

# Thermal conductivity of alumina-carbon composite brick and its related phase analysis in a dissected blast furnace

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**Abstract.** Excellent performance of refractories in blast furnace hearth is one of the important factors to ensure longevity of blast furnaces. As an emerging refractory for application in blast furnace, alumina-carbon composite brick combines the superior properties of carbon and alumina. Firstly, the thermal conductivity of alumina-carbon composite brick was measured by the laser flash method and the new device method to verify the feasibility of the new device method for thermal conductivity measurement. Secondly, the influence of heating temperature of the heating furnace and cooling water flow on the thermal conductivity of the alumina-carbon composite brick, and the comparison of the thermal conductivity of carbon brick, alumina-carbon composite brick and corundum brick were investigated to confirm the heat transfer mechanism of alumina-carbon composite brick. High thermal conductivity and erosion resistance to slag and hot metal of the alumina-carbon composite brick are consequent from: (a) reasonable composition combination of  $\text{Al}_2\text{O}_3$ , C,  $\text{SiO}_2$ , SiC, etc., (b) dense structure, small pore diameter, and uniform distribution of the pores, (c) the generated SiC whiskers and  $\text{Al}_6\text{Si}_2\text{O}_{13}$ , which can fill in the pores and reduce the porosity. Finally, the analysis on the phase distribution of the alumina-carbon composite brick in a dissected blast furnace was performed to illustrate the relationship between the erosion resistance and the thermal conductivity of alumina-carbon composite brick.

**Keywords:** blast furnace longevity / alumina-carbon composite brick / thermal conductivity / blast furnace dissection

## 1 Introduction

Low consumption, longevity, large-scale and high efficiency have gradually become the trend in development of blast furnace ironmaking technology [1–4]. From the perspective of the heat transfer structure of the blast furnace, the belly, bosh, hearth and bottom are the key areas of blast furnace longevity, and excellent performance of refractories is an important basis to extend the blast furnace campaign [5–7]. There are currently four typical hearth lining refractories for blast furnace: (a) carbon brick; (b) corundum brick; (c) alumina-carbon composite brick; (d) castable [8,9]. The main component of carbon brick is carbon, and that of corundum brick and castable is alumina, alumina-carbon composite bricks are mainly composed of carbon and alumina. Carbon has excellent thermal conductivity and can fully utilize the cooling system [10]. However, the inherent disadvantages of carbon bricks such as poor

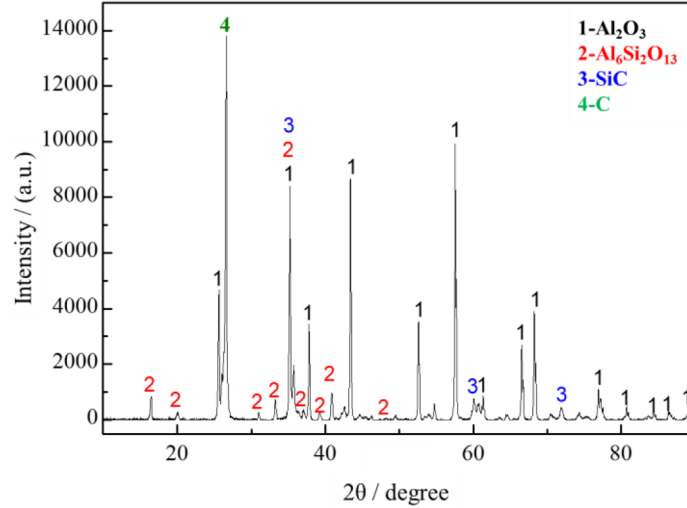
resistance to molten iron infiltration, poor oxidation resistance and low compressive strength [11], are more serious in the case of water shortage or leakage of the cooling system, and even lead to the risk of blast furnace hearth breakout. Alumina processes strong resistance to molten iron infiltration and harmful element destruction, but high brittleness, poor toughness, large thermal expansion and poor thermal conductivity of corundum brick, and its large volume expansion after alkali metal erosion, will cause structural damage and affect the blast furnace campaign [12,13].

Alumina-carbon composite brick was developed by reasonably introducing carbon into the  $\text{Al}_2\text{O}_3$ -containing refractory. Therefore, the alumina-carbon composite brick could effectively give play to the advantages of high thermal conductivity of carbon bricks and excellent properties of traditional corundum brick such as strong resistance to molten iron infiltration, high compressive strength and high wearability [14,15], which could be used as ceramic cups or instead of hearth carbon bricks. It intends to greatly improve the safety of blast furnace

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**Table 1.** Chemical compositions of alumina-carbon composite brick.

| Composition | Al <sub>2</sub> O <sub>3</sub> | C     | SiO <sub>2</sub> | SiC  | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | Na <sub>2</sub> O |
|-------------|--------------------------------|-------|------------------|------|--------------------------------|------------------|-------------------|
| wt. %       | 73.05                          | 10.20 | 8.18             | 6.00 | 0.90                           | 0.11             | 0.29              |

**Fig. 1.** XRD pattern of alumina-carbon composite brick.

hearth when smelting strength changes, and extend the blast furnace campaign. The higher the thermal conductivity, the faster the heat transfer when the hearth lining has a large temperature change, the smaller the temperature gradient inside the hearth lining refractory, the stronger the resistance to thermal stress, the longer the service life of the refractory, and the more extensive of the blast furnace campaign [16]. Therefore, the detection of the thermal conductivity of alumina-carbon composite bricks is of great practical significance. The thermal conductivity of alumina-carbon composite brick is relatively high that not much lower than that of carbon bricks measured through the traditional laser flash method, but due to the strong limitations of the determination of the thermal diffusion coefficient and the specific heat capacity [17–19], it is rarely possible to accurately measure the thermal conductivity of composite materials. Few studies on the thermal conductivity measurement of alumina-carbon composite brick are reported, and the heat transfer mechanism still needs further analysis, and as an emerging hearth lining refractory, there is relatively rare application in blast furnaces, the actual service in a blast furnace is still unknown. Hence, it is necessary to confirm the thermal conductivity of alumina-carbon composite brick, and determine the influencing factors of heat transfer mechanism through laboratory experiments, and clarify the thermal conductivity of the brick after service and corresponding erosion resistance through blast furnace dissection, aiming to provide a theoretical reference for the future application of alumina-carbon composite brick in blast furnace, and promote the blast furnace iron-making technology towards low carbon and longevity.

