Numerical simulation and parameter sensitivity analysis for the cooling of rolling rubber-film on cooling-drums

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Abstract. Cooling of the rolling rubber-film on cooling-drums is a common practice in the final stage to achieve good quality of the rubber-film. In this paper, the stable heat transfer process of the rubber-film on the cooling-drums was simulated with a simplified fluid rubber-film method. The temperature at the film on each cooling-drum is obtained and compared with experimental measurements. It is found that the simulation results well agree with the measurements, indicating that the method proposed here is valid. In addition, parameter sensitivity on the cooling efficiency of the system were studied to provide the references for engineering applications.

1. Introduction

The cooling-drums are common components for cooling and shaping of the rolling rubber-film. The rubber-film is extruded from the cold feed extruder and transferred to the calendar for extrusion by the conveyor. The temperature of the rubber-film is high after leaving the drum of the calendar. Therefore, a set of cooling-drums are required to cool the rubber-film sufficiently to shape the rubber-film and eliminate the internal stress in the forming process before the rubber-film is rolled into bundles. In recent years, many scholars have studied the design, manufacture and cooling effect of the cooling-drums or similar structure. Yang yun [1] introduced the key technology and technological measures of cooling-drum processing. Chen hongbing [2] analyzed and tested the chemical composition and microstructure of the spray welding layer of the self-developed material. Han yana [3] analyzed the mechanical processing technology of the cooling-drums and the problems prone to occur in the process, and proposed solutions. Guo qian [4] used the method of finite element analysis to obtain the distribution characteristics of the temperature field and flow field of the cooling-drum. Chen beirong [5] analyzed the failure of the cooling-drums and made a local improvement, which greatly improved the working reliability of the cooling-drums of the printer.

Although cooling-drums are widely used for cooling the rubber-film, at present, their design is mainly based on experience, lacking accurate heat transfer analysis and calculation methods. One of the problems is that the contact surface between the rubber-film and the cooling-drums is constantly changing, and with the solid moving boundary, it is difficult to carry out effective numerical simulation for the heat transfer. In this study, the moving solid rubber-film was simplified to be the
fluid rubber-film, and the heat transfer process between the rubber-film and the cooling-drums was numerically simulated and verified experimentally. In addition, parameter sensitivity on the cooling efficiency were studied to provide the references for engineering design and optimization of the rubber-film cooling system.

2. The system of the cooling-drums and analysis of the rubber-film cooling process
The cooling device of the rubber-film studied in this paper includes the frame, the drive motor and several cooling-drums. The double-layer structure above and below the cooling-drums are installed on the frame. The driving motor drives the cooling-drums to rotate together with the belt and the pulley, and keeps pace with the speed of the rubber-film moving. The structure of the cooling-drum consists of a double-layer steel cylinder and the rotating shaft, intake and outlet pipes, the rotating mechanism and the end-plate of the cooling-drum. The inner part of the cooling-drum is a jacket structure, which is composed of an inner cylinder and an outer cylinder. The inner drum is hollow and welded with spiral splints. The normal section of the splints is rectangular, so cooling water passage is formed between the outer drum, inner drum and splints. The internal structure of the cooling-drum is shown in figure 2. The three-dimensional geometric model of the cooling-drums and the rubber-film is shown in figure 1.

3. Simulation of the heat transfer process between the rubber-film and the cooling-drums

3.1. Verification of finite element mesh independence
Since there are a large number of meshes in the whole model, in order to reduce the calculation amount and improve the calculation efficiency, cooling of the rubber-film on one are adopted to verify the grid independence. The results are shown in figure 3, it can be seen that the change in the calculation results is relatively small after the number of meshes exceeds 3.13 million. Therefore, in this paper, 3.13 million meshes of a single drum are selected for calculation, and the finite element mesh model is shown in figure 4.

