Analysis On Heat Transfer Characteristics For Bosh Copper Cooling Stave With Shaped Tube

HUO Ye, CHEN Liang-yu
School of Mechanical Engineering and Automation, Northeastern University, Shenyang, Liaoning, P. R. China, 110819.
Corresponding author: CHEN Liang-yu, E-mail: meiqiuchixiaoji@126.com

Abstract. The finite physical model of copper cooling stave in the blast furnace bosh is established. By changing the cooling pipe shape (circle, ellipse, double circle, three circle, rectangle and hexagon), the heat transfer characteristics of copper cooling staves for different pipe shapes are simulated. It provides theoretical guidance for the optimization and improvement of copper cooling stave structure in furnace bosh.

1. Introduction
At present, the pipe shape of the copper cooling stave in the blast furnace bosh is almost round, and some shapes are oval. Domestic and foreign scholars lack quantitative analysis and research on the pipe type of copper cooling stave in the blast furnace bosh\(^1,2\). In this paper, taking copper cooling stave as the research object, a finite element model of the cooling stave of different shapes of pipes is established for analyzing the influence of cooling water pipe shape on heat transfer characteristics and mechanical properties.

2. Establishment of model
The thermal structures of the furnace abdomen are the furnace shell, packing, cooling stave and brick from outside to inside. The whole furnace bosh are mainly surrounded by 48 identical copper cooling staves and the working environment of each cooling stave is basically the same\(^3\). The clearance between adjacent cooling staves and between cooling staves and furnace shells are packed by packing. The physical model is shown in figure 1.
3. Simulation conditions

3.1. Boundary conditions

According to actual production and related thermal test, the air temperature is 25℃ outside the furnace shell, the average temperature of cooling water is 30℃ and furnace gas temperature is 1200℃ [4]. In practical engineering, because the ratio of long axis and short axis is usually 0.6, the calculation is based on 0.6 in this paper. To prevent the generation of scale and increase the cooling strength, the cooling water speed is generally greater than 2 m/s. In this paper, the cooling water speed is 2 m/s.

(1) The heat exchange between the outer wall of furnace shell and air is natural convection heat transfer. According to empirical formula, the coefficient of convection heat transfer is:

\[ h_t = 9.3 + 0.058t \]  

where \( t \) is the environment temperature around the furnace shells.

(2) The equivalent diameter of different water pipes is calculated by wetted perimeter method. The formula is:

\[ D_e = \frac{4A}{S} \]  

Under the same cross-sectional area, the equivalent diameter of each shaped pipe is shown in the table 1.

Table 1. The equivalent diameter of each shaped pipe (mm)

| name                | circular tube | ellipse tube | double circle tube |
|---------------------|---------------|--------------|--------------------|
| equivalent diameter | 50            | 47.661       | 47.567             |
| name                | three circle tube | rectangle tube | hexagon tube      |
| Equivalent diameter | 50.282        | 48.136       | 50.122             |

Under the same perimeter case, the equivalent diameter of each shaped pipe is shown in the table 2.

Table 2. the equivalent diameter of each shaped pipe (mm)

| name                | circular tube | ellipse tube | double circle tube |
|---------------------|---------------|--------------|--------------------|
| equivalent diameter | 50            | 41.072       | 45.253             |
| name                | three circle tube | rectangle tube | hexagon tube      |
| Equivalent diameter | 50.572        | 36.815       | 45.345             |

According to the formula:

\[ Re = \frac{\rho v l}{\mu} = \frac{v l}{\nu} \]  

\( \rho \) is the fluid density, \( \nu \) is the fluid velocity; \( l \) is the characteristic length; \( \mu \) is hydrodynamic viscosity; \( \nu \) is the viscosity of fluid motion.

When the cooling water velocity is 2m/s, the cooling water is turbulent. According to the formula:

\[ Nu = 0.023 Re^{0.8} Pr^0.7 \]  

\( Nu \) = h \cdot D_e / k \]  

When temperature of the cooling water is 30 ℃ and temperature of cooling water pipe wall is 40 ℃, \( k = 0.618 W / (m \cdot ^\circ C) \), \( v = 0.805 \times 10^{-6} (m^2 / s) \), \( Pr = 5.42 \).

Under the same cross-sectional area, convection heat transfer coefficient of cooling water of each tube type [5] is shown in the table 3.

