Optimal Design and Numerical Simulation of High Reliability Meltblown Die

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Abstract. Double-slit nozzles are widely used in meltblown equipment. During the production process, two streams of high speed, high temperature hot air are ejected from two slits on both sides of the spinneret and converge to stretch and refine the polymer melt extruded from the spinneret. If we know the changes of airflow temperature and velocity in the flow field, we can simulate the fiber stretching and refinement process and predict the fiber properties to understand the fiber stretching mechanism, so as to guide the optimization design of meltblown process and improve the product quality and cost saving. In this thesis, a new meltblown die nozzle flow field model is developed based on the existing meltblown double-slot nozzle structure, which was improved from the theoretical model of meltblown double-slot nozzle developed by Ting Chen et al. In this thesis, the calculation area is determined and divided into meshes, and the Reynolds stress model is selected to simulate the flow field numerically, and the velocity and temperature distribution of the flow field along the axis of the spinneret is obtained.

Keywords: optimal design; numerical simulation; high reliability meltblown die

1. Introduction
Among the many processing technologies for nonwoven materials, meltblown is a new and promising technology. Compared with the traditional nonwoven processing technology, this technology has the advantages of advanced technology, short process, low cost, easy access to raw materials, unique performance and wide application, etc. It is based on synthetic polymers as raw materials, spinning and then directly into the network. Meltblown nonwoven products have ultra-fine fiber structure, the fiber diameter is generally about one micron, while the diameter of general textile fibers is about one micron, so meltblown nonwoven products have good uniformity and denseness, and can be used not only as gas-solid phase and liquid-solid phase filtration materials, but also as advanced filtration materials for environmental purification and biological cleanliness [1]. In addition, meltblown nonwoven products have the properties of softness, non-permeability to moisture and bacteria, insulation and oil absorption, so they can be widely used in medical and health care, insulation materials, battery diaphragms, warm clothing and so on. Especially in recent years, with the rapid development of industry and the strengthening of environmental protection, meltblown nonwovens technology and market are developing rapidly [2]. The principle of meltblown process is to extrude the
polymer melt from the spinneret hole of the die head to form a fine stream of melt, and the heated stretching air is blown at high speed from the ducts on both sides of the spinneret hole, also known as air slits, to stretch the fine stream of polymer melt. Cooling air is added from both sides at a certain position below the die head to cool and crystallize the fibers, and a spraying device can be set up below the cooling air device to further cool the fibers quickly. A vacuum suction device is set up under the screen curtain of the receiving device, so that the ultra-fine fibers stretched and formed by the high-speed airflow are uniformly collected on the screen curtain or drum of the receiving device, and become meltblown nonwoven materials by their own bonding or other reinforcement methods [3].

Figure 1. Schematic diagram of the working of the die head assembly

The die head assembly is the most critical piece of equipment in the meltblown production line, consisting of the polymer melt distribution system, die head system, stretching hot air piping channels and heating and insulation elements, as shown in Figure 1. The role of the polymer melt distribution system is to ensure that the polymer melt in the entire meltblown die length direction of uniform flow and uniform retention time, while avoiding excessive thermal degradation of polymer caused by melt flow dead space, so as to ensure that the meltblown nonwoven materials in the entire width of the small surface density deviation and other physical and mechanical properties of the difference, and has a better network uniformity, the current meltblown process is mainly The hanger-type polymer melt distribution system is currently used [4]. The die system of meltblown die assemblies usually consists of a base plate, a spinneret, an air plate, a heating element, etc. [5]. Spinneret spinneret holes are arranged in a single row, commonly used diameter is one, the length to diameter ratio should be greater than, commonly used hole distance is one. Spinneret processing methods such as mechanical drilling, arc deep hole and capillary welding process, the processing accuracy required to ensure that the entire width of each spinneret hole extrusion polymer flow equal [6]. In the meltblown process, the meltblown die head is required to maintain the same hot air flow rate and flow rate over the entire working width in order to obtain a uniform stretching effect on the fine flow of the polymer melt. In recent years, with the continuous development of science and technology, meltblown equipment, the number of nozzles and the width of the nozzle has increased, while the nozzle in the longitudinal and lateral fiber network has also undergone significant changes. Meltblown equipment nozzle installation form has been developed from the earliest fixed installation to movable installation, while the realization of meltblown die can be installed vertically with the fiber output direction and tilt installation, and meltblown equipment die has been developed from the earliest slit type for square, round and other shapes of the spinning hole [7]. This new nozzle equipment can not only significantly reduce costs and save energy, but also significantly improve product quality. The level of automation and mechatronics of meltblown nonwovens equipment is also increasing [8]. The production process has developed from the early single-component fiber production to two-component fiber and multi-component fiber production, and now the meltblown equipment has developed from a single type of equipment to a variety of composite equipment. With the development of meltblown raw materials...
and technology, its products have been developed from the ordinary single type to a variety of composite type. Its products are characterized by good heat preservation, soft feel, good drapability, low strength, poor abrasion resistance, very fine fibers, and large surface area.

