Preliminary Study of the Effect of Secondary Airflow on Fiber Attenuation During Melt Blowing

Huawei Xu¹, Zhijun Zhou², Jie Liu¹, Lie Zhao¹, Sheng Xie³*, and Junfeng Zhang¹*

¹Hexin Kuraray Micro Fiber (Haiyan) Co., Ltd., Jiaxing 314300, China
²Zhejiang Hexin New Material Co., Ltd., Jiaxing 314033, China
³Nanotechnology Research Institute, College of Material and Textile Engineering, Jiaxing University, Jiaxing 314001, China

(Received May 25, 2022; Revised July 17, 2022; Accepted July 22, 2022)

Abstract: In order to enhance the fiber attenuation during the melt-blown process, a pair of air nozzle, which could erupt airflow as secondary airflow, below the spinning die was arranged and used. Firstly, the effect of applying secondary airflow on the whole airflow was explored by Computational Fluid Dynamics (CFD) simulation. The simulation results demonstrate the interactive relationship between the primary airflow from the spinning die and the secondary airflow. Then, the air velocity of the whole airflow at conditions of with and without secondary airflow was experimental verified. Finally, the effect of secondary airflow on the fiber diameter and the fiber evenness was investigated by a spinning experiment. The spinning results reveal that the application of secondary airflow does not certainly enhance the fiber attenuation. The fiber diameter decreases only when the inlet velocity of secondary airflow is higher than a critical value. In addition, the spinning experiment indicates that the application of secondary airflow improves the evenness of fiber.

Keywords: Melt blowing, Secondary airflow, CFD simulation, Fiber attenuation, Spinning

Introduction

Melt-blown technology once attracted unprecedented attention during the outbreak period of COVID-19 pandemic. In melt-blown process, high-speed heated gas streams impinge on molten jets as the jets emerge from a heated spinning die. The force of the gas upon the molten jets causes rapid attenuation of the jets to fine diameters [1]. Commonly fibers with diameter of several micrometers can obtained by melt blowing [2], fibers of 0.1 μm diameter also can be made under some special conditions [3]. Due to high insulating value, high cover per unit weight, high surface area per unit weight [3], the melt-blown fiber materials is widely used as a filter [4-6], an absorbent medium [7], or others [8].

The airflow is what drives the melt-blown process. Numerous work including the numerical simulation [9-17] and experimental verification [9,10,19-21] revealed that, during the melt-blown process, the air firstly converges into a combined airflow, and the air velocity rapidly increases to a maximum value. However, the maximum speed did not last and subsequently declined sharply. In order to reduce the disadvantage of velocity rapidly decreasing, lots of researchers explored new method for improving the delay of the air velocity. Shambaugh et al. [29] explored that introducing a plate into the air field results in substantially higher fiber attenuation for a given air flow rate [22]. Wang [23] improved the airflow field by applying an inner stabilizing piece into annular die. The inner stabilizing piece can diminish the recirculation area, inhibit the interaction of the jet and the nearby gas, and change the path of the air stream. Hasson and Pourdeyhimi et al. [24] numerically investigated that applying air constrictors around the primary air jets was conductive to maintain the maximum air velocity and temperature in longer distance. Moreover, supersonic Laval nozzle was numerical explored and was expected to be applied into melt-blown spinning with super attenuation [25,26]. Chelikani and Sparrow [27] involved controlling edge effects during fiber laydown by using flat or convex plates, resulting in a more uniform laydown pattern at the edge of the collected sheet flat or convex plates.

Some other methods have emerged to improve the airflow field by adding auxiliary devices under the melt-blown die, Chen et al. [28] numerically investigated that adding an auxiliary nozzle can further decrease the fiber diameter. Shambaugh et al. [29] explored that the air flow field below a melt blowing die could be modified by placing louvers in the airfield, the air velocity at the trailing edge of the louvers was as much as 60% higher than for when no louvers were present, and their spinning experiment verified that fiber diameter reductions of 30 % or more was possible by using louvers [30]. Hao et al. [31] introduced a thermal insulation tube with heating ability into the air flow field during the melt blowing process. Their experiments results indicated that a die with a thermal insulation tube can achieve a higher polymer jet attenuation.

