Optimization of Air Flow Field of the Melt Blowing Slot Die via Numerical Simulation and Genetic Algorithm

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Received 26 November 2008; accepted 13 July 2009
DOI 10.1002/app.31109
Published online 7 October 2009 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The air flow field plays a key role in melt blowing. In this article, an optimal design procedure that improves the airflow field of melt blowing is proposed. A parameter, stagnation temperature which is a combination of static temperature and kinetic temperature, is proposed to evaluate the air flow field. The stagnation temperature is obtained via computer simulation, while optimization is accomplished by genetic algorithm. Four main geometry parameters of the slot die: slot width, nose piece width, slot angle, and setback are investigated. The optimal results were achieved in the 40th generation. The results also show that the smaller slot angle and larger slot width can result in the higher stagnation temperature. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 115: 1540–1545, 2010

Key words: genetic algorithm; numerical simulation; stagnation temperature; parameter optimization; melt blowing slot die

INTRODUCTION

Melt blowing is a single step process to produce microfibers. A fiber-forming polymer is extruded from the die into two jets of hot air, which rapidly attenuate the molten polymer into ultra-fine fibers. The fibers are collected as nonwoven webs directly. Nonwoven fibers find applications in an increasing number of fields, such as filtration, absorbency, hygiene, and apparel. Many significant efforts have been made to better understand the technology and to improve the equipment by researchers and engineers around the world.

In this work, we focus on predicting the air flow field because this field plays a key role in fiber formation process of melt blowing. Several researchers have studied air flow field by experimental method and numerical simulation. Researchers[1–5] measured velocity and temperature fields during single-hole melt blowing experimentally. Bresee and Ko[6] presented experimental measurements to provide air velocity and temperature information of a 600-hole die in a commercial-like melt blowing. In recent years, numerical simulation is being developed to study air flow field of melt-blowing dies. Krutka and Shambough[7] studied the air flow field of the slot die by numerical simulation, and they obtained an agreement of the simulation results and the experimental data. Unfortunately, the air velocities they used (the greatest is 34.6 m/s) during simulation were much smaller than those in commercial melt blowing process, which are usually subsonic or supersonic. The air in their simulation was considered as incompressible, which is not suitable under the condition of a mach number greater than 0.3. Moore and Shambaugh[8] considered compressibility of the air in their simulation; however, the simulation was under isothermal condition. In other words, the temperature decay of the air was not considered. To know the inherent physical principles of the air flow field of the slot die, we[9] simulated the air velocity and temperature fields of the slot die and analyzed the effects of the slot angle, slot width, and nose piece on the velocity and temperature fields. Krutka et al.[10,11] used numerical simulation to analyze the velocity and temperature field from multiple jets in the Schwarz melt-blowing die, which is with arrays of annular jets.

Unlike conventional melt spinning, the air jet used in melt blowing process not only provides a substantial forwarding force but also has a function of preventing polymer solidification. As the polymer exits the melt-blowing die, the velocity of the air causes momentum transfer to the fiber, which results in rapid attenuation of the polymer. Concurrently, the high temperature of the air keeps the polymer at a high temperature, which aids attenuation by keeping the polymer viscosity low. The air velocity and air

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Contract grant sponsor: National Natural Science Foundation of China; contract grant number: 50976091.
Contract grant sponsor: Shanghai Dawning Program; contract grant number: 05SG37.

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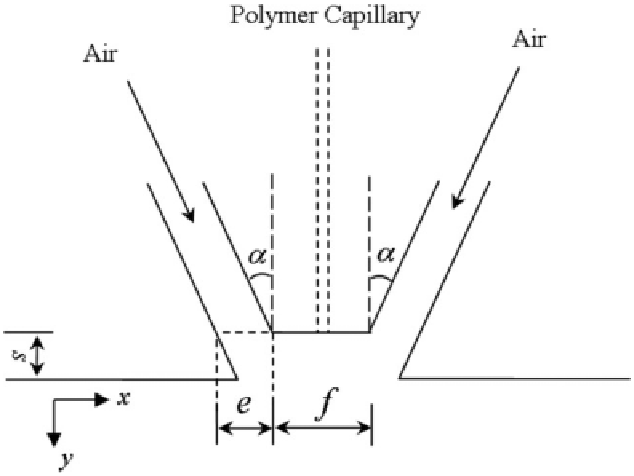

