Numerical Analysis of Airflow Fields from New Melt-Blowing Dies for Dual-Slot Jets

Yudong Wang,* Jianping Zhou, and Xiaoping Gao

ABSTRACT: The melt-blowing process uses high-speed and high-temperature airflow from the die head to draw polymer melt into micron-sized fibers. In this work, to reduce the diameter of the melt-blowing fibers, three new slot dies have been designed based on the common slot die. With computational fluid dynamics technology, the two-dimensional flow fields from these new types of slot dies were numerically calculated. To verify the validity of the calculation, the simulation data was compared with the experimental data. The numerical result shows that the internal flow stabilizers could increase the velocity peak and the pressure peak on the centerline of the flow field and could reduce the reverse velocity, temperature decay, and maximum value of turbulence intensity near the die head. Compared with the common slot die, the slot dies with cuboid bosses could increase the air velocity and temperature on the spinning line in most areas and reduce the air pressure within 1.5 cm below the die. The slot dies with internal flow stabilizers and cuboid bosses have the optimal flow field performance and would be beneficial to the production of thinner fibers.

1. INTRODUCTION

Melt-blowing technology is an industrial method that could directly make polymer chips into nonwoven fabrics. The melt-blowing fiber diameters are between 0.5 and 10 μm, which belong to the rank of superfine fiber.1 The melt-blowing fibers have such excellent characteristics as a small diameter and a large specific surface area, which are unmatched by most ordinary fibers. Therefore, the emergence of the melt-blowing fibers has greatly expanded the application fields and development prospects of textile fibers, and their products are made of antihaze masks, high-efficiency air filters, multifunctional biochemical protective clothing, etc.2−4

The common slot die is one of the most core components in melt-blowing equipment and is most commonly used in fiber production. As shown in Figure 1, the hot air is ejected from the slots and forms a high-velocity and high-temperature flow field under the die head. The flow field from the die head could provide a strong draft for the polymer melt and affect the diameter of the melt-blowing fibers. Therefore, the study of the airflow field from the die is the basis for exploring the stretch mechanism of the melt-blowing fiber. To reduce the fiber diameter and improve the melt-blowing nonwovens performance, many researchers have carried out related work on the slot die and the flow field.

Harpham and Shambaugh5,6 used a pitot tube and a thermocouple to measure the velocity and temperature distribution below the slot die. Through statistical analysis of the experimental data, they obtained the empirical equations for the velocity and temperature distribution in the field. Tate and Shambaugh7 measured the velocity distribution at low speeds. It was found that when the nose width was zero and the air-slot inclination angle was 60°, the die had the maximum velocity on the centerline of the flow field. Wang and Ke8 used a laser Doppler velocimetry to measure the flow fields of the slot die and the flow field.

Figure 1. Two-dimensional geometry of a common slot die.
several slot dies with various geometric parameters. Their research shows that as the slot angle increases, the die head had a higher air velocity in the flow field. Xie and Zeng investigated the relationship between the fiber whipping and the velocity distribution of the flow field with a hot wire anemometer. They found that the structure of the melt-blown fibers exhibited a two-dimensional motion. Wang et al. added a pair of louvers under the slot die and performed online measurement using a pitot tube. Wang and Zhou applied a hot wire anemometer to conduct online experimental measurements. Krutka and Shambaugh et al. investigated the relationship between the velocity distribution of the airflow field and a hot wire anemometer. Their results revealed that in the three-dimensional flow field below the slot die, the fibers exhibited a two-dimensional motion. To increase the airflow stretching speed, Shambaugh et al. added a pair of louvers under the slot die and performed online measurement using a pitot tube. Wang and Zhou applied a hot wire anemometer to conduct online experimental measurements of the airflow field under the new slot die. This result shows that the air velocity on the centerline of the new slot die was higher than that of the common slot die.