**Table 2.** Physical properties of alumina-carbon composite brick.

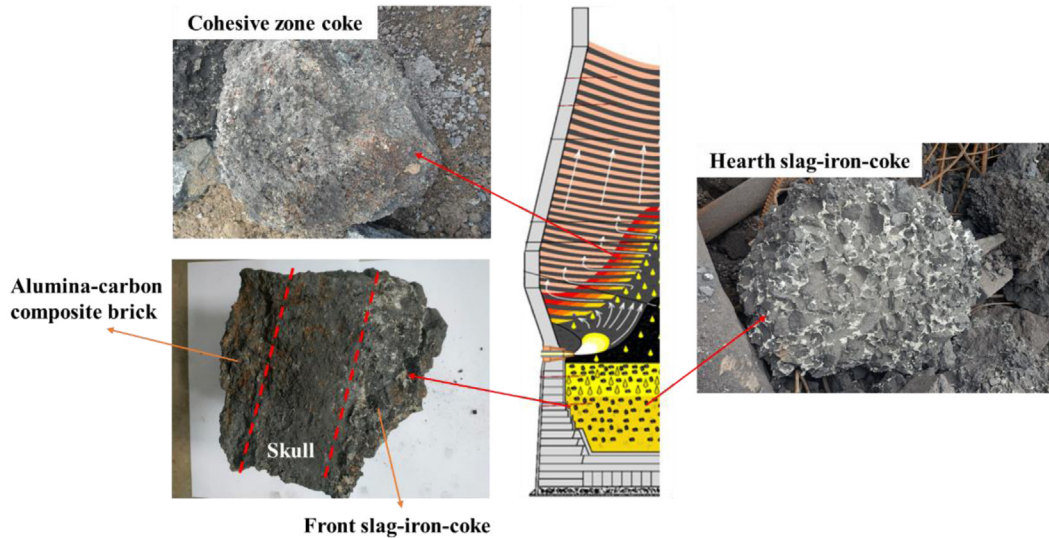
| Index                                        | Value |
|----------------------------------------------|-------|
| Apparent porosity, %                         | 10.9  |
| Bulk density, g/cm <sup>3</sup>              | 2.98  |
| Average pore diameter, μm                    | 0.238 |
| Pore volume (<1 μm), %                       | 80.44 |
| Compressive strength (Room temperature), MPa | 78.4  |

## 2 Materials and method

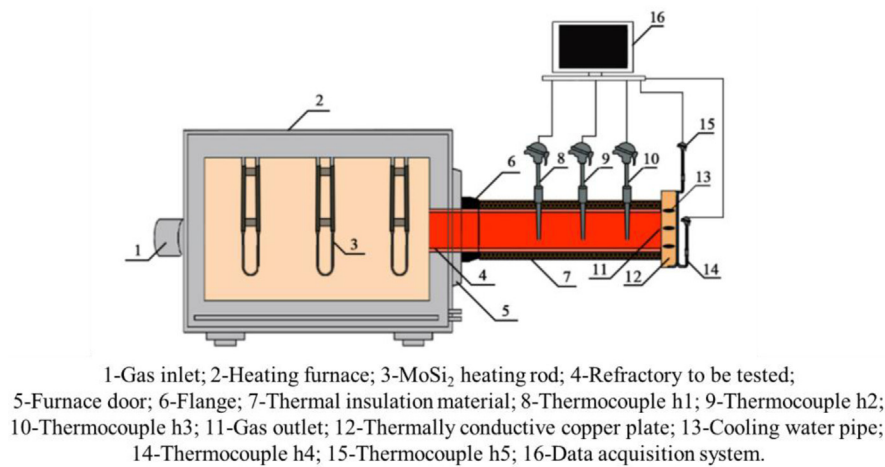
### 2.1 Materials preparation

The alumina-carbon composite brick was developed and produced by Henan Wunai Group Industry Co., Ltd., the main chemical compositions of which are 73.05 wt.% Al<sub>2</sub>O<sub>3</sub>, 10.20 wt.% C, 8.18 wt.% SiO<sub>2</sub> and 6.00 wt.% SiC, as shown in Table 1, the main phases are Al<sub>2</sub>O<sub>3</sub>, C, SiC and Al<sub>6</sub>Si<sub>2</sub>O<sub>13</sub> (mullite) exhibited in Figure 1. Table 2 displays some fundamental physical properties. In comparison with conventional carbon brick, the apparent porosity is a little bit lower, 10.9%; the bulk density is larger, 2.98 g/cm<sup>3</sup>; the average pore diameter is greater, 0.238 μm; the pore volume (<1 μm) is relatively lower, 80.44%; and the compressive strength (room temperature) is higher, 78.4 MPa, respectively [20,21].

The original brick was processed into a small cube with a length of 2.78 mm for X-ray computed tomography (XCT) detection (YXLON FF35, Germany), some rectangular



**Fig. 2.** Schematic diagram of sampling in a dissected blast furnace.



**Fig. 3.** Principle and schematic diagram of the new device method.

samples of 346 mm in length, 150 mm in width and 98 mm in height for thermal conductivity measurements, some powders for chemical composition analysis and X-ray diffraction (XRD) (Rigaku SmartLab, Japan) detection after ground in agate mortar for 30 min, and some regular lumpy specimens for scanning electron microscope and energy dispersive spectrometer (SEM-EDS) (FEI Quanta 250, Holland) detection.

The samples after service were taken from Chinese Tongcai No. 2 dissected blast furnace, composing alumina-carbon composite brick, skull, front slag-iron-coke, hearth slag-iron-coke, and cohesive zone coke, as shown in Figure 2. All the samples were subjected to chemical composition analysis and XRD detection for comparative analysis, and the micromorphology and element distribution of alumina-carbon composite brick and skull were performed through SEM-EDS detection for interpretation of the relationship between the erosion resistance and the thermal conductivity of the brick.

