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Experimental study on heat transfer characteristics of blast furnace copper staves

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Abstract: Much attention has been paid to copper staves because they have excellent performance and longevity. The hot test of copper staves was carried out using all-scale stave experiment system and according to the results, the temperature distribution and heat characteristics were studied. The result shows that copper stave possesses outstanding heat transfer ability, a well-distributed temperature field and low temperature on the hot side. In addition, a model was established to calculate the cooling water channels' inner face temperature. The calculation results indicates that the highest temperature of the inner wall of the channels is 42 ℃, and at the same time, the cold side of the stave temperature is 42-43 ℃. That is to say, the temperature in the stave is quite uniform.

Key words: BF; copper stave; hot test

1 Introduction

Cooling staves are the essential elements for containing blast furnace campaign so far. There are two ways to improve the performance of staves. One is to optimize the structure of staves by designing properly. Four generations of staves have been developed in Japan and experimental and calculation results have been got [1]. The other way is to use high-quality materials. For example, nodular cast iron has been used for the purpose and recently copper staves have been applied in some blast furnaces in Europe, North America, Japan and China [2-4]. There are mainly three types of copper staves used in the world [5]. In China, Wuhan Steel Works has chosen PW-OU type for the new-built BF (Blast Furnace). It is becoming a trend to use copper staves in China because they have excellent heat transfer performance and have been used successfully for several years in about 50 BFs in some foreign countries. However, BF conditions in China are different from that abroad and there is almost no direct practical and experimental datum in our country except one copper stave is being used in Capital Steel Group of China. There are some theoretical researches in China [6, 7]. To put copper staves into wide application, it is necessary to set up a full scale experimental system, in which many experiments, such as the experiments of temperature distribution inside and outside a stave and interaction of structural factors and operation conditions, etc., can be carried out.

A full-scale stave experimental system was built up in Shantou Huaxing Metallurgical Spare Parts Corporation of China, which is producing copper staves in order to meet domestic demands. The copper staves from the corporation are made of copper slabs, whose purity reach 99.95%. Cooling water channels are drilled through the slab directly without tube casting inside the slab. This process is easier than casting one and the products have more excellent performance. An experiment was carried out to study heat transfer characteristics of a copper stave which was made as a prototype.

2 Experimental system

The copper stave experimental system includes four parts: experimental chamber, combustion chamber, circulatory cooling water system and instrumental system with computer data collection. **Figure 1** shows the experimental furnace structure, which mainly includes experimental chamber and combustion chamber. Experimental chamber simulates thermal boundary conditions in BF, in which case, a certain temperature and gas velocity are guaranteed. Combustion chamber offers hot gas by oil firing. Cooling water flows through stave channels and goes back to the fountain designed for cooling water heated in the stave. In circulatory cooling water system, the water volume, pressure, temperature should be regulated easily. The instrumental system is composed of end instruments (thermocouple, resistance bulbs, manometers, flowmeters, *etc.*) and a computer which collects signals from end instruments through A/D, displays and stores the data timely.

The sizes of the biggest stave which can be installed

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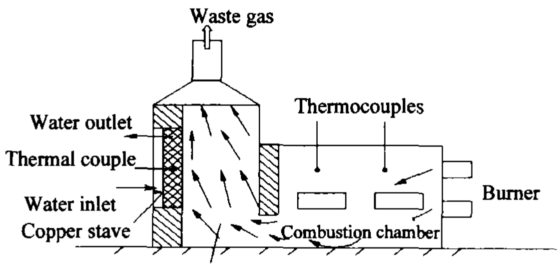

Figure 1 Experimental furnace for copper stave.

in the experiment system is 1 200 mm×300 mm×2 200 mm (width × thickness × length). The heat flux of maximum is 250 kJ/m^2·h.

3 Experiment and results

The size of the tested copper cooling stave is 992 mm ×145 mm×1 970 mm (width × thickness × length), which was made of rolled copper slab. There are 5 channels going through the stave along the length direction, and the channel diameter is 40 mm. The interval between every two channels is 210 mm. The hot surface is inlaid with SiC bricks.