Figure 1 2-D model of slot die (cross sectional view).

temperature are two key factors that affect the air flow field of a melt-blowing die. So in this article we are trying to optimize the slot parameters in order to get a high performance airflow field. However, the optimization of slot die parameters by traditional search method only is still difficult to achieve even in the case of numerical simulation. Nowadays, the progress of Genetic algorithm (GA) has provided powerful tools for engineering optimization, which is essentially adapted for finding the optimal solution of numerical problems. Therefore, an optimal design method of the die geometry based on the combination of GA and numerical simulation is proposed in this article.

NUMERICAL SIMULATION AND GA SETTINGS

Numerical simulation

There are different die geometries that are used to produce melt blown fibers, and the slot die is one of the most commonly used dies. Figure 1 shows the 2-D model of the slot die. There are four major geometry parameters of the slot die: slot width *e*, slot angle α, nose piece width *f*, and setback *s*. The calculation domain of the air flow field was developed based on the experiments of Harpham and Shambagh,[1,2] and Tate and Shambaugh.[3] Figure 2 shows the computational domain and the boundary conditions. The slot height was fixed to be 5 mm, and the computational domain below the die head was 100 mm × 30 mm. The calculation domain was half of the total air flow field, which is symmetric about the centerline. With the help of boundary condition of "symmetry," the calculation time was saved much.

In this research, the airflow field was obtained by solving the Navier-Stokes equations through the commercial software FLUENT 6.2.

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{1}$$

$$\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}=\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+F_x \tag{2}$$

$$\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+F_y \tag{3}$$

$$\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}=\frac{\partial}{\partial x}\left(\frac{k}{C_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{C_p}\frac{\partial T}{\partial y}\right)+S_r \tag{4}$$

Equations (1)–(4) expresses the mass conservation, momentum conservation, and energy conservation of air jet, where ρ is the air density, u and v are the resolution of velocity in x and y directions, Γ is the stress caused by viscosity of air, F is gravity, T is temperature of air jet, C_p is heat capacity, k is convective heat-transfer coefficient, S_r is term of vicious dissipation.

To simulate the nonisothermal air flow filed, the air was modeled as an ideal gas with Sutherland viscosity. We use eq. (5) to describe relationship of its density, temperature, and pressure.

$$P=\rho RT \tag{5}$$

where R is molar gas constant.

The viscosity of ideal gas was expressed by Sutherland's model, shown by eq. (6)

$$\mu=\mu_0\frac{T_0+C}{T+C}\left(\frac{T}{T_0}\right)^{3/2} \tag{6}$$

where μ is dynamic viscosity at temperature T, μ_0 is reference viscosity in at reference temperature T_0, C is Sutherland's constant for the gaseous material in question.

The inlet of the calculation domain ($A-A'$) was defined as a "pressure inlet" with an absolutely pressure of 1.4 atm, total temperature was 543 K. Under "pressure inlet" boundary condition, the air jet was considered to be compressible. The outlets of the computational domain ($B-B'$ and $O'-B'$) were defined as pressure outlets with atmospheric condition. The boundary condition of "symmetry" was

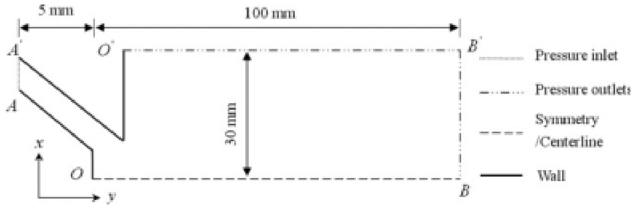

Figure 2 Computational domain and boundary conditions.

used at the centerline ($O - B$) of the flow field. All other boundaries were assigned the default setting of being a nonslip wall. k-ε turbulence model was adopted, and the turbulence parameters $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ were set as 1.24 and 2.05, as recommended by Krutka and Shambaugh.[7] The inlet and outlet boundary parameters are also based on the study of Krutka and Shambaugh[7] who ever did experiments to verify these parameters. As a result, the turbulence specifications of the inlet boundary were set with an intensity of 10% and a hydraulic diameter equal to the slot width. While at the pressure outlets, turbulence intensity was 10% and the length scale was 10 mm.