## 2.2 Method of thermal conductivity measurement

The new device method for measuring thermal conductivity is schematically shown in Figure 3. This device is to emulate the environment of refractory in a blast furnace, primarily containing temperature field simulation. The measurement system mainly consists of heating furnace, cooling system, refractory to be tested and data acquisition system. Therein, the temperature of the heating furnace represents the temperature of the hot surface that the refractory facing; the cooling system simulates the cooling stove; the refractory to be tested is selected from the lining refractory; the data acquisition system collects the temperature values of different positions on the refractory.

The device follows the principle that one end of the refractory is close to the constant temperature area of the heating furnace, the other end is close to the cooling system, and the refractory is sealed with thermal insulation material around the periphery, so as to ensure as much as

**Table 3.** Experimental scheme for thermal conductivity measurement.

| Number | Brick                          | Heating temperature of the heating furnace, °C | Flow of cooling water entering into the cooling system, mL/min |
|--------|--------------------------------|------------------------------------------------|----------------------------------------------------------------|
| 1      | Alumina-carbon composite brick | 500                                            | 1500                                                           |
| 2      | Alumina-carbon composite brick | 850                                            | 1500                                                           |
| 3      | Alumina-carbon composite brick | 1200                                           | 1500                                                           |
| 4      | Alumina-carbon composite brick | 1500                                           | 1500                                                           |
| 5      | Alumina-carbon composite brick | 1200                                           | 900                                                            |
| 6      | Alumina-carbon composite brick | 1200                                           | 1200                                                           |
| 7      | Carbon brick                   | 1200                                           | 1500                                                           |
| 8      | Corundum brick                 | 1200                                           | 1500                                                           |

possible that the heat transfer of the refractory is one-dimensional radial heat transfer. When the measurement system reaches a steady state, the temperature values of each measurement point are obtained through the thermocouples, and the heat flow intensity of the system can be calculated combined with Fourier's law for one-dimensional heat transfer, further the high-temperature thermal conductivity of the refractory is acquired correspondingly [22,23].

Under the condition of one-dimensional heat transfer, the cross-sectional heat flow of the refractory ( $Q_1$ , W) is equivalent to the heat flow of the cooling water ( $Q_2$ , W).

$$Q_1 = Q_2 \quad (1)$$

$$Q_2 = C_{pw} \cdot Q_m \cdot (T_4 - T_3) \quad (2)$$

$$\lambda = (Q_1/A) \cdot (\Delta L / (T_2 - T_1)) \quad (3)$$

where  $C_{pw}$  represents the heat capacity of cooling water, equals  $4.2 \times 10^3 \text{ J}/(\text{kg} \cdot \text{K})$ ;  $Q_m$  is the mass flow of cooling water, kg/s;  $T_1$  and  $T_2$  are the temperatures of thermocouples on the refractory, °C;  $T_3$  (temperature of thermocouple h4) and  $T_4$  (temperature of thermocouple h5) are the temperatures of inlet and outlet cooling water, °C;  $\Delta L$  is the distance between two thermocouples corresponding to  $T_1$  and  $T_2$  on the refractory, m;  $A$  is the cross-sectional area of the refractory,  $\text{m}^2$ ;  $\lambda$  is the thermal conductivity of refractory,  $\text{W}/(\text{m} \cdot \text{K})$ . Moreover,  $T_1$  and  $T_2$  are the temperatures of thermocouples h2 and h1 when determining the thermal conductivity of refractory between the thermocouples h2 and h1. Similarly,  $T_1$  and  $T_2$  are temperatures of thermocouples h3 and h2 when determining the thermal conductivity of refractory between the thermocouples h3 and h2, and are temperatures of thermocouples h3 and h1 when determining the thermal conductivity of refractory between the thermocouples h3 and h1.

The experiment was carried out using the control variable method, that is, a single variable was changed while ensuring that the rest of the conditions remained unchanged. The specific experimental scheme is shown in Table 3, the thermocouple temperatures, cooling water flow and the inlet and outlet water temperatures of the

cooling system are collected during the experimental process. Therefore, the thermal conductivity of the refractory under different heating temperature and cooling water flow conditions, and the thermal conductivity of different types of brick can be calculated.

## 3 Results and discussion

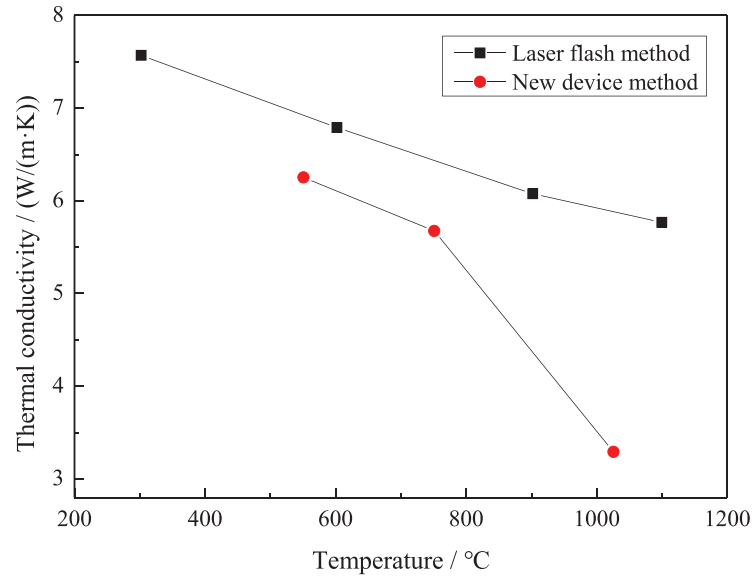
### 3.1 Feasibility of the new device method

The thermal conductivities of alumina-carbon composite brick at different temperatures were measured by the laser flash method and the new device method, the consequences are shown in Figure 4.