![Figure 1. Geometrical model of the rubber-film and cooling-drums](image-url)
3.2. Setting of material properties
The relevant materials are defined in fluent materials database, and the properties of materials are listed in table 1. Referring to the ANSYS18.0 help document, turbulence simulation can be turned off.
in the specified fluid region using either the k-ε model or the Spalart-Allmaras model to simulate turbulence. The "Laminar Zone" option sets the turbulence viscosity to zero and disallows turbulence generation in the fluid region. In order to further verify and improve the calculation efficiency, a single cooling-drum was used in this study to calculate the temperature of cooling water and the rubber-film leaving the drum under different dynamic viscosity. As shown in table 2, it was verified that changes in dynamic viscosity had no effect on the calculation results.

Table 1. Material property parameters of the rubber-film and cooling-drum

| Material          | Density/kg·m⁻³ | Specific heat capacity J·kg⁻¹·K⁻¹ | Coefficient of thermal conductivity W·m⁻¹·K⁻¹ | Dynamic viscosity /kg·m⁻¹·s⁻¹ |
|-------------------|----------------|----------------------------------|-----------------------------------------------|-------------------------------|
| Carbon Steel      | 8030           | 502.48                           | 16.27                                         | /                            |
| Cooling Water     | 998.2          | 4182                             | 0.6                                           | 0.001003                     |
| Rubber-film       | 1200           | 1700                             | 1.5                                           | 1000                          |

Table 2. Influence of dynamic viscosity of the rubber-film on calculation results

| Dynamic viscosity /kg·m⁻¹·s⁻¹ | Temp. of cooling water leaving the drum /℃ | Temp. of the rubber-film leaving the drum /℃ |
|------------------------------|-------------------------------------------|---------------------------------------------|
| 0.01                         | 21.03                                    | 50.61                                      |
| 1                            | 20.98                                    | 50.62                                      |
| 10                           | 20.98                                    | 50.61                                      |
| 100                          | 20.98                                    | 50.61                                      |
| 1000                         | 20.98                                    | 50.61                                      |

3.3. Setting of boundary conditions

1) The boundary of cooling water inlet adopts the boundary conditions of velocity inlet. The inlet velocity is calculated by the flow of cooling water and the inlet pipe inner cross section.

2) The outer surface of the rubber-film in contact with the air and the side of the rubber-film are set as the convection heat transfer boundary conditions. In the production process, the temperature of the rubber-film surface is 54℃, and the temperature of the air is 14℃. The basic physical parameters of air at this average temperature are obtained by consulting the thermal manual [6]: the dynamic viscosity of air is 1.91×10⁻⁵ kg/(m·s), and the thermal conductivity of air is 2.76×10⁻² W/(m·K), Pr=0.699. The formula [7] of convective heat transfer coefficient \( h_1 \) between the rubber-film and the air is as follows:

\[
h_1 = 0.402 \frac{\lambda_v}{L} \frac{Pr^{1/3}}{[1 + (0.0336/Pr)^{2/3}]^{1/4}} \times 0.699^{1/4} = 0.402 \times \frac{2.76 \times 10^{-2}}{0.76} \times 6732.56^{1/2} \times \frac{0.699}{[1 + (0.0336/0.699)^{2/3}]^{1/4}} = 1.48 \text{ W/(m·K)}
\]

3) The surface of the upper and lower end of the cooling-drum in contact with the air is set as the convection heat transfer boundary condition. The surface temperature of the cooling-drums is 35℃, and the air temperature is 14℃. Basic physical parameters of the air at the average temperature are obtained by consulting the thermal manual [6]: The kinematic viscosity of the air is 1.65×10⁻⁵ kg/(m·s); \( a \) is the volume change coefficient; Pr=0.701, \( C = 0.53 \), \( n = 0.25 \). The convective heat transfer coefficient \( h_2 \) of the contact surface between the cooling-drums and the air is determined by the following formula [8]:

\[
h_2 = \frac{\lambda_v}{D} \left( \frac{\alpha C \Delta T D}{\nu^2} \right)^n = \frac{2.71 \times 10^{-5}}{0.72} \times 0.53 \left( \frac{1 \times 9.81 \times (308-287) \times 0.72}{2.76 \times 10^{-2} \times (1.65 \times 10^{-7})} \right)^{0.53} = 3.2 \text{ W/(m²·K)}
\]
4. Results and Discussions

