Numerical Simulation on the Production of Glass Fiber Filter Product and Uniformity Improved on Cross-Direction

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Abstract. Glass fiber felt is produced by flame blowing process, but in the traditional flame blowing process, the uniform of product is affected by the airflow. When glass fiber through the air flow jet into the diffuser duct and reach to the web curtain, it is difficult to diffuse the width of the product needs. Researches show that, the size and shape of diffuser duct is critical to the movement of the glass fiber suspension in the duct, eventually the width and density distribution at the web curtain. In this paper, numerical analysis with experiment-based boundary conditions were used to the redesigned diffuser duct. The redesigned duct was built and produced, the product uniformity on cross-direction was tested and it has a good agreement with simulation analysis results. Through the redesign of the diffuser duct, improved the fabric weigh of the product in the cross-direction, get a more uniform product.

Keywords. Numerical analysis; ultra-fine glass fiber filter; process design; flow properties; flame blowing process.

1. Introduction

Glass fiber felt is a porous material with high porosity and excellent thermal, mechanical and chemical stability properties. Glass fiber felt has been widely used in construction, transportation, aerospace and other fields because of its sound-absorbing and heat-insulating properties [1]. There are two main manufacturing processes of glass fiber felt, centrifugal spinnneret blow and flame blowing process [2]. The differences between the two manufacturing processes are shown in table 1. In this paper, the flame blowing process is used to product glass fiber filter, the diameter of fiber is chiefly consideration to get better Filtration effect.

Illustration of flame blowing process are shown in figure 1. The glass frits are sifted to remove any defect ones and then melted into a liquid in an electric melting furnace. The viscous melt fluid is passed through the nickel alloy leakage plate and form to the original glass filament by the drawing roller. Under the action of the air flow from the combustion nozzle, the original glass filament is divided into glass fiber. The glass fiber is carried by the air-flow jet to the diffuser duct. At the same time, the negative pressure generated by the jet stream brings the secondary air flow into the diffuser duct. The fiber suspension moves along the diffuser duct, expands certain width, and lands on the web curtain. Finally, at the end of the duct, the polypropylene glue is sprayed onto the glass fiber of the screen and cured at a certain temperature to form the glass fiber felt.

In flame blowing process, the shape of diffuser duct contributes to the movement of the air flow in the duct [3], eventually the width and density distribution at the web curtain. What’s more, the design of diffuser duct can influence the proportion of the mixture of airflow from the nozzle and the secondary airflow, which will determine the temperature at the diffuser duct outlet for felt formation.
Figure 1. Illustration of flame blowing process.

Table 1. Comparison between Centrifugal spinneret blow and Flame blowing process.

| Manufacturing processes | Centrifugal spinneret blow | Flame blowing process |
|-------------------------|---------------------------|-----------------------|
| Fiber diameter (μm)     | 1.5-3                     | 0.1-3                 |
| Fiber diameter distribution | Small dispersion         | Large dispersion      |
| Manufacture advantages and disadvantages | Production equipment is complex, high production, low energy consumption, the diameter of glass fiber is large, product produce process control is easy to achieve. | Production equipment is simple, low production, high energy consumption, the diameter of glass fiber is minor, product produce process control is hard to achieve. |

In the past, the research focused on the uniformity of the primary layer of glass fiber product [4, 5], and the uniformity of the birth layer of glass fiber was studied by visual means [6]. In the centrifugal spinneret blow, Yang [7] obviously improved the uniformity of the product by calculating and optimizing the swing law of the duct. At present, there are few reports about the influence of diffuser duct on flame blowing process and its final product, which leads to the lack of understanding of fiber movement in diffuser duct.

In this paper, numerical analysis method is used to simulate the airflow movement in the diffuser duct, and the final product is studied and analyzed through experiment. The influence of the design of diffuser duct on the forming of glass fiber felt is obtained. The research results can be used in the design and optimization of the diffuser duct in the flame blowing process to obtain a good homogeneity of glass fiber felt products.