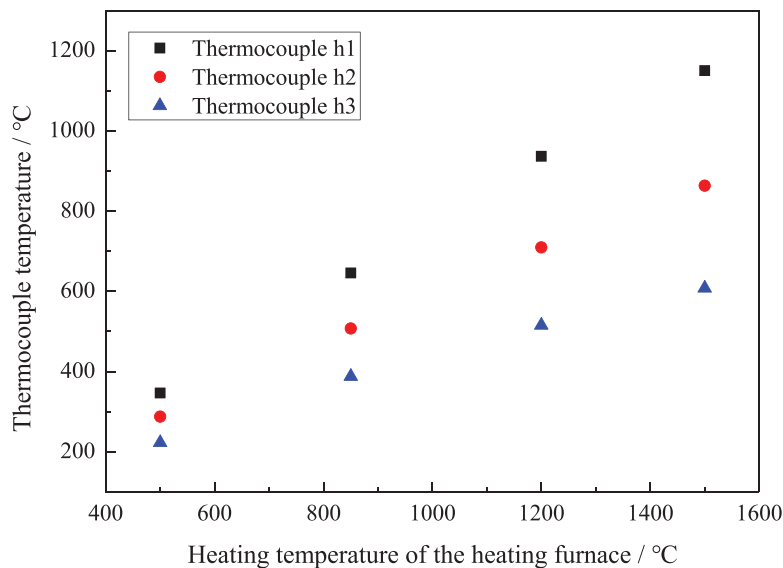
It can be seen from Figure 4 that the thermal conductivity measured by both methods decreases with increasing temperature, the thermal conductivity measured by the new device method basically corresponds to that measured by the laser flash method, while the values measured by the new device method is lower than that measured by the laser flash method. When the temperature exceeds about  $750^\circ\text{C}$ , the thermal conductivity measured by the new device method has a greater downward trend than that measured by the laser flash method. It should be noted that different factors of type of alumina-carbon composite brick, heating temperature of heating furnace and cooling water flow lead to different intervals of thermal conductivity.

### 3.2 Influence of heating temperature on thermal conductivity of alumina-carbon composite brick

The flow of cooling water entering into the cooling system was controlled to 1500 mL/min, and the heating temperature of the heating furnace was arranged to be  $500^\circ\text{C}$ ,  $850^\circ\text{C}$ ,  $1200^\circ\text{C}$  and  $1500^\circ\text{C}$  respectively, the thermal conductivity of the alumina-carbon composite brick could be calculated by collecting the temperatures of thermocouples h1, h2, h3, h4 and h5. The temperatures of thermocouples h1, h2, h3 at different heating temperatures are shown in Figure 5. The difference in heating temperature will bring about large difference in the temperature of the same thermocouple. For instance, the temperatures of thermocouple h1 are  $346^\circ\text{C}$ ,  $645^\circ\text{C}$ ,  $937^\circ\text{C}$  and  $1150^\circ\text{C}$  respectively, when the heating furnace is



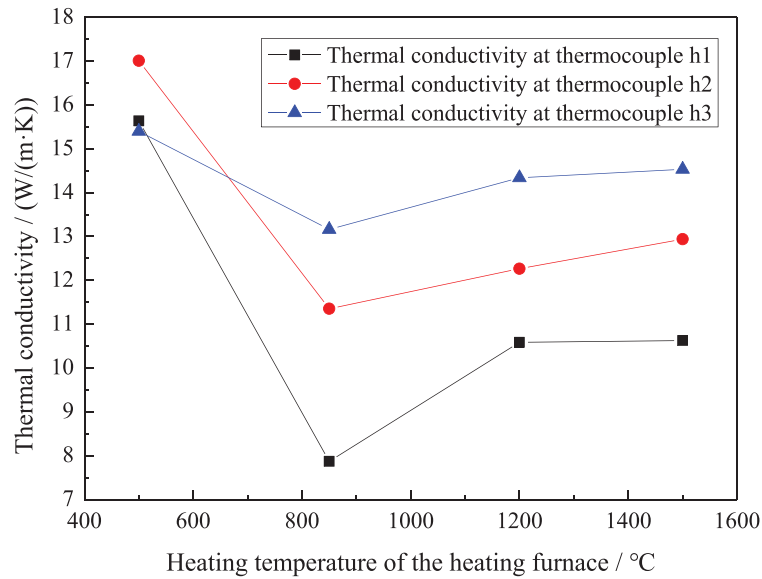
**Fig. 4.** Variation of thermal conductivity of alumina-carbon composite brick with temperature.



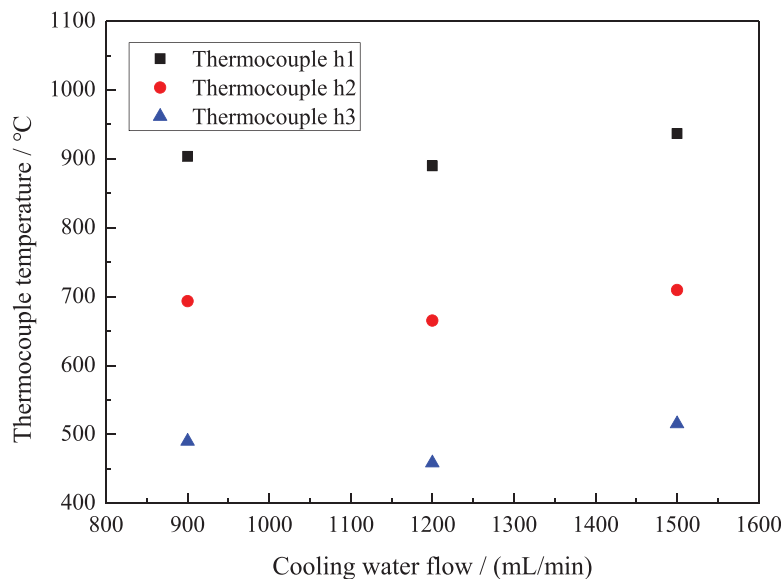
**Fig. 5.** Variation of thermocouple temperature vs. heating temperature.

heated to 500 °C, 850 °C, 1200 °C and 1500 °C, respectively. The temperatures of thermocouples h2 and h3 also follows the same principle, that is, the higher the heating temperature, the higher the temperature of thermocouples. When the heating temperature is constant, the temperature of thermocouple h1 is the highest, which is higher than that of thermocouples h2 and h3. As the heat transfers from the hot to the cold surface, a heat loss emerges, and the temperature continues to descend from thermocouples h1 to h3. When the heating temperature increases, the temperature gradient between adjacent thermocouples enlarges. It is because that the heat flux intensity ( $Q_1/A$ ) increase with increasing the heating temperature, and the thermal conductivity of refractory decreases in the same situation, the temperature gradient enlarges definitely.