The present work was inspired by the work of Shambaugh et al. [29,30], who used a pair of louvers below the spinning die to enhance higher air velocity. This work applied a pair of air nozzle to generate secondary airflow for the expectation of obtaining higher airflow velocity. It is worth noting that

*Corresponding author: xie@zjxu.edu.cn
*Corresponding author: zhangjunfeng@hexin-kuraray.com
the air nozzle of this work has an air eruption function, however, the louvers did not have [29]. This paper focuses on exploring the effect of secondary airflow on the fiber attenuation during melt blowing, and was carried out by approaches of numerical simulation, air velocity measurement, and fiber spinning.

Experimental

Melt-Blown Spinning

As shown in Figure 1(a), in the present work, a pair of air nozzle below the spinning die was arranged. Here, the airflow from these air nozzles is called secondary airflow. The application of secondary airflow was expected to have a better effect on fiber attenuation. The melt-blown spinning die used in this work was a sharp die with V structure air-slot in it [15]. As shown in Figure 1(b), this sharp die has half air-slot angle \( \alpha \) of 30 °, the melt orifice diameter \( d \) of 0.5 mm, the width \( e \) and the length \( l \) of the air slot of 0.5 mm and 7 mm, respectively. The pair of air nozzle below the die has air-slot width of 0.5 mm, and length of 62 mm. As shown in Figure 1(a), the angle between the secondary inlet flow and the lateral direction was \( \beta = 45 \) °. The distance between the tips of the pair of nozzles was 36 mm, and the tip was 45 mm below the spinning die face.

In the spinning experiment, a polypropylene (PP) with melt flow rate of 1200 g/10 min was used as received (Hangzhou Chenda new material Co., Ltd., Hangzhou, China). The polymer flow rate of 2.7 cc/min and polymer temperature of 220 °C were used. The inlet air velocity of the die \( v_1 \) was 47.6 m/s with same temperature of polymer. However, the inlet velocity of the secondary airflow \( v_2 \) was arranged from 0 m/s to 117 m/s with ambient temperature. The melt-blown fibers were collected 20 cm below the spinning die.

Numerical Simulation

The melt-blown airflow field was numerical simulated by the approach of computational fluid dynamics (CFD). A two-dimensional model of airflow in \( x-z \) plane was established in the Gambit, the structure of the CFD model was same as that in the experiment. The airflow model below the die face has 18.5 mm width (i.e., distance between \( o \) and \( d \)) and 150 mm height (length of \( o-j \)). The primary inlet region \( o-a-b-h-c \) had length of 5 mm, line \( a-h \) is the velocity inlet boundary. The inlet region of the secondary airflow \( c-f-g-h \) also had length of 5 mm, and line \( f-g \) is the velocity inlet boundary. Lines of \( o-a, b-c, c-d, e-f, \) and \( g-h \) are the non-slip wall boundary. Line of \( o-j \) is the symmetric boundary. Lines of \( d-e \), \( h-i \) and \( i-j \) are pressure outlet boundary.

The whole computational domain was firstly meshed with 0.15 mm length cell in the Gambit, then the important region near the spinning die and the air nozzle (gray color in Figure 2) was re-meshed in the FLUENT 6.3.26. The re-meshed region had the cell length of 0.075 mm, which was small enough for getting exact numerical simulation results [15]. The numerical simulation was obtained by solving the N-S equation through FLUENT. In the Fluent, the standard \( k-\varepsilon \) model with default parameters was used to calculate the two-dimensional airflow field. The averaged steady airflow was calculated by this simulation. In order to investigate the effect of the secondary airflow on the whole airflow at different conditions, airflow in computational models with different inlet air velocities \( (v_1 \) and \( v_2 \) were simulated.