4.1. Temperature field distribution

The temperature distribution on the surface of the rubber-film is shown in figure 5. Clearly, the temperature distribution of the rubber-film decreases gradually from contacting with the first cooling-drum to departure from the last cooling-drum. The temperature distribution of the rubber-film on the drum 1 is shown in figure 6. As the rubber-film is cooled by convection heat transfer on both sides, the temperature on both sides is slightly lower than the temperature middle film. In addition, because the cooling water flows along the axial direction of the cooling-drum, the temperature near the cooling water outlet side of the rubber-film is slightly higher than the temperature at the inlet side.

The temperature distribution of the cooling-drums surface is shown in figure 7. The temperature distribution from drum 1 to drum 10 decreases gradually. The temperature distribution on the outer surface of drum 1 is shown in figure 8. Along the axis of the cooling-drum, the temperature in the contact area with the rubber-film is high, and the temperature on the inlet side of the cooling water is slightly lower than that on the outlet side.

4.2. Experimental verification

The simulation results of a working state were verified by the experimental measurements as shown in figure 9 and figure 10. It is seen that:

1) During the cooling process from drum 1 to drum 10, as shown in figure 9, the temperature of the rubber-film leaving each cooling-drum, the temperature of cooling water leaving the drums and the average temperature of the cooling-drums are all gradually decreasing, but the scale of the decline is diminishing. This happens because the rubber-film cools down after passing through each cooling-drum, and as a result, the temperature difference between the rubber-film and the cooling water decreases, and the heat transfer between the two decreases. The temperature difference of cooling water entering and leaving the drums decreases, which indicates that the front drums have higher cooling efficiency than the rear drums.

2) Compared with the experimental data, the relative error of the simulation results of the temperature of the cooling water is lower than 6%, as shown in figure 10, indicating that the simulation method is reliable.

3) The data in table 3 are the energy passing through each heat exchange surface, the energy released by the rubber-film is mainly absorbed by the cooling water, and the energy lost to the air is negligible, meaning that the cooling-drum plays a crucial role in the rubber-film cooling process.

![Figure 5. Temperature distribution at the whole rubber-film](image-url)
Figure 6. Temperature distribution at the rubber-film on the drum 1

Figure 7. Temperature distribution at the outside surface of all cooling-drums

Figure 8. Temperature distribution at the outer surface of the drum 1
Table 3. Energy transfer in the rubber-film cooling system

| Number | The energy absorbed by the cooling water /W | Heat transfer by convection between the rubber-film and the air /W | The heat released by the sides of the cooling-drums /W | The heat released by the surface of the inner cylinder of the cooling-drums /W |
|--------|---------------------------------|-------------------------------------------------|---------------------------------|-------------------------------------------------|
| 1      | 4674.12                         | 58.42                                           | 12.3                            | 26.4                                            |
| 2      | 4019.39                         | 55.66                                           | 11.2                            | 23.2                                            |
| 3      | 3607.98                         | 50.75                                           | 10.3                            | 22.1                                            |
| 4      | 3122.86                         | 43.24                                           | 9.54                            | 21.08                                           |
| 5      | 2794.29                         | 37                                               | 8.82                            | 20                                              |
| 6      | 2448.57                         | 31.5                                            | 8.11                            | 19.1                                            |
| 7      | 2106.3                          | 26.69                                           | 7.6                             | 18.3                                            |
| 8      | 1727.1                          | 21.27                                           | 7.32                            | 17.71                                           |
| 9      | 1521.53                         | 16.39                                           | 7.03                            | 17.2                                            |
| 10     | 1324.42                         | 13.32                                           | 6.85                            | 16.75                                           |

Figure 9. Simulation and experimental Temp. of the cooling water leaving the drums

Figure 10. Temperature difference of cooling water entering and leaving the drums
4.3. Analysis of the influence of various parameters on the cooling efficiency of the rubber-film
In engineering, the rubber-film could change in parameters such as the temperature of the rubber-film entering the drum, the thickness and width of the rubber-film, the speed of production line and the amount of cooling water should also change with rubber-film parameters.