The thermal conductivity of alumina-carbon composite brick under different heating temperatures of heating furnace is exhibited in Figure 6. It changes depending on the heating temperature of the heating furnace. The thermal conductivity of alumina-carbon composite brick at same thermocouple position at 500 °C is higher than that at 850 °C, 1200 °C and 1500 °C, and obey the rule that the thermal conductivity at same thermocouple position decreases from 500 °C to 850 °C, increases from 850 °C to 1500 °C. For instance, the thermal conductivity of alumina-carbon composite brick at thermocouple h2 is 17.01 W/(m·K) at heating temperature of 500 °C, 11.35 W/(m·K) at 850 °C, 12.27 W/(m·K) at 1200 °C, 12.94 W/(m·K) at 1500 °C. When the heating temperature is a constant, including at 850 °C, 1200 °C and 1500 °C, the thermal conductivity increases from thermocouple h1 to h3, while



**Fig. 6.** Variation of thermal conductivity vs. heating temperature.



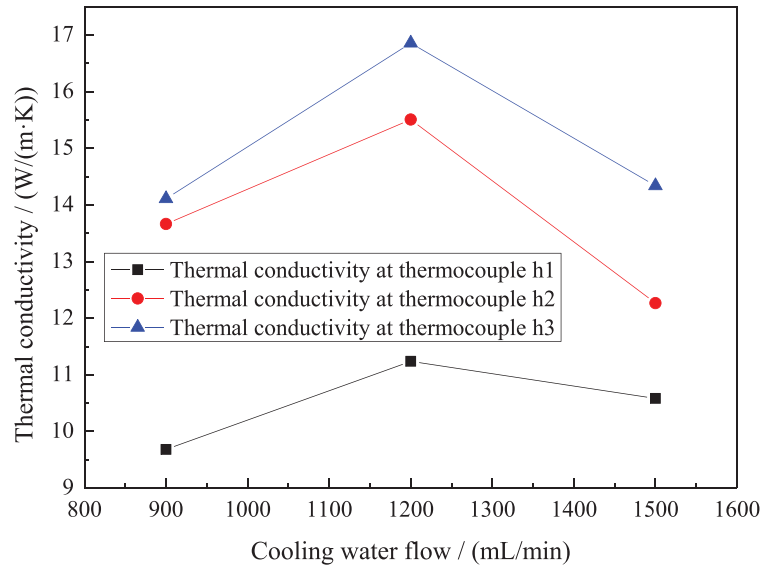
**Fig. 7.** Variation of thermocouple temperature vs. cooling water flow.

at 500 °C, the thermal conductivity at thermocouple h2 is the highest, and the one at thermocouple h3 is the lowest. It is mainly originated from the difference in heat flux intensity of cooling water and the heating temperature. However, the thermal conductivity fundamentally follows the law that increased temperature results in decreased thermal conductivity for alumina-carbon composite brick.

### 3.3 Influence of cooling water flow on thermal conductivity of alumina-carbon composite brick

The flow of cooling water entering into the cooling system was set to be 900 mL/min, 1200 mL/min and 1500 mL/min, respectively, to investigate the influence of cooling water flow on thermal conductivity of alumina-carbon composite brick

by recording the temperatures of thermocouples h1, h2, h3, h4 and h5, when the heating temperature of the heating furnace was kept at 1200 °C. It can be observed from Figure 7 that the temperature measured by the same thermocouple decreases first and then increases as the cooling water flow increases. For example, the temperature of thermocouple h1 is 903 °C, 890 °C and 936 °C, when the cooling water flow is controlled to 900 mL/min, 1200 mL/min and 1500 mL/min. Although the cooling water flow is increasing, the heat flux intensity of cooling water does not increase gradually, but reaches a maximum of 34857 W/m<sup>2</sup> at the cooling water flow of 1200 mL/min, resulting in the lowest temperature of the same thermocouple at the cooling water flow of 1200 mL/min. Overall, the cooling water flow has comparatively less influence on the same thermocouple's temperature than



**Fig. 8.** Variation of thermal conductivity vs. cooling water flow.

the heating temperature of the heating furnace. When the cooling water flow remains unchanged, the thermocouple temperature decreases from h1 to h3 because of the loss of heat during transfer.

Figure 8 demonstrates the thermal conductivity of alumina-carbon composite brick under different cooling water flows. It serves to show that thermal conductivity at the same thermocouple increases when cooling water flow is increased from 900 mL/min to 1200 mL/min, and then decrease when cooling water flow is increased from 1200 mL/min to 1500 mL/min. As for the cooling water flow being constant, the thermal conductivity at thermocouple h1 is always greater than that at thermocouple h2 and h3. This is opposite correspondence exactly to the variation of thermocouple temperature vs. cooling water flow. Combined with Figures 5, 6 and Figures 7, 8, it can be concluded definitely that the thermal conductivity of alumina-carbon composite decreases with increasing temperature, which conforms to the measurement results presented in Figure 4. It also formalizes the feasibility of the new device method for measuring the thermal conductivity of alumina-carbon composite brick.

### 3.4 Comparison of the thermal conductivity of carbon brick, alumina-carbon composite brick and corundum brick

The heating furnace was heated to 1200 °C, and the cooling water flow was controlled to 1500 mL/min, to study the thermal conductivity of carbon brick, alumina-carbon composite brick and corundum brick through the collection of the temperatures of thermocouples h1, h2, h3, h4 and h5. It can be seen from Figure 9 that the thermocouple temperature changes significantly with the variety of refractory. The temperatures of thermocouples h1 for carbon brick, alumina-carbon composite brick and corundum brick are 985 °C, 937 °C and 826 °C. The same temperature variation is observed at thermocouples 2

and 3. The reason mainly lies in the disparate components of the refractory, that carbon brick contains most carbon with high thermal conductivity, and the main component of corundum brick is  $\text{Al}_2\text{O}_3$ , which has relatively low thermal conductivity. For the same type of refractory, the gradual reduction in thermocouple temperature from h1 to h3 is observed owing to the heat loss during transfer in refractory. The temperature gradient of corundum brick is larger than carbon brick and alumina-carbon composite brick, which results from the low thermal conductivity of corundum brick and high heat loss during heat transfer.