Table 3. convection heat transfer coefficient of cooling water in different types of pipes

| name                | circular tube | ellipse tube | double circle tube |
|---------------------|---------------|--------------|--------------------|
| convective heat transfer coefficient | 3509.775\nu^{0.8} | 3872.556\nu^{0.8} | 3689.296\nu^{0.8} |
| name                | three circle tube | rectangle tube | hexagon tube      |
Under the same perimeter case, convection heat transfer coefficient of cooling water of each tube type is shown in the table 4.

| name               | circular tube | ellipse tube | double circle |
|--------------------|---------------|--------------|---------------|
| convective heat    | 3509.775v^{0.8} | 4272.71v^{0.8} | 3877.947v^{0.8} |
| transfer coefficient |
| name               | three circle tube | rectangle tube | hexagon tube |
| convective heat    | 3470.077v^{0.8} | 4766.773v^{0.8} | 3870.079v^{0.8} |
| transfer coefficient |

The heat exchange between the hot surface of the furnace wall and the hot gas is a forced convection heat transfer. The comprehensive convection heat transfer coefficient is:

\[ h_t = -5.606 + 0.2073t_f + 8.414 \times 10^{-5}t_f \quad (6) \]

\( t_f \) is the temperature of the hot furnace gas.

3.2. physical property parameters

The physical parameters involved in the analysis of heat transfer and mechanical properties of copper cooling stave include thermal conductivity, Young's modulus, coefficient of thermal expansion and poisson's ratio etc. The physical properties parameters of different materials are shown in table 5.

| name       | temperature (°C) | Young's modulus (Pa) | poisson's ratio | coefficient of thermal conductivity (W/m² °C) | coefficient of thermal expansion (°C⁻¹) |
|------------|------------------|----------------------|-----------------|---------------------------------------------|------------------------------------------|
| furnace shell | 0 30 100 200 500 | 2.06e11 1.7e11 | 0.3 0.3 | 52.34 48.85 44.19 | 1.159e-5 |
| packing  | 400 700 | 0.21e11 0.21e11 | 0.2 0.2 | 1.45 1.45 | 4.5e-6 |
| cooling stave | 20 100 300 | 1.1e11 1.08e11 0.95e11 | 0.33 0.33 0.33 | 373 359 | 17.64e-6 18e-6 18.5e-6 |
| brick | 200 500 800 1000 1200 1370 | 0.21e11 0.15e11 0.12e11 0.07e11 | 0.2 0.2 0.2 0.2 | 19.5 18.1 18 18 | 4.7e-6 |
4. Calculation results

According to the above boundary conditions, the temperature distribution of the circle tube copper cooling stave of the blast furnace was calculated. In the picture, the highest temperature of copper cooling stave is 148.389℃ that is below the limit temperature of the copper cooling stave. It is located in the heat surface of the bottom rib of the copper cooling stave, because it is far from the cooling water pipe and the outer wall of the furnace shell and its heat slow. Temperature and stress distribution of the copper cooling stave are shown in figure 2.

![Figure 2. temperature and stress distribution of the copper cooling stave](image)

![Figure 3. the maximum temperature of the cooling wall of different pipe type with the same cross-sectional area](image)

![Figure 4. the maximum temperature of the cooling wall of different pipe type with the same perimeter case](image)

As shown in figure 3, under the same cross-sectional area, the maximum temperature of the cooling stave of elliptical tube is significantly lower than that of the cooling stave of circular tube. The maximum temperature of rectangular tube and circular tube cooling stave is basically the same. The maximum temperature of cooling stave of three circle tube and regular hexagon tube increased obviously.

As shown in the figure 4, under the same perimeter case, in different tubular cooling staves, the maximum temperature of the cooling stave of oval tube is the lowest, followed by double circle tube and rectangular tube. The maximum temperature of the cooling stave of the three circle tube and regular hexagon tube is higher than that of the cooling wall of the circular tube.

In figure 5, when the ratio of rectangular tube length axis to short axis is 0.3, the highest temperature of copper cooling stave decreases more obviously than other proportions of rectangular tube cooling stave. However, considering the difficulty of processing and the easy occurrence of stress concentration points in the working process, rectangular tube is most suitable between 0.6 and 0.7.

In figure 6, when the ratio of ellipse tube length axis to short axis is 0.3, the highest temperature of copper cooling stave decreases more obviously than other proportions of ellipse tube cooling stave. But considering comprehensively the heat transfer, flow resistance, machining difficulty and the
influence of the long axis of the oval tube on the radial force of the cooling stave, oval tubes with a ratio of 0.5~0.9 for long and short axes are most suitable.

5. Conclusion
Under the same perimeter case and the same cross-sectional area, the maximum temperature of oval tube cooling stave is slightly lower than that of other tube cooling staves. Considering comprehensive heat transfer characteristics, etc, oval is the best shape.

For rectangular tubes with different length axis ratios, considering the radial bearing capacity and stress concentration of the stave, the rectangular tubes stave with the length ratio of 0.6~0.7 is the best choice. For oval tubes with different length axis ratios, the oval tubes with the length ratio of 0.5~0.9 is the best choice.

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