Stagnation temperature

In melt blowing process, the air jet is responsible for exerting the drag force to attenuate the fiber. Higher air velocity provides larger drag force and therefore results in finer fibers. However, in the flow field, air temperature also affects fiber attenuation. During the process, as soon as the molten polymer is extruded from the die, its temperature starts declining, and began to be solidified in the position of some centimeters below the die. Therefore, it is generally desirable to have the air jet temperature equal to or greater than the polymer temperature. Furthermore, it is usually desirable to maintain a high air temperature along a long distance from the die. Higher air temperature will delay the solidification of the polymer, and therefore increase the period of fiber attenuation.

To determine the optimal air flow field of the die, a parameter that combines the air velocity and air temperature is required. By converting the kinetic energy of the flow field to internal energy and adding it to the local static enthalpy we can get stagnation temperature. Stagnation temperature is composed of two parts: one is the temperature of the air (i.e., static temperature), the other is kinetic temperature. It can be expressed as:

$$T^* = T + \frac{v_a^2}{2C_p} \quad (7)$$

where T^* is stagnation temperature, T is static temperature, $\frac{v_a^2}{2C_p}$ is kinetic temperature, v_a is resultant velocity of air. Stagnation temperature combines the air velocity and air temperature; therefore, it is the parameter we are looking for.

Milligan and Haynes[12] studied the correlation about the average fiber diameter and some melt blowing process parameters including the air stagnation temperature and finally got an empirical equation for common melt blowing process.

$$\delta = C_1 + C_2\Gamma^{-1.49}\,\beta^{-0.65}\,\phi^{-1.12}\,\theta^{-0.347}\,\xi^{-0.92} \quad (8)$$

All the variables in eq. (8) are dimensionless where δ is the diameter radio, β is the polymer throughout radio, ϕ is the die face width radio, θ is the polymer temperature radio, Γ is the mass flux radio, ξ is defined as the air stagnation temperature divided by a reference die stagnation temperature (375°F), C_1 and C_2 would be determined for the particular melt blowing line and polymer. From eq. (8) we can conclude that fiber diameter will decrease as increasing the air stagnation temperature. Therefore, it is desirable to maintain a high stagnation temperature along a long distance from the die.

In this article, the performance of the air flow field is determined in the term of stagnation temperature. According to the experiments of former researchers,[1–5] the fibers are mainly located along the spinneret axis and the area occupied is very narrow. Therefore, we should focus the stagnation temperature on the centerline where fibers locate. Krutka[13] did a deep research of the effect of fiber on flow field. He found the effect decreases as the distance from the die face increases so that it can be neglected at the far field. To decrease the effect of fiber on the flow field, we choose point B on the centerline, which is farthest point from the die face. The goal of the following work is to determine the die geometry that gives the largest stagnation temperature at point B.

GA operation and settings

GA is a search technique used to find exact or approximate solutions to optimization and search problems. It is categorized as global search heuristics which inspired by evolutionary biology such as inheritance, mutation, selection, and crossover. Nowadays, this technique has been used in many research fields. In this article, GA is aimed at finding the parameter values that minimize an objective function.

$$J = -T^*(T, v_a) \quad (9)$$

In this research, the static temperature T and airflow velocity v_a, are obtained from the simulation. Each of the four parameters, slot width e, slot angle α, nose piece width f, and setback s, is set in the domain $[a_i, b_i]$. To find the optimal values of the parameters in the feasible region, the domain for each parameter is much larger than that of former researches.[7–9] Table I shows the domains of the four parameters.