The thermal conductivity varies with the type of refractory, as shown in Figure 10. The largest thermal conductivity of refractory at the same thermocouple is carbon brick, followed by alumina-carbon composite brick, and the smallest is corundum brick. The thermal conductivities of carbon brick, alumina-carbon composite brick and corundum brick at thermocouple h1 are 14.28 W/(m·K), 10.63 W/(m·K) and 5.92 W/(m·K), respectively, and the thermal conductivities at thermocouples h2 and h3 follow the same reduction order. For alumina-carbon composite brick and corundum brick, the thermal conductivity at thermocouple h1 is the lowest, followed by the thermal conductivity at thermocouple h2, and the one at thermocouple h3 is the highest. While for carbon brick, the thermal conductivities at h1, h2 and h3 are 14.28 W/(m·K), 15.35 W/(m·K) and 15.09 W/(m·K). Because most of the carbon brick are carbon with high thermal conductivity, its thermal conductivity is not sensitive to changes in temperature. Excluding the influence of heat flow intensity of cooling water on the experimental results, the thermal conductivity of refractories basically obeys the law of decreasing with increasing temperature. Moreover, although alumina-carbon composite brick owns high  $\text{Al}_2\text{O}_3$  content, its thermal conductivity is not much worse than that of carbon brick.

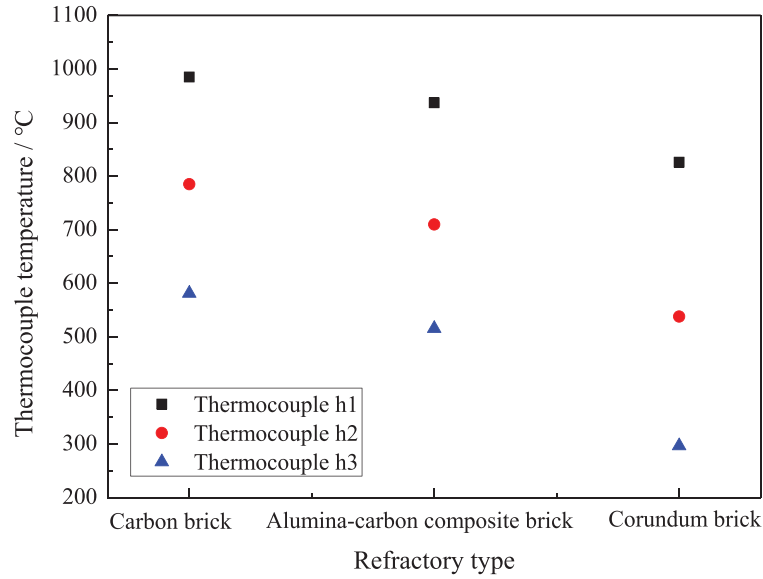


Fig. 9. Variation of thermocouple temperature vs. refractory type.

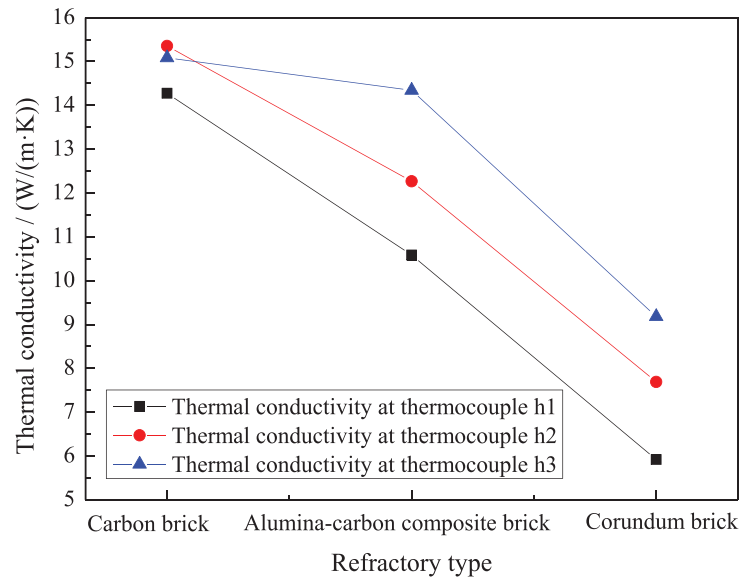
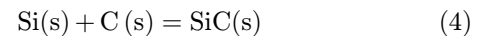


Fig. 10. Variation of thermal conductivity vs. refractory type.

### 3.5 Heat transfer mechanism of alumina-carbon composite brick

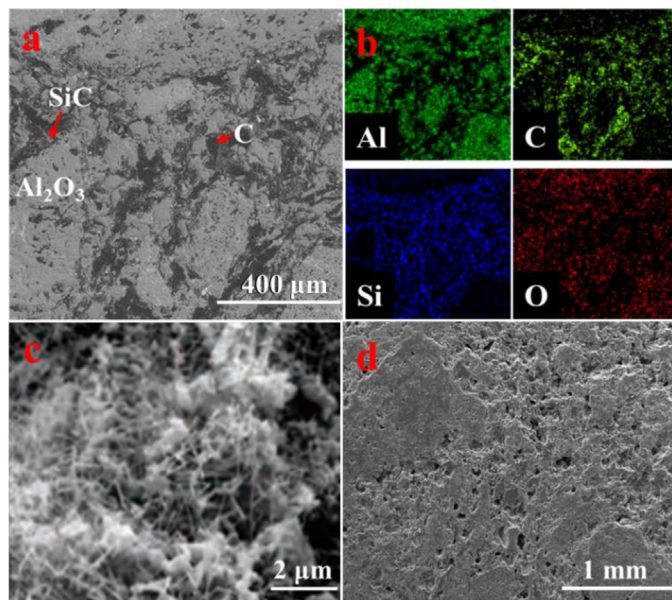
Based on the consequences illustrated in Figures 4, 6, 8 and 10, the thermal conductivity of alumina-carbon composite brick essentially follows the principle of decreasing with increase in temperature. The variation trend of thermal conductivity with temperature is related to SiC. The alumina-carbon composite brick contains a small number of free electrons, so the heat transfer is mainly depended on phonons generated by lattice vibration which counts on the degree of lattice vibration deviating from simple harmonic motion. As an endothermic reaction to generate SiC in situ as expressed in equation (4), increasing the temperature

causes the reaction to proceed in a positive direction, promoting the precipitation of more SiC in the brick. More SiC magnify the degree of lattice vibration deviating from simple harmonic motion, thus reducing the phonons transferring heat [24,25]. Therefore, the thermal conductivity of the alumina-carbon composite brick decreases with the increase in temperature.