To provide references for engineering applications, the parameter sensitivity analysis on the cooling efficiency of the rubber-film was also performed using a single variable method on a single cooling-drum. As listed in table 4 and shown in figure 11, a reasonable range is given for each parameter and the relative variation is defined as the percentage of value change over the minimum value. Relative range of temperature difference of the rubber-film entering and leaving corresponding to relative variation in parameter values is extracted from the numerical simulation which reflects the cooling efficiency of system. Clearly, increasing the temperature of the rubber-film entering the drum, the thickness and width of the rubber-film, the speed of production line and the amount of cooling water, the cooling efficiency increases but at different extent. For the temperature of the rubber-film entering the drum, if the temperature is high, more heat comes in and heat exchange would be more intensified, in other words, the cooling efficiency would be more enhanced. For the width of the rubber-film, however, as the length of the drum would change with width of the rubber-film, heat exchange in unit length of the drum would not change significantly. For the amount of cooling water, of course, a large amount of cooling water would be more efficient to cool the rubber-film.

To method is used to compare the influence of each parameter on the rubber-film cooling efficiency. The relationship between the relative variation of various parameters and temperature difference of the rubber-film entering and leaving the drum is shown in figure 11. The evaluation of the influence of various parameters for the cooling efficiency of the rubber-film is listed in table 4.It is seen that:

(1) The temperature of rubber-film leaving the cooling-drum increases slightly with the width of rubber-film. In general, the width of the rubber-film has less effect on the cooling process of the rubber-film.

(2) In general, the thickness of the rubber-film has a great effect on the cooling of the rubber-film. In actual production, when the thickness of the produced rubber-film is relatively thick, it is necessary to improve the cooling efficiency of the rubber-film by adjusting the process parameters such as the flow of cooling water and the temperature of cooling water in the cooling loop.

(3) In general, the speed of production line of the rubber-film has a great influence on the cooling process of rubber-film.

(4) The temperature difference between rubber-film and cooling water increases with the increase of the temperature of the rubber-film entering the drum, that is, the heat transfer intensity between rubber-film and cooling water increases, the cooling efficiency of the rubber-film increases. In general, the temperature of the rubber-film entering the drum has a great influence on the cooling process of the rubber-film.

(5) The greater the amount of cooling water is, the lower the temperature of the rubber-film leaving the drum becomes. In general, the amount of the cooling water has a relatively large influence on the cooling process of the rubber-film.
Table 4. Evaluation of the influence of various parameters for the cooling efficiency of the rubber-film

| Parameters                              | Relative range of temperature difference of the rubber-film entering and leaving the drum(The absolute value) | Assessment of influence level |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------|-------------------------------|
| Width of the rubber-film(600mm~800mm)  | 0.75%~2.76%                                                                                           | Small(<5%)                    |
| Amount of cooling water(68.645~411.87L/min) | 7.16%~21.76%                                                                                       | Relatively Large(5%~25%)      |
| Speed of production line (4.5~27 m/min) | 25.00%~50.51%                                                                                       | Large (>25%)                  |
| Thickness of the rubber-film (1.4mm~6.4mm) | 33.33%~74.39%                                                                                       |                               |
| Temp. of the rubber-film entering the drum (44.5°C~94.5°C) | 34.6%~172.32%                                                                                       |                               |

Figure 11. Relationship between the relative variation of parameters and temperature difference of the rubber-film entering and leaving the drum

5. Conclusion
(1) A simplified fluid rubber-film method was proposed to numerically simulate the moving rubber-film cooling on the rotating cooling-drums.
(2) Temperature distribution at the rubber-film on each cooling-drum is obtained from the numerical simulation and is compared with the experiment measurements, and the results show that the relative error is less than 6%.
(3) Parameter sensitivity analysis was performed to investigate the cooling efficiency of the system.
(4) The temperature of the rubber-film entering the drum is the biggest parameter to affect the cooling efficiency while the width of the rubber-film has almost no effect on the cooling efficiency.

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