The GA starts with a set of random solutions in a population; typically, a population is composed of between 10 and 100 individuals.[14] Huang and Tang[15] optimized parameters successfully in melt

TABLE 1

	Slot width/mm	Slot angle/°	Head width/mm	Set back/mm
a_i	0.1	10	0.5	0
b_i	2	80	5	1.5

spinning by GA with the population size as 10, so in this article we also set the population size as 10. Each individual in the population is a chromosome. A chromosome is a binary string, including binary representations of all parameter values. The length of the binary string stands for the precision of the parameter. Considering the dimension precision of the slot die, we set the precision of each parameter as 0.001 mm, which means the length of chromosome is 53 bits. The search of an optimal solution to the problem is conducted over a space in a binary representation. We input parameter values of each chromosome to numerical simulation procedures in order to calculate the static temperature, air velocity, and finally get the value of objective function J. The objective function J is used to provide a measure of how individuals have performed in the problem domain. However, the value of J is negative, which is not suitable for "selection." On the other hand, it may slow the convergence speed of GA. Therefore, we use a linear scaling function, eq. (10), to calculate the fitness of each individual.

$$F(x_i) = 2 - \text{MAX} + 2(\text{MAX} - 1)\frac{x_i - 1}{N_{\text{ind}} - 1} \quad (10)$$

where MAX is the upper bound of J for every generation, N_{ind} is the population size, x_i is the phenotypic value of individual i, and F is the resulting relative fitness.

The genetic operations, namely reproduction, crossover and mutation, create the next generation. There are several methods for the process of reproduction. In this study, the stochastic universal sampling (SUS) is adopted. It selects a new population with respect to the probability distribution based on fitness values with minimum spread and zero bias. Because the GA is a method which mimics the metaphor of nature biological evolution, the rates of generation gap, crossover, and mutation all have their limits.[16] Without loss of generosity, the generation gap is specified as 0.9, which means the fractional difference between the new and old population sizes is 0.9. The crossover and mutation rates, which determine the number of chromosomes to mate and the number of genes to mutate, respectively, are both between 0 and 1. The mutation occurs with a small probability, typically in the range 0.001 and 0.01.[16] In the crossover operation, several pairs of

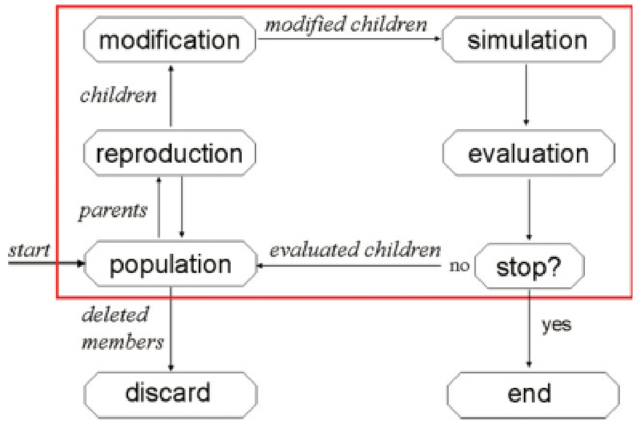

Figure 3 Flow chart of optimizing process. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

chromosomes are randomly selected, and it generates the offspring by swapping the genes from the cut-point to the end of the chromosome for each pair. The mutation operation flips one of the bits of the chromosome string at a randomly selected location. For this article, the crossover rate is 0.7 and the mutation rate is 0.005. The evolution of the population repeatedly until the termination condition is satisfied which will be discussed below.

RESULTS AND DISCUSSION

Figure 3 shows the flowchart of the optimizing process. The first step in GA is to create an initial population consisting of random chromosomes in the problem domain. After that this generation is carried out in airflow field simulation procedure to calculate air velocity, static temperature, and stagnation