The experiment lasted 73.5 h and during the experiment the temperature in the furnace went up gradually from environmental temperature to 1 100 ℃. Water velocity in stave channels is 0.5-2.65 m/s (in most cases, the velocity is less than 2.0 m/s). Water temperature at channel inlet was 32-34 ℃ and at channel outlet 33-36.6 ℃.

3.1 Temperature on hot surface of the stave

On hot surface of the stave there are grooves in which the SiC bricks are inlaid. Because the thermal properties of the refractory are very different from those of copper, their temperature responses will be different, too. **Figure 2** shows the results with two curves. The steep curve represents the temperature increase of refractory with time increasing. The other is the result of copper. Under the same boundary conditions, temperature of refractory is higher than that of copper, which results from the far difference of heat conduction coefficients. That is, high heat resistance due to low conduction coefficient results in high temperature on hot side of stave. According to the result of experiment, when the temperature in the combustion chamber reaches 1 050 ℃, the highest temperature on refractory is 125 ℃, but on the nearby face, the copper temperature is only 51 ℃.

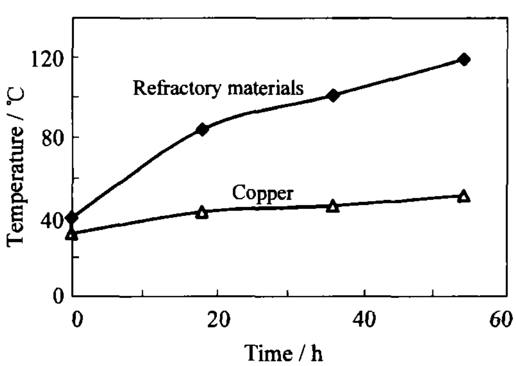

Figure 2 Temperatures of copper stave hot side.

In a word, excellent performance of copper slabs in heat transfer guarantees very low temperature in staves, which is really good for BF's long campaign.

3.2 Cold side temperature distribution of copper stave

Four curves in **figure 3** represent temperature distributions on the cold side of the stave at different heights with the chamber temperature at 1 017 ℃ and velocity of cooling water at 2.0 m/s. The 4 curves are all undulant shapes where the lowest values are on the centerlines of cooling water channels, and the highest ones on the centerlines of two channels. On the cold side, temperature distribution is quite uniform. Average temperature is 46 ℃ and the highest and the lowest are 50 and 30 ℃ respectively.

According to above data, it can be concluded that the distance between the cooling water channels in the copper stave influences little the temperature distribution.

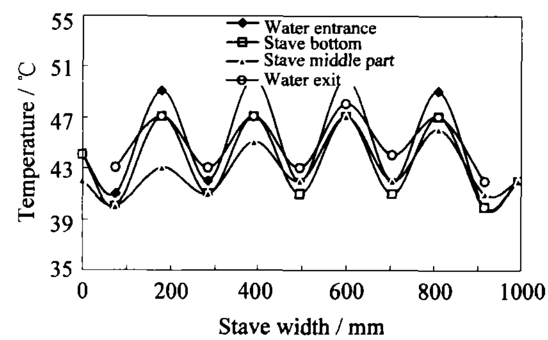

Figure 3 Temperature distribution of copper stave cold side.

3.3 Temperatures inside the staves

On the same depth of the stave, temperatures under the refractory and in the copper stave are different (**figure 4**). In the latter test period, the average difference of temperatures is 43 ℃. The copper covered by refrac-

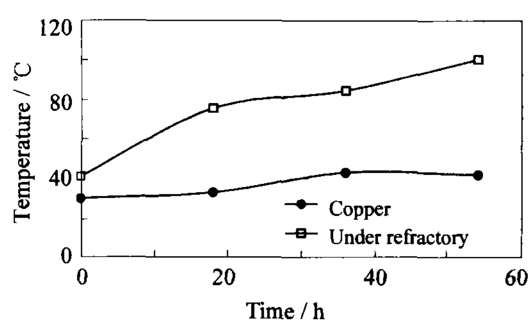

Figure 4 Temperatures of inner points.

tory has to endure higher temperature. That is, refractory reduce the stave's cooling performance.

The curves also indicate that, under the same conditions, temperature response under the refractory is much violent. The temperature under the refractory started from 40 ℃ to 100 ℃, but during the same time, the temperature difference in the copper is only 12 ℃.