2. Experiment

2.1. Simulation

The purpose of the numerical simulation is to obtain the flow situation of airflow in different ductlines, and the influence on the weight uniformity of the product fabric on cross-direction. Through the numerical simulation, the modification cost of flame blowing process can be saved.

ANSYS code 16.0 is a software which usually used to calculate the air flow in the computational domain. In this paper, the three-dimensional structured mesh code was used, and Reynolds-averaged Navier-Stokes equations (RANS) were used [8].

For this case, airflow from the nozzle was compressible flow. In the RANS approach the mass conservation equation (1), the momentum conservation equations (2) and the energy conservation equation (3) together with the equations of the turbulence model (4) and (5) form a closed set of
The mass conservation equation reads
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \] (1)

The momentum conservation equation is
\[ \frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla P + \nabla \cdot (\mu \nabla U) \] (2)

The energy conservation equation is
\[ \frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho U e) + \frac{\partial \rho K}{\partial t} + \nabla \cdot (\rho U K) - \nabla \cdot (\alpha_{\text{eff}} \nabla e) = -\nabla \cdot (\rho U) \] (3)

For the present case a two-equation \( k-\epsilon \) RNG turbulence model by Launder and Spalding was applied. Additional equations read
\[ \frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho k U) = \nabla \cdot (\alpha_{k} \mu_{\text{eff}} \nabla k) + P_{k} - \rho \epsilon \] (4)

And
\[ \frac{\partial (\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \epsilon U) = \nabla \cdot (\alpha_{\epsilon} \mu_{\text{eff}} \nabla \epsilon) + C_{1\epsilon} \frac{\epsilon}{k} P_{k} - C_{2\epsilon} \rho \frac{\epsilon^{2}}{k} \] (5)

where \( \alpha_{k} \) and \( \alpha_{\epsilon} \) are the inverse effective turbulent Prandtl numbers, \( \mu_{\text{eff}} \) is the effective viscosity, \( P_{k} \) represents the generation of turbulent kinetic energy due to the mean velocity gradients and \( C_{1\epsilon} \) and \( C_{2\epsilon} \) are model coefficients.

2.2. Boundary Condition Setup
The simulation requires the determination of four input parameters: the temperature of the air flow jet, the mass flow of the air flow jet, and the mass flow rate of the surrounding air, and the pressure-outlet of the suction channel.

In this paper, the airflow jetted from combustion nozzles was set as inlet, so that, the temperature and mass flow rate must be cleanly of this area. Because of the high temperature of the combustion nozzles, we use the Platinum rhodium thermocouple to measure temperature. The temperature of the flame was measured to be 1350°C.

The amount of burning gas used is 56 m\(^3\)/h, the gauge pressure of the gas is 0.03 MPa (i.e., 0.3 atmosphere pressure), 3.69 times of the air amount is required for full combustion. According to the law of mass conservation, the total air jet quantity equal to the burning gas and oxygen required for gas combustion, and the mass flow rate of the blow nozzle is calculated as 0.101 kg/s.

As the heat exchange of air must be consideration in the production process, we calculate the air exchange with the outside world roughly through the ventilation equipment of the factory building. The mass flow rate about ventilation was 3 kg/s.

In the actual production process, the glass fiber falls on the web curtain result in air resistance. In order to measure the pressure suction air during the actual work, the pitot tube was used to measure the wind speed. The pressure of the suction channel can be calculated as -200 Pa.

2.3. Design of Diffuser Duct
Under the definite boundary conditions, change the size of diffuser duct and recalculated the case. Due to the glass fiber filter product has a certain width, the width of diffuser duct outlet equal to the width of web screen. So in design of diffuser duct, we focus on the ratio of length to width at the entrance of the diffuser duct.
Define $\alpha$ as

$$\alpha = \frac{\text{The width of duct inlet}}{\text{The height of duct inlet}}$$  \hspace{1cm} (6)

By changing the $\alpha$ while the area of the entrance of the diffuser duct invariant, modifying the diffuser duct. Comparison the air flow state of the modified diffuser duct, get the most optimized duct design at the same time conducting production experiments for simulation calculation.