Compared to the experimental measurement method, it is more convenient to obtain the airflow field distribution under the slot die with computational fluid dynamics (CFD) technology. The CFD technology not only saves the cost and time of the experimental test but also could obtain some data in the area that could not be measured in the experiment. Krutka and Shambaugh et al. first studied the airflow field under a melt-blowing slot die using the CFD technology. They found that after the parameters in the turbulence model had been adjusted, the simulated calculations were more consistent with the experimental measurements. Krutka and Shambaugh et al. used numerical simulation methods to investigate the effect of geometric parameters on the airflow field of the slot dies. They found that the change in the structure of the melt-blowing die had a great impact on the distribution of the flow field. Chen and Huang studied the two-dimensional airflow field under the slot die with PHOENICS. They found that as the slot width increased, the velocity and temperature on the centerline also increased. Sun and Wang used orthogonal experimental design and single-objective genetic algorithm combined with the CFD technology to optimize the airflow field under the common slot die. Wang et al. designed a novel slot die and numerically analyzed its two-dimensional airflow field.

Through aerodynamic and thermal analysis and turbulence analysis, the kinetic energy loss in the flow field of a common slot die could be obtained, which limit the drafting efficiency and further reduce the fiber diameter. First, the triangular recirculation zone below the jet is full of separation vortices, which is a typical loss of kinetic energy. Second, two separate jets are spread to both sides during the movement, which is another reason for the loss of jet energy. Third, after the two jets are fused, they would exchange kinetic energy with the surrounding low-speed fluid, causing the speed of the draft flow to drop. Fourth, the rapid decay of the temperature of the airflow on the centerline of the flow field causes the polymer to solidify within a short distance and has a certain effect on the refinement of the fiber.

Some researchers have tried to decrease the fiber fineness by reducing the inner diameter of the spinneret or increasing energy consumption. On the one hand, in the melt-blowing process, reducing the diameter of the spinneret and the polymer melt injection rate would undoubtedly result in fibers with smaller diameters. However, it would sacrifice fiber production and dramatically increase production costs. On the other hand, increasing the pressure at the air inlet or the width of the slot would also be helpful in decreasing the fiber diameter and the gas and energy consumption per kilogram of the melt-blowing product would increase rapidly. Therefore, the above methods are not desirable in the commercial production of melt-blowing fibers. In this article, without reducing the fiber yield and increasing the energy consumption of the melt-blowing production, three new slot dies were designed to decrease the kinetic energy loss of the flow field and reduce the thickness of the fiber. In addition, CFD software was used to numerically calculate the airflow fields of these new slot dies.

2. DIE CONFIGURATION

Figure 1 shows the common slot die, which is called “blunt die”. The common slot die is used to compare with the other three new slot dies to test their effectiveness.

As shown in Figure 2, the nose piece of new die 1 has an internal flow stabilizer on each side. The purpose of increasing the internal flow stabilizer is to suppress the generation of the separation vortex and reduce the diffusion of the two separate jets. The cross sections of these two internal flow stabilizers are right triangles. The inclined surface of the internal flow stabilizer is on the same plane as the inner wall surface of the air slot. Moreover, the bottom edge of the internal flow stabilizer is coplanar with the nose piece.

In new die 2, there is a cuboid boss on the outside of the air slot (see Figure 3). Also, the two cuboid bosses are parallel to the slot exit. The cuboid boss has a certain height in the z-axis direction, which could prevent the radial diffusion of a single jet formed by the fusion of two jets.

Figure 4 demonstrates the structure of new die 3. The new slot die 3 combines the designs of new die 1 and new die 2 and has both internal flow stabilizers and cuboid bosses. Theoretically, this new type of die has the best effect and minimizes the kinetic energy loss of the jets.

New die 1, new die 2, and new die 3 are all designed on the basis of the blunt die. Therefore, these four slot dies have three identical structural parameters: nose piece width, slot width, and slot inclination. The nose piece width \( f \), slot width \( e \), and slot inclination \( \alpha \) are 1.28 mm, 0.65 mm, and 60°, respectively, which refer to previous studies. The length of the internal flow stabilizer and the length of the cuboid boss in the y-axis direction are all equal to the length of the slot. The height of the internal flow stabilizer \( i \) is 0.76 mm, and the angle...
between the hypotenuse of the internal flow stabilizer and the nose piece is 60°. The height \( b \) of the cuboid boss in the \( z \)-axis direction is 20 mm, and the distance \( w \) between the cuboid boss and the \( z \)-axis is 10 mm. In addition, the cuboid boss extends in the \( x \)-axis direction to the edge of the die.

### 3. Numerical Simulation

#### 3.1. Computing Domain Size and Meshing Methods.

Figure 5 shows the computational domain of the blunt die. We consider this as an example to show the calculation domain size and meshing method of these several slot dies. Because the three-dimensional flow field below the slot die has a two-dimensional distribution characteristic,\(^5,12\) in this paper, two-dimensional numerical calculations were carried out.