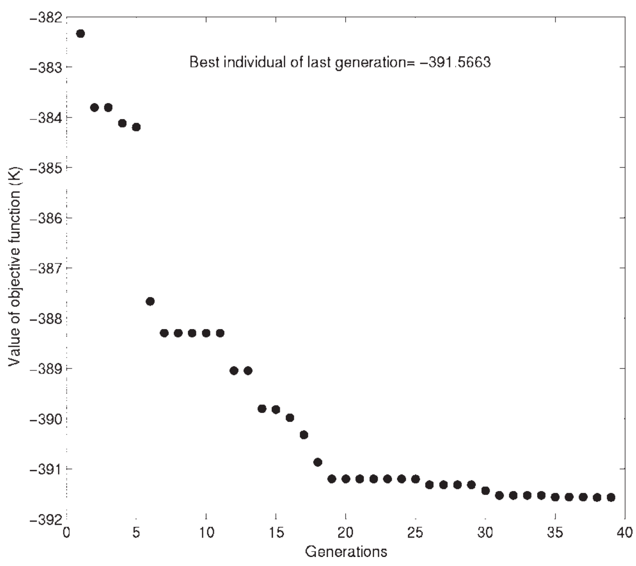

Figure 4 Values of objective function versus GA iterations.

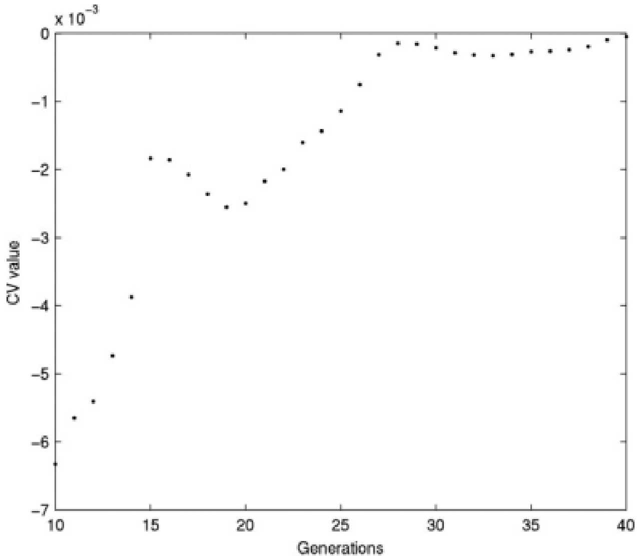

Figure 5 Variation of CV for every 10 generations.

temperature for each individual. According to the fitness, the genetic operations can be continued to produce the offspring. In every generation, the best individuals are left while the others are discarded. As a result, the generation will be better than the former ones during the iteration. From the view of time-saving, the search process can be restrained as soon as it reaches the maximum number of generations or maximum CPU time. However, it is some arbitrary. As the objective value may remain static for number of generations before a superior individual is found, so the coefficient of variation (CV) is used in this paper. In other word, the termination condition in this work is that checking the individuals' CV for continuous 10 generations. For example, the CV value at generations 10 in Figure 5 is calculated based on the stagnation temperature of generations from 1 to 10, and the CV at generations 11 is based on the generations from 2 to 11, and so on so forth. When the CV is small enough which means the objective J reached a plateau, the searching process is stopped, and the parameters corresponding to the minimum objective function J are then considered as the optimum value. The CV is set to -5×10^{-5}, and finally 40 generations are carried out before the procedure is stopped. Considering the population size is 10, so there are 400 air flow fields of the slot dies simulated in this research. It took about half an hour for every generation on the Dawning High-Performance computer clusters with 32 quad-cord 2.0 GHz Intel processors.

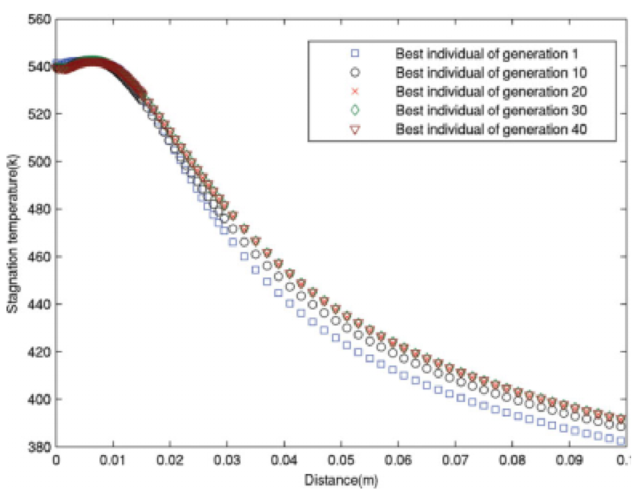

Figure 6 Centerline stagnation temperature of best individual. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