Measurement

The melt-blown air velocity was measured by a ZC1000-1F type electric Pitot tube (Shanghai YIOU instrument equipment Co., Ltd., Shanghai, China) in absence of spinning fiber. This Pitot tube has a capacity for measuring maximum air velocity of 288 m/s with a resolution of 0.01 m/s. Air velocities at different discrete positions along the spinning line (i.e., \( z \)-axis) were measured, the measured positions were located from \( z=0 \) mm to about \( z=140 \) mm with interval of 2.5 mm. It’s worth noting that the Pitot tube couldn’t work in high temperature. Therefore, the Pitot tube measurements were taken at ambient temperature, i.e. ambient air was erupted from both the spinning die and the secondary nozzles. Some CFD simulations are not shown here but can

Figure 1. (a) Schematic of the melt-blown process with secondary airflow and (b) section view and top view of the spinning sharp die used in this work.
support that the inlet air temperature of the spinning die (220 °C) had neglected effect on air velocity.

In order to measure the melt-blown fiber diameter, the microstructure of a piece of nonwoven sample was firstly characterized by a Phenom Pure scanning electron microscopy (Phenom Scientific, Netherlands). In this process, the magnification of the microscope was ranged from 200 to 400 times for different samples, about five to ten SEM images were got for each sample. Then, the fiber diameter was measured by importing SEM image into Image J (National Institutes of Health, Bethesda, USA). The fiber diameters of each sample were totally measured more than 100 times. Fiber mean diameter and standard deviation were summarized by processing these discrete diameter data.

Results and Discussion

Effect of Secondary Airflow on the Whole Airflow Field (Simulation)

Figure 3 shows the comparison of the air velocities between the situations with and without secondary airflow. Figure 3 indicates that, in the case of \( v_1 = 150 \) m/s (erupt from the die), the air velocity increases little by using secondary airflow with \( v_2 \) in the range of 50 m/s to 150 m/s. However, if the \( v_1 \) was set to be 100 m/s, as shown in Figure 4, it can be found that obvious increasing of velocity in the region below the pair of air nozzle, the air velocity is about 20 m/s at \( z = 150 \) mm position without using secondary airflow. However, the air velocity is about 40 m/s at the same \( z \)-position when using \( v_2 = 150 \) m/s. As shown in Figure 5, the effect of secondary airflow becomes more and more significant on increasing the air velocity when \( v_1 \) more decrease to 50 m/s, the air velocity with \( v_2 = 150 \) m/s at \( z = 150 \) mm position is about three times higher than that without using secondary airflow.

Figures 3 to 5 indicate that applying secondary airflow does not certainly enhance the airflow velocity, but it mainly depends on the relative values of \( v_1 \) and \( v_2 \). Actually, it seems like that there is an adversary relationship between the primary airflow (erupted from the die) and the secondary flow. Figure 6 shows the contours of air velocities at same conditions of Figure 3. It shows that the main airflow with \( v_1 = 150 \) m/s is strong, and the pair of secondary airflow is blown away by the primary air flow and is difficult to converge together, making the secondary airflow has little contribution to increase of airflow velocity along the spinning line. Figure 7 shows the contours of air velocity at same conditions of Figure 5. When the \( v_1 \) decreases from 150 m/s to 50 m/s, the main airflow is no longer very strong compared to the secondary airflow, in this situation, the secondary airflow can converge together, resulting in the obvious increase of air velocity. Figure 7 also shows that the greater the inlet velocity of the secondary airflow, the greater the inhibition effect on the primary airflow. When \( v_2 = 50 \) m/s, the primary airflow can develop continuously in the whole

![Figure 3](image3.png)

Figure 3. Development of the air velocit along the spinning line below the sharp die with and without secondary airflow. The inlet velocity of the primary airflow is 150 m/s, and the inlet velocities of the secondary airflow are 0, 50, 100 and 150 m/s.