In meltblown equipment, a double-slit nozzle is widely used. During the production process, two streams of high speed, high temperature hot air are ejected from two air slits on both sides of the spinneret hole and converge to stretch and refine the polymer melt extruded from the melt hole. If we know the changes of airflow temperature and velocity in the flow field, we can simulate the fiber stretching and refinement process and predict the fiber properties to understand the fiber stretching mechanism, so as to guide the optimization design of melt blown process and improve the product quality and cost saving. In this thesis, the theoretical model of the jet flow field of the meltblown double-slotted nozzle established by Ting Chen et al. is improved according to the existing actual production situation, and a new flow field model of the meltblown die head nozzle hole is established. Secondly, based on the newly established flow field model, the Reynolds stress model was chosen as the turbulence model and the controlling equations of the Reynolds stress model were determined, including the turbulence equations consisting of turbulent dissipation term, stress-strain term, dissipation term, energy exchange term, continuity equation and momentum equation. After that, in order to carry out the next step of simulation, this thesis discretizes the control equations of the Reynolds stress model to obtain the difference equations of the control equations, and chooses the simple algorithm, which is one of the more common methods for calculating the flow field in the pressure-velocity correction method, to solve these difference equations.

2. Mathematical model of the meltblown jet field

2.1. Three-dimensional numerical simulation

The object of the study of melt jet flow field is the flow of high temperature and high speed air jet in the given boundary conditions, the process of air jet motion must follow some basic physical laws, namely, the law of conservation of mass, the law of conservation of momentum, the law of momentum moment balance, the law of conservation of energy, the first law of thermodynamics, these four laws are the most basic physical laws governing fluid motion, the first three of which are the category of mechanics, the fourth is the category of thermodynamics The first three of them are in the field of mechanics, and the fourth one is in the field of thermodynamics. In addition, in order to solve the unknown quantities from the set of equations constructed by these laws, other equations have to be added, which involve the intrinsic and state equations in terms of fluid material properties. Since the conclusions drawn from the momentum equilibrium law are not new compared to the conservation of momentum law, but only prove the symmetry of the stress tensor again, they are not described in detail in this chapter. The basic equations of hydrodynamics are the continuity equation, the equation of motion, and the equation of energy conservation.

The law of conservation of mass is one of the fundamental laws that should be observed for fluid motion, it means that the mass of fluid contained in a fluid system remains constant during motion, or the rate of reduction of the mass of fluid in a fixed space is equal to the mass flux through its surface during this period. Following this law leads to the continuity equation.

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} + \frac{\partial \rho}{\partial t} = 0 \tag{1}
\]

where \( \rho \) is the density, \( t \) is the time, and \( u, v \) and \( w \) are the components of the velocity vector in, and direction. The above equation gives the mass conservation equation for a transient three-dimensional compressible fluid. In fluid mechanics, it is usually considered that if the Mach number of the flow field is less than 0.3, the fluid can be considered incompressible, i.e., the density is constant at this time, which will bring great convenience to the calculation, but because the velocity of the gas jet at the exit of the meltblown die is usually subsonic or higher, the Mach number is close to or higher at this time, and the air must be considered compressible. In addition, this chapter focuses on the analysis...
of the steady-state flow field distribution law, do not consider the flow field changes with time, so the formula changes to.

\[
\left[ \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} \right] = 0
\]  