2.4. Measurement

The fabric weight (FAW) was used to quantify the uniformity of material. FAW reflects the weight per unit area of materials which is defined by:

$$\text{FAW} = \frac{\text{weight of materials}}{\text{area of materials}}$$  \hspace{1cm} (7)

In this test, the sample were divided into 8 pieces as a group through across direction of product, shown as figure 2, and the size of samples were 50 cm $\times$ 17 cm. 10 group of samples was test. Because of the glass fiber filter product was bonded by adhesive, all specimens were treated in the electric muffle furnace for 30 minutes at 500 $^\circ$C. After the adhesive was removed, we weighing the sample to get the weight of glass fiber exactly.

3. Results and Discussion

In the flame blowing process, when the air jet enters the diffuser duct, it creates a huge negative pressure because of Bernoulli’s Principle. The Bernoulli Equation reads

$$P + \frac{1}{2} \rho v^2 + \rho gh = \text{constant}$$

It indicates that in stable flow, the pressure is small where the velocity is high, and strong where the velocity is low. It is the reason of secondary airflow enters the diffuser duct. In the condition of production, the air jet from the nozzle have to mixture about 20 times its own mass flow rate secondary airflow. The air jet from the nozzle and the secondary air flow can be well mixture or not that will determine the uniformity of the glass fiber products.

Under the size of outlet of the diffuser duct invariant, we choose four variates of $\alpha$, 3/1, 4/3, 3/4 and 1/3. Through the simulation of production, it is found that, with the value of $\alpha$ decreasing, the airflow velocity at the outlet of the duct becomes more homogeneity, shown as figures 3-6, that means the air
jet form the nozzle at the outlet of the duct mixture very well with the secondary airflow. In the four calculated case, when the $\alpha$ is 1/3, the velocity of outlet of diffuser duct is the most uniform (figure 7).

Figure 3. Contours of diffuser duct outlet with the $\alpha=3/1$.

Figure 4. Contours of diffuser duct outlet with the $\alpha=4/3$.

Figure 5. Contours of diffuser duct outlet with the $\alpha=3/4$.

Figure 6. Contours of diffuser duct outlet with the $\alpha=1/3$.

Figure 7. Velocity of outlet of the diffuser duct on horizontal center line.

The reason of this consequence, under the different value of $\alpha$, the pressure distribution on the duct inlet is different, shown as figure 8, when the secondary airflow enters the diffuser duct from the up and down part of the duct inlet by the negative pressure, the air jet and secondary airflow mixture more easily. On the contrary, when the secondary airflow enters the diffuser duct from the side part of the duct inlet by the negative pressure, the air jet and secondary airflow are hard to mixture.

The numerical simulation results show the movement of air flow and ambient air flow around the
product line. In order to explore how air flow affects the fabric weight of the glass fiber product, we assume that the glass fiber is evenly distributed in the air flow. At the same time, three kinds of diffuser duct are designed and constructed to verify the simulation results. The design size of the diffuser duct is shown in figure 9, and the specific size is shown in Table 2. The temperature and velocity at the outlet of duct were measured by platinum-rhodium thermocouple and pitot tube respectively. The experimental temperature and velocity at the end of the diffuser duct were compared in Table 1 with the simulated results.

![Figure 8. Contours of the diffuser duct inlet with the $\alpha = 3/1$.](image8)

![Figure 9. Illustration of diffuser duct (mm).](image9)

**Table 2.** Dimensional design of diffuser duct.

| Duct | $W_1$ (mm) | $H_1$ (mm) | $H_2$ (mm) |
|------|------------|------------|------------|
| A    | 600        | 200        | 300        |
| B    | 550        | 400        | 450        |
| C    | 250        | 550        | 300        |

Table 3 shows that the simulated analysis results has a good agreement with the experimental data. It shows that the boundary conditions we used could do a great numerical analysis calculation of airflow.