![Figure 4](image4.png)

Figure 4. Development of the air velocit along the spinning line below the sharp die with and without secondary airflow. The inlet velocity of the primary airflow is 100 m/s, and the inlet velocities of the secondary airflow are 0, 50, 100 and 150 m/s.

![Figure 5](image5.png)

Figure 5. Development of the air velocit along the spinning line below the sharp die with and without secondary airflow. The inlet velocity of the primary airflow is 50 m/s, and the inlet velocities of the secondary airflow are 0, 50, 100 and 150 m/s.
compute domain. However, when the $v_2$ increases to be 100 m/s, the continuity of the primary airflow's diffusion began to be interrupted, that is why the airflow velocity decreases and fluctuates at the intersecting region of the primary and secondary airflow (as shown in Figures 3 to 5).

Verification of Air Velocity

The above simulation results show that, in order to improve the airflow speed, the inlet velocity of the secondary airflow should be more higher than that of the primary inlet velocity. Therefore, the air velocity verification was carried out by using a low primary inlet velocity and relative higher secondary airflow inlet velocity. Figure 8 shows the air velocity distributions that were experimentally measured by the Pitot tube. Figure 8(a) shows the effect of secondary airflow on the improvement of whole air velocity at condition of $v_1=47.6$ m/s and $v_2=117$ m/s. It shows that the secondary airflow increases the air velocity below $z=60$ mm.
And the airflow velocity fluctuation at the intersecting region of the primary and secondary airflow was also found. However, the obvious decreasing of air velocity in this region was not found by this experiment. As shown in Figure 8(b), if the primary inlet velocity $v_1$ increase to be 71.4 m/s, the fluctuation in the intersecting region of the primary and secondary airflow disappeared, indicating that higher primary airflow overcomes the inhibition effect by the convergence of the secondary flow, and can develop continuously in the whole domain.

**Effect of Secondary Airflow on Microfiber Spinning**

Figure 9 shows the fiber diameter probability distribution at different experimental cases, the corresponding SEM images are also attached in each sub-figure. In Figure 9, the inlet velocity erupted from the die, $v_1$, is constant at 71.4 m/s, and the inlet air velocity of the secondary airflow, $v_2$, are 0 m/s, 15.9 m/s, 37.2 m/s, 58.5 m/s, 79.7 m/s and 100.1 m/s (namely, case 1 to case 6).

Figure 10(a) shows the average fiber diameter at different experimental conditions, which are the same as them in Figure 9. Figure 10(a) shows that, at condition of no secondary airflow, the mean fiber diameter is about 17.6 μm, with increasing the inlet velocity of secondary airflow $v_2$, from 0 m/s to 15.9 m/s and 37.2 m/s, the fiber diameter increases to 19.5 and 22.5 μm. However, the mean fiber diameter decreases with further increasing the $v_2$, the fiber diameter finally decreases to 13.4 μm when $v_2$ increases to be 100.1 m/s. Figure 10(a) indicates an interesting result that fiber attenuation dose not increase by applying the secondary airflow with the inlet velocity less than a critical value ($v_2=37.2$ m/s in this work). On the contrary, the attenuation effect decreases, resulting in fiber diameter increase. The fiber attenuation effect is enhanced at the condition of that $v_2$ is applied larger than the critical value. The reason for the phenomenon shown in Figure 10(a) is that the secondary airflow used in the present work does not contain higher temperature, the secondary airflow with high velocity has positive effect on fiber attenuation, however, it will accelerate the cooling process of the melt fiber. In this work, if the $v_2$ is larger than the critical value of 37.2 m/s, the positive effect of fiber attenuation is greater than the negative effect of fiber cooling. Similarly, when the $v_2$ is less than the critical value of 37.2 m/s, the negative effect of fiber cooling is greater than positive effect of fiber attenuation, resulting in fiber diameter increases.