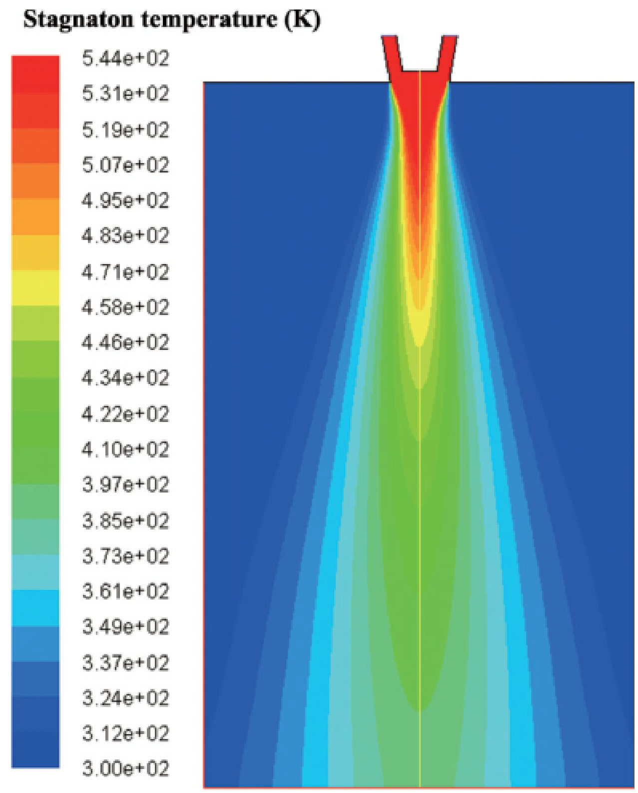

Figure 7 Contour of stagnation temperature of airflow filed. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The value of objective function J can be obtained from the value of stagnation temperature according to eq. (9). Figure 4 shows the evolution of the minimum objective function J. The convergence is fast initially, and after 19 generations, the convergence slowed down and eventually led to the halting of the iteration process after 40 generations. Figure 5 shows the CV among the invidious of 10 generations. The finally CV at the 40 generation is -4.642×10^{-5}.

The temperature of the air jet will decrease as soon as it ejects from the die, while the velocity will increase to its maximum and then decrease along the centerline.[7] As for the stagnation temperature which combines the air velocity and air temperature, it will be more complicated. Figure 6 gives the centerline stagnation temperature profile. The distance is from the polymer capillary outlet (*O*) to the pressure outlet of the computational domain (*B*) (ref. Fig. 2). The stagnation temperature of the air keeps at around 540 K several millimeters before it starts declining. This can also be seen from the contour of stagnation temperature of airflow field just below the die head in Figure 7. We can see that the best individual of generation 40 has the greatest stagnation temperature at *B*, which is on the outlet of computational domain $B - B'$. Finally, the optimal geometry of the slot die is with the parameters of slot width $e = 1.981$ mm, slot angle $\alpha = 10.009°$, nose piece width $f = 4.770$ mm, and setback $s = 1.417$ mm. The corresponding value of objective function $J = -391.6$ K, which means the highest stagnation temperature is 391.6 K.

CONCLUSIONS

This article proposes a systematic approach, which combines the application of numerical simulation and genetic algorithm, to optimize the airflow field of melt blowing slot die. The stagnation temperature, which obtained through airflow numerical simulation, is used to evaluate the performance of the airflow field. The slot width, slot angle, nose piece width, and setback are investigated by using GA method. During the GA optimizing process, the coefficient of variation is used as the terminal condition from the time-saving view. It has proved that the systematic approach combining the application of numerical simulation and genetic algorithm is an effective way to optimize the geometry parameters of the melt blowing slot die. The optimal geometry parameters are: slot width $e = 1.981$ mm, slot angle $\alpha = 10.009°$, nose piece width $f = 4.770$ mm, and setback $s = 1.417$ mm. And the corresponding highest stagnation temperature is 391.6 K. The results also show that the smaller slot angle and larger slot width result in the higher stagnation temperature.

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