(2)

2.2. Equations of motion

The law of conservation of momentum is also a fundamental law that must be satisfied by any fluid system. This law can be expressed as the rate of change of the momentum of a fluid in a micro-element with respect to time is equal to the sum of the various external forces acting on the micro-element. According to this expression, the equations of motion for steady-state flow in the x, y and z directions can be derived as follows.

\[
\left. \frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z} \right|_{f_x} = \rho d x
\]  

(3)

\[
\left. \frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z} \right|_{f_y} = \rho d y
\]  

(4)

\[
\left. \frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z} \right|_{f_z} = \rho d z
\]  

(5)

Where, \( d(\rho xq) \) represents the dispersion is the pressure on the fluid micro-element. Since the object under study is air, which is a Newtonian fluid, the viscous stress is proportional to the deformation rate of the fluid. The temperature of the gas jet at the meltblown die head is usually at one, while the ambient temperature is room temperature, and there is a very large temperature gradient between the inlet and outlet of the flow field, so this flow field is a non-isothermal flow field, we need to study not only the velocity field, but also the temperature field. The law of conservation of energy is the basic law that must be satisfied in a flow system containing heat exchange. This law can be expressed as the rate of increase of energy in the micro-element is equal to the net heat flow into the micro-element plus the work done by the body and surface forces on the micro-element.

3. Reliability optimized design

3.1. Determination of boundary conditions

In order to facilitate the simulation of fiber motion, the initial conditions of fiber motion and other conditions during the motion are assumed and the boundary conditions for the termination of the calculation are specified in this thesis. In the meltblown process, factors such as the inhomogeneity of the polymer raw material and the instability of the meltblown process conditions can cause the randomness of fiber breakage, i.e., there are uncertainties in the location of fiber breakage, the length of the fiber after breakage, and the state of the fiber at breakage during the stretching thinning and oscillation process, as shown in Figure 2. Therefore, this thesis assumes that the continuous fiber breaks at a distance of 2 cm from the die head, and the length of the broken discontinuous fiber is 3 cm, and the diameter of the fiber in a fully straightened state and the velocity at the beginning of the motion can be obtained according to the meltblown process conditions, and the velocities of the balls that make up the fiber model are equal. In order to simplify the calculation, other assumptions were made in this thesis: first, the interaction between the fibers is not considered; second, the diameter of the fibers remains constant over the entire length; third, the length of the spring remains constant due to the characteristics of the free motion of the fibers and the fact that the elongation return force is
about 1000 times the bending return force and air resistance. The boundary conditions of the simulation are such that the program cycle is terminated when any of the balls in the fiber model exceeds the calculation area of the flow field.

Figure 2. Fiber trajectory

Fiber trajectory can be seen, the fiber in the process of movement of its tilt angle gradually increased, the outer end of the fiber gradually away from the spinning line, that is, the fiber has a tendency to spread outward, while the fiber form more and more curved or zigzag. Fiber movement of this phenomenon can be explained as follows high-speed airflow from the die on both sides of the air slit and convergence, no longer subject to any solid boundary restrictions, air velocity in the direction and direction are gradually reduced. Therefore, the force of the airflow on the head end of the fiber in both direction and direction is smaller than that on the tail end of the fiber, which makes the displacement of the head end of the fiber smaller than that of the tail end in both directions at each step. Therefore, when the fibers are placed parallel, the tail end gradually upward, so the fiber tilt slowly increase, and the fiber head end gradually close to the spinning line, as shown in Figure 3. For the case of tilted fiber placement, because in the direction of the fiber head end and tail end of the displacement difference than in the direction of the flow field calculations show that the velocity component of the flow than the velocity component decay faster, so the head end of the tilted fiber will continue to go up. For both cases of parallel and inclined fiber placement, the fibers spread outward, which is attributed to the diffusion characteristics of the free jet.