Figure 10(b) shows the evenness of the fibers, which are obtained at the same conditions of Figure 10(a). The parameter of Coefficient Variance (CV) was applied and used, the CV is defined as the standard deviation divided by the mean diameter. Figure 10(b) shows that the CV of
fibers obtained by applying secondary airflow increases with increasing \( v_2 \) of secondary airflow. The previous work indicates that the air turbulence intensity has positive-correlation relationship with the value of fiber evenness [15]. Figure 11 shows the numerical simulated turbulence intensity of the airflow with and without the secondary airflow, the simulating parameters are same with them in Figure 5. Figure 11 indicates that the airflow turbulence intensity obtained by applying secondary airflow increases with increasing the \( v_2 \) of secondary airflow. That is why the CVs increase by applying larger \( v_2 \), as shown in Figure 10(b). Moreover, Figure 10(b) also shows an interesting phenomenon that the CVs of fibers obtained with secondary airflow are generally lower than that without applying secondary airflow. However, Figure 11 shows that applying secondary airflow can increase the turbulence intensity of the whole airflow. This contradictory conclusion of CV and air turbulence intensity maybe due to the effect that: the primary airflow field from the die can produce uneven melt-blown fibers. When these uneven fibers fall into the airflow field controlled by the secondary airflow, the fiber unevenness generated by the secondary airflow will neutralize the existed unevenness. This neutralization effect is similar to the effect of yarn combination, after \( N \) times of combination, the total yarn’s unevenness will decrease to be \( CV = \sqrt{CV_0/N} \) (\( CV_0 \) is the evenness of single yarn). In the present work, the \( N \) should be \( N=2 \), representing the twice time of fiber attenuation by the primary and the secondary airflow during melt blowing.

**Conclusion**

In this work, a pair of secondary nozzles were arranged below the melt-blown die, and the effects of the secondary flow on fiber attenuation during melt blowing were investigated by numerical and experimental approaches. This work reveals that:
1. The secondary airflow obviously increase air velocity along the spinning line at conditions that inlet velocity of the secondary nozzle is larger than a critical value.
2. If the inlet velocity of the secondary airflow is less than a critical value, they have disadvantage effect on fiber attenuation. Therefore, the enhanced fiber attenuation needs larger inlet velocity of the secondary airflow. It is worth noting that this conclusion is obtained under the condition that the secondary flow was applied by ambient air.
3. Although the applying of secondary airflow into the melt blowing can increasing the airflow turbulence intensity along the spinning line, the evenness of the fiber diameter (CVs) decreases. It is due to that the fiber unevenness generated by the secondary airflow will neutralize the existed unevenness of the fiber erupted from the main spinning die.

**Acknowledgement**

This work is supported by the National Natural Science Foundation of China (11702113), the Jiaxing Project of Science and Technology (2022AY10002), the Open Project Program of Key Laboratory of Yarn Materials Forming and Composite Processing Technology of Zhejiang Province (MTC-2022-02).