As shown in Figure 5, the coordinate system of the calculation domain of the blunt die is the same as that in Figures 1–4. \( O \) is the origin of the calculation domain. The \( z \)-axis is along the \( OH \) direction and perpendicular to the nose piece of the slot die. The \( x \)-axis is along the \( OD \) direction and is coplanar with the nose piece. The calculation domain consists of two parts: the slot and the calculation domain below it. The vertical distance from the slot entrance to the following calculation domain is 5 mm. The size of the calculation area under the blunt die is 100 × 30 mm\(^2\), which is along the positive direction of the \( z \)-axis and the \( x \)-axis, respectively.

Due to the geometrical characteristics of the two-dimensional computational domain of the blunt die, the partitioning method could be used to divide the slot area and the area under the die into quadrilateral structural grids. Consequently, the grid size of the area from the slot entrance to 35 mm in the \( z \)-axis direction and from \( OH \) to 6 mm in the \( x \)-axis direction is 0.5 mm. In the rest of the calculation domain, the size of the quadrilateral grid is 0.1 mm.

#### 3.2. Turbulence Model and Boundary Condition Settings.

The standard \( k-\varepsilon \) model\(^12\) was used to calculate the two-dimensional flow field of the melt-blowing slot dies. Based on previous research conclusions,\(^12,16,17\) the turbulence model parameters \( C_{\varepsilon 1} \) and \( C_{\varepsilon 2} \) were modified to 1.24 and 2.05.

\( AC \) was set as the pressure inlet in the slot area of the calculation domain. The pressure value of the compressed airflow at the slot inlet was 1.25 atm, and the temperature value of the airflow was 400 K. The hydraulic diameter at the slot entrance was equal to the slot width, and the turbulence intensity of the airflow was set to 10%. \( DG \) and \( GH \) were defined as the boundary conditions of “pressure outlet”, and their air temperature and pressure were the same as those of the atmospheric environment. The length scale and turbulence intensity of \( DG \) and \( GH \) were set to 10 mm and 10%, respectively. \( OH \) was set to a symmetric boundary condition, which could greatly reduce the amount of calculation and calculation time. The other boundaries were defined as nonslip walls with a temperature of 480 K.

#### 3.3. Experimental Verification.

To verify the validity of the numerical calculation results of the flow fields of the four slot dies, the air velocity measurements were compared with the numerical calculation data obtained by applying the standard \( k-\varepsilon \) model in this section.

The members of this research team have used a dynamic flow velocity measurement system of Dantec StreamLine to measure the airflow field below a common slot die, whose structure and dimensions are exactly the same as those of the “blunt die” (see Figure 1). The experimental test conditions were as follows: the pressure and temperature at the air inlet were 1.3 atm and 400.15 K, respectively. The high-pressure gas was supplied by an air compressor and heated to a set temperature before reaching the die head assembly. During the
measurement of the airflow velocity, the influence of the melt-blowing fibers on the flow field is ignored. The measurement results and calculation data of the air velocities on the centerlines of the flow field are shown in Figure 6. It could be seen that the velocity on the centerline measured by the hot wire anemometer is basically consistent with the results obtained by numerical calculations.

4. RESULTS AND DISCUSSION

It was found in the fiber production experiments that 96% of the fiber diameter reduction was within 1.5 cm from the nose piece of the die head.23 Also, this range of 1.5 cm below the slot die is called the main draft zone. In addition, during the melt-blowing process, the fibers mainly move near the centerline of the flow field from the slot die. Therefore, the centerline of the flow field is also called the spinning line. In the work, the velocity, pressure, temperature, and turbulence intensity distribution on the spinning line within 1.5 cm below the die were mainly investigated.

4.1. Velocity Distributions on the Spinning Lines. In Figure 7, the air velocities on the spinnings of the blunt die and three other new slot dies are shown. Due to the existence of the reverse reflow zone (see Figure 8a), the velocity in the vicinity of the blunt die head is negative, which is opposite to the direction of the fiber movement and is bad for fiber drawing. Figure 7 reveals that the reverse velocities on the centerline of the new die 1 and new die 3 are much smaller than those of the blunt die. It could be seen from Figure 8b,d that the presence of an internal flow stabilizer reduces the volume of the recirculation zone; as a result, the reverse speeds in new die 1 and new die 3 are reduced. A comparison of Figure 8a,c shows almost no difference in the areas of the reflow zone in the new die 2 and the blunt die. The finding proves that the cuboid boss could not improve the reverse speed.