Generally, the thermal conductivity of materials can also be confirmed as expressed in equation (5).

$$\lambda = (1 - p) \cdot \lambda_s \quad (5)$$



**Fig. 11.** SEM-EDS result of original alumina-carbon composite brick.

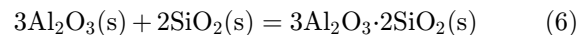
where  $p$  represents the porosity of the material, %;  $\lambda_s$  is the thermal conductivity of solid materials,  $W/(m \cdot K)$ . Therefore, the factors determining the thermal conductivity of alumina-carbon composite brick are mainly the thermal conductivity of each solid substance that constitutes the brick, as well as the porosity.

(1) The main components in the alumina-carbon composite brick are  $Al_2O_3$ , C, SiC and  $Al_6Si_2O_{13}$  (mullite).  $Al_2O_3$  and C exist interleaved, and SiC is generally located at the junction of  $Al_2O_3$  and C as manifested from **Figures 11a** and **11b**. For carbon possesses relatively high thermal conductivity, its dispersed distribution can improve the thermal conductivity of the alumina-carbon composite brick. In addition, carbon has a strong resistance to slag erosion,  $Al_2O_3$  owns a strong resistance to hot metal erosion, the combination of carbon and  $Al_2O_3$  can enhance the resistance of alumina-carbon composite brick to slag and hot metal erosion as a whole [26–28]. SiC, whether it is directly added or generated in situ by adding silicon powder, involving the SiC whiskers displayed in **Figure 11c** [11], has a higher thermal conductivity than  $Al_2O_3$ , and the resistance of SiC to both of slag and hot metal erosion is relatively great. However, it is not that the higher the content of SiC, the higher the thermal conductivity of the brick. Higher SiC content will reduce the heat transfer of phonons, leading to the decrease in the thermal conductivity of the alumina-carbon composite brick.

(2) It can be observed from **Figure 11d** that the surface of the alumina-carbon composite brick is relatively smooth, and the pore diameter is relatively small and evenly distributed on the brick, indicating that the brick is well calcinated. **Figure 12** shows the result of XCT detection, demonstrating the phase and pore distribution of original alumina-carbon composite brick. It can be observed that massive  $Al_2O_3$  emerges in irregular lump with large density, C is dispersed and densely distributed in the

brick matrix with small density, the pores are distributed pervasively in  $Al_2O_3$  and C, and at the junction between them, that is,  $Al_2O_3$ , C and the pores coexist with each other in the alumina-carbon composite brick. The distribution situation of aluminum, carbon and pores in the brick is shown in **Figures 12d**, **12e** and **12f**, it is more obvious that  $Al_2O_3$ , C and pores are tightly interlaced. The volume of pores is  $0.52 \text{ mm}^3$ , the porosity is calculated to be 2.42%. Lower porosity contributes to higher thermal conductivity, higher resistance to slag and hot metal erosion by reducing the penetration of slag and hot metal and the dissolution of carbon in brick, and higher strength by decreasing the actual stress.

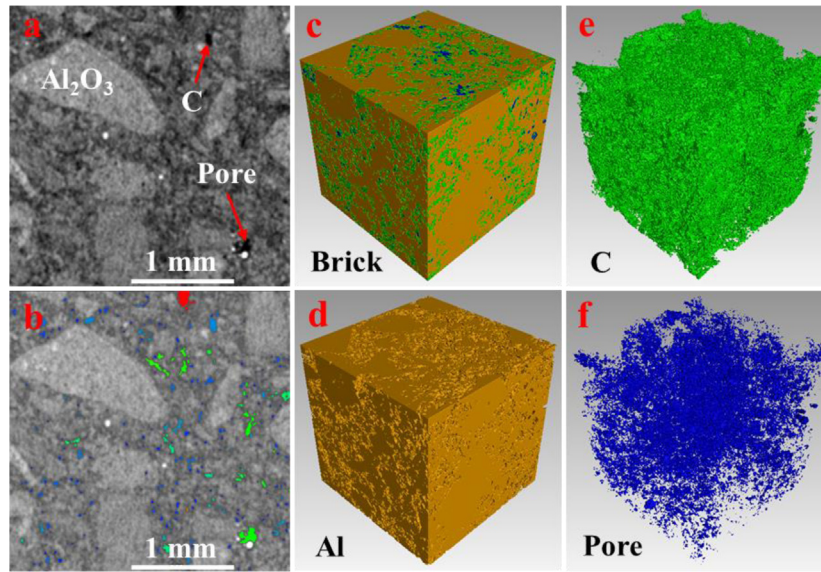
(3) The SiC whiskers generated in situ as equation (4) proceeds, can fill in the pores to reduce the porosity of the alumina-carbon composite brick. On the one hand, it is conducive to raising the thermal conductivity by lowering the porosity, and on the other hand, the brick's erosion resistance to slag and hot metal and strength is intensified. Besides, the  $Al_2O_3$  and silica additive will react to form  $Al_6Si_2O_{13}$  as equation (6) shows during the production process of the brick, which can block the pores and reduce the porosity of the brick [29]. Therefore, the thermal conductivity of the brick will also be improved.



Summing up the above analysis, in the case that alumina-carbon composite brick contains 73.05 wt.%  $Al_2O_3$ , and the thermal conductivity of  $Al_2O_3$  is relatively low, the brick has a higher thermal conductivity for the following reasons: (a) 10.20 wt.% C added into the brick is beneficial to improving the thermal conductivity of the alumina-carbon composite brick; (b) Well calcinated with small and uniform pores creates high thermal conductivity for low porosity; (c) Appropriate content of SiC whiskers generated in situ and produced  $Al_6Si_2O_{13}$  fills in the pores to decrease the porosity, thereby strengthening the thermal conductivity.

