet pressure and forming belts. 3D simulations of water jets impinging on the forming wires are performed. A mathematical model based on the simulated average vorticity in the MD around wires is developed. The peeling force model predictions are in excellent agreement with experimental results.

The magnified images of the forming belt show that after the fabric is separated from the forming belt, some fibers are left caught by the wires. For a coarser mesh forming belt, more fibers are left caught by the forming wires for a given jet pressure and fiberweb. When other processing conditions are the same, more fibers are left caught by the wires for the fiberweb with a smaller basis weight after the fabric is removed. It is concluded that the primary reason why a force is required to separate the fabric from the forming belt is fiber entrapment (fibers are entangled around the wires and pushed into the knuckles) by the forming wires.

Experimental and numerical investigations both show that for any given type of a forming belt, the peeling force increases with the increase of the jet pressure for a given basis weight of the fiberweb, and increases with the decrease of the fiberweb basis weight at a given jet pressure. It is also found that when the other process parameters are the same, the use of a coarser mesh forming belt leads to more fibers caught between the wires in the knuckles, hence a larger peeling force.

The authors are the first to investigate the peeling force. The developed peeling force modeling provides a tool for designing forming surfaces and selecting the correct blend of fiber, fiberweb, and jet pressure to manufacture fabrics with high degree of entanglement and performance while minimizing the peeling force required separating the fabric from the forming belt.