**Table 3.** Comparison between simulation and reality.

| Duct | Situation | Average velocity of air flow | Average temperature of air flow |
|------|-----------|------------------------------|--------------------------------|
| A    | Experiment| 6.8 m/s                      | 124 °C                         |
|      | simulation| 7.53 m/s                     | 121 °C                         |
| B    | Experiment| 7.4 m/s                      | 108 °C                         |
|      | simulation| 8.75 m/s                     | 105.64 °C                      |
| C    | Experiment| 6.3 m/s                      | 117 °C                         |
|      | simulation| 7.23 m/s                     | 112.95 °C                      |

The diffuser duct A and B, because of the ratio of length to width at the entrance of the diffuser duct, the secondary airflow mainly enters from side of the duct. In this way, the air jet from the nozzle could not able to mixture evenly with secondary airflow. The mass flow rate of airflow in center was higher than other parts of diffuser duct. Final, the fiber suspension flow arrived at the web screen (figure 10), the center of the web screen has large mass flow rate of airflow, and result in the droppoint
of glass fiber at the web screen was not on a horizontal line.

At diffuser duct C, change the size of the diffuser duct inlet, successfully mixture the air jet from the nozzle and secondary airflow, when the fiber suspension flow arrived at the web screen (figure 11), the droppoint of glass fiber at the web screen was on a horizontal line.

In order to quantify the uniformity of product, we take samples from the product as subsequence through across direction shown as figure 12. Through measuring fabric weight of the sample sequence, the FAW redistribution in the sample cross direction is obtained. Shown as figures 13 and 14, increasing height and reducing width to modified the diffuser duct can improve the uniformity on cross direction.

**Figure 10.** Design A’s diagram of web screen: simulation (up) and experiment (down).  
**Figure 11.** Design C’s diagram of web screen: simulation (up) and experiment (down).

**Figure 12.** Diagram of sample delivered from the production line through across direction.  
**Figure 13.** Fabric weight of glass fiber product production by duct of design A.
4. Conclusions
This paper presents a research of the air flow in the duct at flame blowing process and its influence on final Product. The relationship between air jet and secondary airflow was assessed by numerical analysis. At the same time, three different kinds of diffuser duct were built and experimented. The simulation and experiment were compared by temperature and speed. Through numerical simulation, the data of the production process were studied. A good correlation between the diffuser duct size and the FAW on cross direction was determined, it shows that the significance of the former for the quality of the product. We estimate that glass fiber felts quality can be improved by improving the design of diffuser duct.

References
[1] Bergonnier S, Hild F, Rieunier J B and Roux S 2005 Strain heterogeneities and local anisotropy in crimped glass wool Journal of Materials Science 40 5949-5954.
[2] Bauer J and Manville J 2004 Properties of glass fiber for filtration: Influence of forming process International Nonwovens Journal os-13 1558925004os-13.
[3] Yang Y, Chen Z, Xu T, Wu C, Awuye D E and Chen Z 2018 Comparing the uniformity of light glass fiber felt based on process improvement, microstructural forming mechanism and physical properties Textile Research Journal 89 3447-3456.
[4] Sirok B, Blagojevic B and Novak M 2002 Influence of blow away velocity field on the primary layer fibre structure in the mineral wool production process Glass Technology 43 188-194.
[5] Bajcar T, Blagojevic B, Sirok B and Dular M 2007 Influence of flow properties on a structure of a mineral wool primary layer Experimental Thermal and Fluid Science 32 440-449.
[6] Trdič F, Širok B, Bullen P R and Philpott D R 1999 Monitoring mineral wool production using real-time machine vision Real-Time Imaging 5 125-140.
[7] Yang Y, Chen Z, Chen Z, Fu R, Li Y and Sheng C 2015 Processing technique and uniformity affecting tensile strength and hydrophobicity properties of glass wool felt Fibers and Polymers 16 1587-1594.
[8] Patankar S 1980 Numerical heat transfer and fluid flow Series in Computational Methods in Mechanics and Thermal Sciences 67.