As could be seen from Figure 7, compared with the blunt die, the maximum air velocities on the centerline of the flow field of the new die with internal flow stabilizers and the new die with cuboid bosses are all increased. The existence of internal flow stabilizers not only prevents the jet from diffusing inward but also greatly suppresses the generation of the separation vortex (see Figure 8a,b). In view of the above finding, the peak of the airflow on the spinning line of new die 1 was increased. It could be seen from Figure 9 that after the diffused jet encounters the left cuboid boss, it would change the movement route and move toward the center of the flow field. Consequently, the energy loss of the fused jet is reduced and the velocity on the spinning from new die 2 increases.

Figure 7 reveals that the combination of the internal flow stabilizer and the cuboid boss has the best effect, and the air velocity on the spinning line of new die 3 is the largest. The airflow speed on the spinning line has a great influence on the draft of the fiber because the square of the velocity difference between the draft airflow and the fiber is proportional to the draft force.24,25 Therefore, using the airflow velocity as an indicator, the new die 3 could produce the smallest fiber.

4.2. Pressure Distributions on the Spinning Lines. Figure 10 shows the air pressure distributions on the spinning centerlines of the four slot dies. Compared to the velocity peaks in Figure 7, the air pressure peaks on the z-axis appear earlier. As could be seen from Figure 10, the peak pressure of new die 1 is higher than that of the blunt die. The reason is that under the Coanda effect, the internal flow stabilizers could make more airflow move along their slopes and have a strong impact on their tips. A greater gas pressure could give the polymer melt a larger radial force, which is beneficial in reducing the fiber diameter. Compared to the blunt die, the pressure peak on the spinning centerline of new die 2 is much smaller. This should be the attraction of the cuboid bosses to direct the airflow to their walls. Under the combined effect of the internal flow stabilizer and the cuboid boss, the maximum pressure of new die 3 on the z-axis is almost the same as that of the blunt die. In most areas after the pressure peak, the pressure values of new die 2 and new die 3 are significantly smaller than that of the blunt die. It could be explained by Bernoulli’s equation,26 and when the air velocity is large, the pressure is relatively small.

4.3. Temperature Distributions on the Spinning Lines. Figure 11 shows the static temperature change curves of the centerline of the common slot die and three other new types of slot dies. In the area near the nose piece, the airflow temperature values on the spinning lines of new die 1 and new die 3 are higher than those of the blunt die and new die 2. There are three main ways of heat transfer: heat conduction, heat convection, and heat radiation. In the actual heat-transfer process, these three methods are often carried out together. Among them, convective heat transfer, as a way of heat transfer, is the most important way of heat transfer in gases. As could be seen from Figure 8a—d, the internal flow stabilizer reduces the area and the reverse velocity in the recirculation zone. It causes a weakening of the convective heat transfer in this area and allows less heat to be taken away. This is why the new slot dies with internal flow stabilizers have a smaller temperature decay rate in the area near the nose piece.

In the interval between 0.5 and 1.5 cm, new die 2 and new die 3 have a greater temperature advantage than the blunt die.
and new die 1. Moreover, as the value of \( z \) increases, the airflow temperature difference on the spinning line between the new slot dies with the cuboid bosses and the other two die heads rise. This is because the cuboid boss has a large volume, and it could transfer a large amount of heat to the centerline.

**Figure 8.** Velocity vectors in the flow fields of four slot dies (unit: m/s).

**Figure 9.** Velocity vector distribution in the range of 1–20 mm below the new die 2 and close to the cuboid boss (unit: m/s).

**Figure 10.** Pressure curves on the spinning lines of four slot dies.

**Figure 11.** Temperature curves on the spinning lines of four slot dies.
area of the flow field through thermal conduction, thermal convection, and thermal radiation (see Figure 9).