**Conflict of Interest**

The author(s) declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

**References**

1. R. L. Shambaugh, J. D. Krutty, and S. M. Singleton, *Ind. Eng. Chem. Res.*, 54, 12999 (2015).
2. C. J. Ellison, A. Phatak, D. W. Giles, C. W. Macosko, and F. S. Bates, *Polymer*, 48, 3306 (2007).
3. R. L. Shambaugh, *Ind. Eng. Chem. Res.*, 27, 2363 (1988).
4. J. Drabek and M. Zatloukal, *Phys. Fluids*, 31, 091301 (2019).
5. N. P. Deng, H. S. He, J. Yan, Y. X. Zhao, E. B. Ticha, Y. Liu, W. M. Kang, and B. W. Cheng, *Polymer*, 165, 174 (2019).
6. M. A. Hassan, B. Y. Yeom, A. Wilkie, B. Pourdeyhimi, and S. A. Khan, *J. Membr. Sci.*, 427, 336 (2013).
7. J. Zhao, C. F. Xiao, and N. K. Xu, *Environ. Sci. Pollut. R.*, 20, 4137 (2013).
8. J. Erben, K. Pilarov, F. Sanetrick, J. Chvojka, V. Jencova, L. Blazková, J. Havlíček, O. Novak, P. Mikes, E. Prosecka, D. Lukas, and E. K. Kostkova, *Mater. Lett.*, 143, 172 (2015).
9. H. M. Krutka, R. L. Shambaugh, and D. V. Papavassiliou, *Ind. Eng. Chem. Res.*, 41, 5125 (2002).
10. E. M. Moore, R. L. Shambaugh, and D. V. Papavassiliou, *J. Appl. Polym. Sci.*, 94, 909 (2004).
11. S. F. Xin and X. H. Wang, *e-Polym.*, 16, 337 (2016).
12. M. A. Hassan, N. Anantharamaiah, S. A. Khan, and B. Pourdeyhimi, *Ind. Eng. Chem. Res.*, 55, 2049 (2016).
13. X. B. Hao, H. Huang, and Y. C. Zeng, *Text. Res. J.*, 89, 3221 (2019).
14. S. Xie, G. J. Jiang, X. Y. Wu, Y. P. Wang, H. S. Fang, and B. Q. Shentu, *Fiber. Polym.*, 22, 703 (2021).
15. J. J. Jia, S. Xie, and C. D. Zhang, *ACS Omega*, 6, 30012 (2021).
16. Y. D. Wang, Y. P. Qiu, C. C. Ji, X. H. Wang, and F. W. Guan, *Text. Res. J.*, 92, 423 (2022).
17. T. Cheng, X. H. Wang, and X. B. Huang, *Text. Res. J.*, 74, 1018 (2004).
18. B. W. Zhu, S. Xie, W. L. Han, and G. J. Jiang, *Fiber. Polym.*, 22, 1594 (2021).
19. C. C. Ji, Y. D. Wang, and Y. F. Sun, *Ind. Text.*, 50, 1409 (2021).
20. Y. F. Sun, B. W. Liu, X. H. Wang, and Y. C. Zeng, *J. Appl. Polym. Sci.*, 122, 3520 (2011).
21. S. Xie, G. J. Jiang, B. L. Ye, and B. Q. Shentu, *Polymers*, 12, 279 (2020).
22. B. R. Shambaugh, D. V. Papavassiliou, and R. L. Shambaugh, *Ind. Eng. Chem. Res.*, 51, 3472 (2012).
23. Y. D. Wang and X. H. Wang, *Ind. Eng. Chem. Res.*, 52, 4597 (2013).
24. M. A. Hassan, N. Anantharamaiah, S. A. Khan, and B. Pourdeyhimi, *Ind. Eng. Chem. Res.*, 55, 2049 (2016).
25. D. H. Tan, P. K. Herman, A. Janakiraman, F. S. Bates, S. Kumar, and C. W. Macosko, *Chem. Eng. Sci.*, 80, 342 (2012).
26. A. Blim, L. Jarecki, and S. Blonski, *B. Pol. Acad. SCI-Tech.*, 62, 43 (2014).
27. S. Chelikani and E. M. Sparrow, *Ind. Eng. Chem. Res.*, 52, 11639 (2013).
28. Y. L. Cheng, L. L. Wu, and T. Chen, *Heat Transf. Res.*, 44, 473 (2013).
29. R. L. Shambaugh, J. D. Krutty, and S. M. Singleton, *Ind. Eng. Chem. Res.*, 54, 12999 (2015).
30. A. F. Kayla and R. L. Shambaugh, *Text. Res. J.*, 89, 3150 (2019).
31. X. B. Hao, Y. Yang, and Y. C. Zeng, *Text. Res. J.*, 90, 606 (2020).