Figure 3. Nozzle motion at different flow rates

3.2. Actual test
As the initial airflow velocity increases, the distance of the fiber vertically away from the spinning line increases. This is in accordance with the results we observed in the actual meltblown production. From
Figure 4 can also be seen, with the initial airflow speed increases, the fiber tilt angle becomes larger, for the initial airflow speed of 300 m/s, the fiber tilt angle is close to 90°, so the fiber will appear serious curling, wrinkling. This is because the same meltblown process conditions when the initial air velocity is large, not only the fiber produced by the fine, and fiber movement by the force is large, so when the fiber movement to a certain position in the airflow imposed by the joint action of axial and tangential forces, easy to deformation, and then the fiber presents folded, flexed state. In this case, the fibers and fibers are easily entangled, resulting in the final fiber network contains a large fiber bundle. Therefore, the airflow speed is large to choose the fiber has not developed into a serious curl state of the small receiving distance.

Figure 4. Relationship between air velocity and vertical reliability of fibers

According to the simulation results of fiber movement, we analyze the influence of receiving distance on the web formation properties. From the above we can see that the closer to the die the smaller the inclination of the fiber, coupled with the faster fiber movement, so when the receiving distance is small, the perpendicular degree of the fiber and the surface of the receiving device is larger, so the fiber collision to the receiving device in the area occupied by the small range, the formation of the fiber network is small, the number of holes, so the pore size uniformity is better, for this reason, the actual meltblown production, in the case of not affecting the The actual meltblown production, without affecting the case of the network, try to use a smaller receiving distance. Fluid mechanics is usually used to define the Reynolds number of fluid flow is turbulent or laminar flow. Reynolds number is small, which means that the fluid flow between the viscous force between the masses of the dominant position, the masses of the fluid parallel to the inner wall of the pipeline flow in a regular manner, laminar flow state. Reynolds number is large, which means that inertia forces dominate, the fluid is turbulent flow state, general pipe Reynolds number Re < 2000 for the laminar flow state, Re > 4000 for turbulent flow state, Re = 2000-4000 for the transition state. Reynolds number of meltblown flow field is very large, usually in the above, the flow belongs to the turbulent form. Therefore, the meltblown flow field at any point in the velocity of the flow characteristics are randomly varying. The basic equations of the flow field obtained in this paper are applicable to the turbulent state, but with the current technology and computer performance can not complete the direct numerical simulation of turbulent flow, and most researchers believe that even if we can really get these pulsation results, it is not very meaningful for solving practical problems. This is because, from the point of view of engineering applications, what is important is the change of the mean flow field caused by turbulence, which is the overall effect. Therefore, the current common practice is to represent the transient pulsations in a time-averaged equation by a model, i.e., the turbulent motion is considered as a superposition of two flows, one is the time-averaged flow and the other is the transient pulsation flow.

In this paper, hysteresis temperature is proposed as an objective function to optimize the meltblown injector flow field. In meltblown spinning process, the flow field not only provides the draft force required for fiber stretching, but also provides a temperature field suitable for fiber stretching to prolong the fiber stretching deformation time. The hysteresis temperature combined with the velocity
and temperature factors of the flow field is more suitable as the objective function of the flow field optimization. In this paper, the orthogonal design method and single-objective genetic algorithm are used to optimize the design of the slit meltblown die head by using the hysteresis temperature as the objective function. In addition, the effect of variation of die head parameters on the meltblown jet flow field is derived. Through the analysis of the intuitive results of the orthogonal design, it is found that the slot width has the greatest influence on the stagnation temperature, followed by the slot tilt angle, and the effect of the head end width is almost negligible compared to the other two factors. With the increase of the slot width and the decrease of the slot angle, the stagnation temperature showed an increasing trend.

4. Conclusion
In this paper, the mathematical model of meltblown jet field was firstly established by finite volume method and solved numerically to obtain the three-dimensional flow field distribution under the slit-shaped meltblown die head. Then the meltblown flow field was measured with a hot-wire anemometer and the validity of the mathematical model was verified by comparing with the simulated data. The flow field distribution law of the meltblown jet field was obtained. After analysis of the simulation and experimental results, the entire meltblown jet field can be divided into three regions by "contact point" and "merging point", i.e., "jet alone flow region", "jet contact fusion region" and "jet merging region". Before the "contact point", the gas jet flows separately, and two gyratory regions are formed in the area between the two jets. After the "point of contact", the jet flows as a single jet and gradually spreads around until it is submerged in the surrounding environment.

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