Temperature is also an important factor affecting fiber diameter.27 During the fiber drawing, the airflow temperature and the polymer temperature all decay rapidly in the area below the die.27 As a result, the melt-blowing fibers reach a freezing point in a short distance below the spinneret and stop stretching. If the air temperature is higher, the decay rate of the air temperature could be reduced, thereby further increasing the fiber drawing distance, which is beneficial to obtaining finer fibers. As a consequence, new die 1, new die 2, and new die 3 are more beneficial for fiber attenuation than the blunt die.

4.4. Turbulence Intensity Distributions on the Spinning Lines. The turbulence intensity curves on the centerlines of the blunt die, new die 1, new die 2, and new die 3 are shown in Figure 12. Combining Figures 7 and 10, it could be seen that the positions of the turbulence intensity peak and the pressure peak are almost the same, which are earlier than those of the air velocity peak. Figure 12 reveals that the difference in turbulence intensity between the blunt die and new die 2 is small in most areas. Especially in the region near the nose piece, their turbulence intensity curves almost completely overlap. This is because the cuboid boss has almost no effect on the reflow area (see Figure 8a,c).

The turbulence intensity peaks on the spinning lines of new die 1 and new die 3 are much smaller than those of the blunt die and new die 2. The reason for this result is that the internal flow stabilizers occupy most of the recirculation zone and inhibit the generation of vortex clusters (see Figure 8b,d). In the second half of the z-axis, the turbulence intensity of new die 1 is slightly smaller than that of new die 3. It means that the cuboid boss could increase the turbulence intensity of the airflow in the area far from the die head.

When the turbulence intensity of the airflow is low in the flow field, it means that the more stable the airflow, the smaller the speed fluctuation of the airflow. In the melt-blowing process, it is desirable that the fluctuation of the air velocity on the spinning centerline is small, which is conducive to the stable stretching of the fiber. Especially in the area near the die head, if the airflow velocity fluctuates sharply, not only would the fiber break rate be increased but also the polymer melt would easily adhere to the die head or be entangled with the surrounding fibers.27 Therefore, among these four dies, new die 1 and new die 3 contribute to the smooth production of fibers.

5. CONCLUSIONS

In this paper, three new slot dies were designed. Their airflow fields were predicted with the CFD technology. Furthermore, the effectiveness of numerical calculations was verified by experimental measurements.

It is found that both the new die with internal flow stabilizers and the new die with cuboid bosses could increase the air velocity and temperature on the spinning line. The slot dies with an internal flow stabilizer could reduce the reflow zone and the reverse velocity. However, the slot die with the cuboid boss has less influence on the reflow zone, and its reverse velocity and velocity fluctuation intensity are almost the same as those of the common die. Compared with the common die, the pressure peak of the new die with internal flow stabilizers is higher, while the extreme pressure value of the new die with cuboid bosses is lower. The turbulence intensity of the slot die with internal flow stabilizers is much smaller than that of the common die. In summary, the new die with both internal flow stabilizers and cuboid bosses maximizes the performance of the flow field and is helpful in fiber attenuation.

6. EXPERIMENTAL AND SIMULATIONAL SECTION

6.1. Measuring Tools. In the flow field experimental measurement process, the hot wire anemometer (Dantec, Denmark) was employed, and its model was Dantec CTA/HWA (Streamline), including hot line host (Dantec StreamLine Frame 90N10), speed measurement module (Dantec StreamLine CTA90C10), temperature measurement module (Dantec StreamLine CTA 90C20), and calibrator (Dantec Calibration System 90H10). One-dimensional probe (5SP11) was used to collect the flow field data.

6.2. CFD Software and the Computer. Fluent 6.3.26 (ANSYS) and T7920 Workstation (DELL) were used to calculate the flow fields of the four slot dies.

AUTHOR INFORMATION

Corresponding Author

Yudong Wang — College of Light Industry and Textile, Inner Mongolia University of Technology, Hohhot 010080, P. R. China; Mechanical Engineering Department, Xinjiang University, Ürümqi, Xinjiang 830046, P. R. China; College of Textile Engineering, Taiyuan University of Technology, Taiyuan 030024, P. R. China; orcid.org/0000-0002-7134-3495; Email: wangyudongwuqiao@163.com

Authors

Jiapeng Zhou — Mechanical Engineering Department, Xinjiang University, Ürümqi, Xinjiang 830046, P. R. China
Xiaoping Gao — College of Light Industry and Textile, Inner Mongolia University of Technology, Hohhot 010080, P. R. China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c01668

Notes

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