In the latter period, with chamber temperature around 1 000 ℃ and the water velocity 2.62 m/s, refractory temperature is up to 100 ℃, but the copper temperature remains lower than that before.

This indicates that even though the chamber temperature is 200 ℃ higher in the latter test period, the increase of the cooling water flow rate contributes a lot to the decrease of stave temperature due to copper's high heat conductivity.

3.4 Heat flux analysis

To study the heat flux in the stave, three thermocouples were installed in the direction of thickness of the stave.

Because the height and width of the stave are much bigger than thickness and the temperatures are picked up in the central area of the stave, the flux can be regarded as one dimensional heat transfer and the heat flux to other directions can be neglected. Thus the heat flux closed to the hot side and the cold side can be calculated respectively.

According to Fourier's law, the results of calculation showed in **figure 5** indicate that:

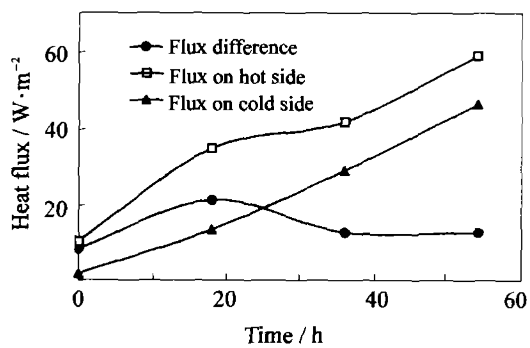

Figure 5 Analysis of stave heat flux.

(1) Flux on hot side increases with the rise of the chamber temperature, and flux on cold side decreases with the increase of the cooling water;

(2) The difference of the fluxes between the hot and cold side is equal to the heat which the cooling water has taken;

(3) In the latter test period, flux on cold side were kept constant as 12.67 kW/m². In the meantime, the heat amount taken by cooling water increases proportionally with the heat flux on hot side increasing. In the later test period, temperature on hot side increased by only 3 ℃ and heat taken by cooling water increased 60%. This is due to the successful processing to drill channels for cooling water in copper staves, which eliminate thermal resistance caused by the contact between interfaces of the pipes and the cast metal if pipes were cast in staves made of another metal materials.

3.5 The cooling water face temperature calculation

A model was established to calculate the cooling water channels' inner face temperature. The calculating process is: (1) when the water velocity and properties in the channels are known, the *Re* and *Pr* can be got and then the *Nu* can be further got by which the α can be determined in the channel; (2) heat can be got by the difference of the hot and cold side heat fluxes, where data can be got by the last section; (3) the cooling water temperature was got by the test; (4) the cooling water channels' inner temperature tb can be got according to Newton's formula of cooling. **Table 1** shows the conditions and results.

Table 1 Calculation of inner wall temperatures of channels in copper stave

Time / h	0	18	54
Colling water rate / $m \cdot s^{-1}$	1.11	1.72	2.62
Heat transfer cofficient by convection / $W \cdot m^{-2} \cdot ℃^{-1}$	4 531	6 455	9 039
Colling water mean temperature / ℃	33	35	36
Heat flux through inner wall / $kW \cdot m^{-2}$	1.92	13.44	46.06
Temperature on inner wall of channels in stave / ℃	33.4	37.1	42.0

The calculation results indicate that the highest temperature of the inner wall of the channels is 42 ℃, while the cold side of the stave temperature is 42-43 ℃. That means that the temperature in the stave is quite uniform.

4 Conclusions

(1) The highest temperature of the refractory in the copper stave reached 125 ℃, while the copper hot side temperature is only 51 ℃. Both temperatures are rather low compared with other staves produced by different materials or processes such as casting iron staves. Good result is due to both the materials and process used in the production of the staves.

(2) Temperature distribution on the cold side of the copper stave shows that the numbers and sizes of the

water channels in the stave can meet the cooling requirement.

(3) Increasing of cooling water flow rate can obviously lower copper temperature but it contributes little to make refractory temperature decreasing.

(4) Calculating results show that inner wall temperatures of channels are rather low, which are 33.42 ℃ in the first test period, 37.1 ℃ in the middle and 42 ℃ in the last.

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