### 3.6 Analysis on alumina-carbon composite brick in a dissected blast furnace

The main chemical compositions and phases of alumina-carbon composite brick, skull, front slag-iron-coke, hearth slag-iron-coke, and cohesive zone coke collected from the Tongcai No. 2 dissected blast furnace are shown in **Table 4** and **Figure 13**, respectively. It can be seen that SiC is almost completely vanished, delaying the overall erosion of the alumina-carbon composite brick. The decrease in thermal conductivity caused by the increase of SiC content will be alleviated, that is, the thermal conductivity of the alumina-carbon composite brick will be improved. The  $Al_2O_3$  and C contents are lower than that of the original brick due to erosion of slag and hot metal, etc. The intrusion into brick lining of harmful elements of K, Na, S will also cause structure expansion, larger porosity, and increased cracks [30,31], hence the thermal conductivity of the brick is reduced accordingly. It is worth mentioning that Zn is not enriched in the skull and does not invade the alumina-carbon composite brick.



**Fig. 12.** XCT result of original alumina-carbon composite brick.

**Table 4.** Chemical compositions of samples from a dissected blast furnace, wt.%.

| Sample                         | Al <sub>2</sub> O <sub>3</sub> | C     | SiO <sub>2</sub> | CaO   | MgO  | K <sub>2</sub> O | Na <sub>2</sub> O | Zn   | S    |
|--------------------------------|--------------------------------|-------|------------------|-------|------|------------------|-------------------|------|------|
| Alumina-carbon composite brick | 58.84                          | 7.96  | 19.62            | 0.76  | 0.23 | 5.01             | 0.47              | 0.01 | 7.10 |
| Skull                          | 63.46                          | 8.64  | 16.23            | 0.10  | 0.13 | 10.30            | 0.97              | 0.01 | 0.16 |
| Front slag-iron-coke           | 11.13                          | 28.29 | 22.16            | 28.12 | 7.96 | 0.78             | 0.15              | 0.03 | 1.37 |
| Hearth slag-iron-coke          | 30.07                          | 7.79  | 29.52            | 25.14 | 4.51 | 0.46             | 0.61              | 0.02 | 1.89 |
| Cohesive zone coke             | 11.84                          | 68.60 | 9.29             | 8.24  | 0.72 | 0.05             | 0.17              | 0.02 | 1.06 |

It can be judged from the compositions and phases of the skull that it is kind of slag-rich layer, and the contents of Al<sub>2</sub>O<sub>3</sub> and C are higher than that of the brick after service, so it is conducive to maintaining the stability of the thermal conductivity of the brick lining and protecting the brick from further erosion. The K<sub>2</sub>O and Na<sub>2</sub>O contents, especially the K<sub>2</sub>O content, are higher than that of the brick after service, and much higher than that of front slag-iron-coke, hearth slag-iron-coke and cohesive zone coke, indicating that the alkali metals in the blast furnace will gradually be enriched in the skull and continue to erode into the brick. The formation of KAlSi<sub>2</sub>O<sub>6</sub> can cause the brick to expand, loose and porous, and also deteriorate the thermal conductivity of the brick in service. S will directly invade the alumina-carbon composite brick, causing damage to the brick.

The SEM-EDS diagram of alumina-carbon composite brick and skull composite shown in Figure 14 demonstrates that the closer to the interfacial surface, the smaller the Al<sub>2</sub>O<sub>3</sub> particles and the lower the Al<sub>2</sub>O<sub>3</sub> concentration, which exhibits the transfer process of Al<sub>2</sub>O<sub>3</sub> into the skull. Al<sub>2</sub>O<sub>3</sub> is continuously enriched in the skull, and when the content of Al<sub>2</sub>O<sub>3</sub> exceeds that of the brick and is stable, it can protect the brick lining and prevent the further deterioration of the thermal conductivity of the brick.

A large amount of K element is found in the brick and skull, and the concentration of K in skull is higher than that in brick, which is consistent with the results in Table 3.

Despite the presence of a large amount of KAlSi<sub>2</sub>O<sub>6</sub>, the integral matrix of the brick seen from Figure 14a is preserved basically intact, indicating that the erosion resistance of alumina-carbon composite brick to alkali metal is stronger than that of ordinary carbon bricks in practical applications to blast furnace. However, the alkali metal load into the blast furnace with raw material and fuels should be controlled within reasonable range, and the circulation and accumulation of alkali metal in the blast furnace should be reduced through the adjustment of the blast furnace operation, in the actual production process of the blast furnace. As a result, high thermal conductivity of alumina-carbon composite brick can be also guaranteed.

## 4 Conclusions

The thermal conductivity of alumina-carbon composite brick was measured by laser flash method and new device method to confirm the feasibility of the new device method. The influence of heating temperature of the heating furnace and cooling water flow on the thermal conductivity of alumina-carbon composite brick, and the comparison of the thermal conductivity of carbon brick, alumina-carbon composite brick and corundum brick were investigated to ascertain the heat transfer mechanism of alumina-carbon composite brick. Some samples taken from a dissected blast furnace, composing alumina-carbon composite brick, skull,

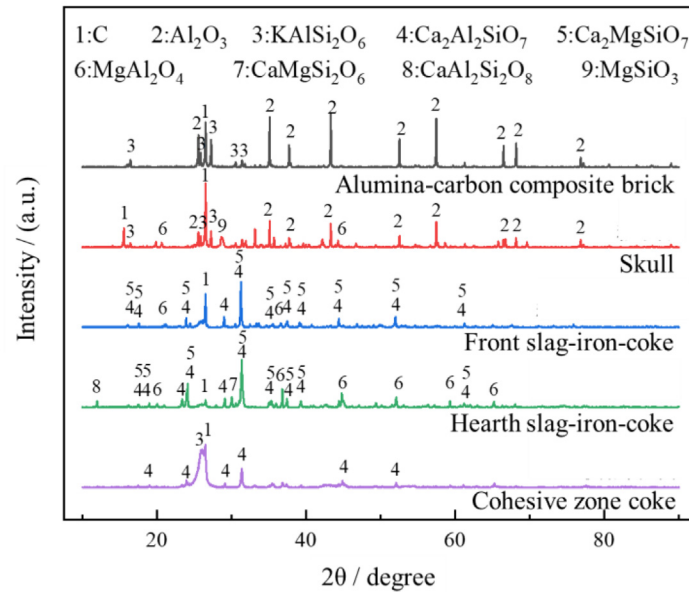


Fig. 13. XRD patterns of samples from a dissected blast furnace.

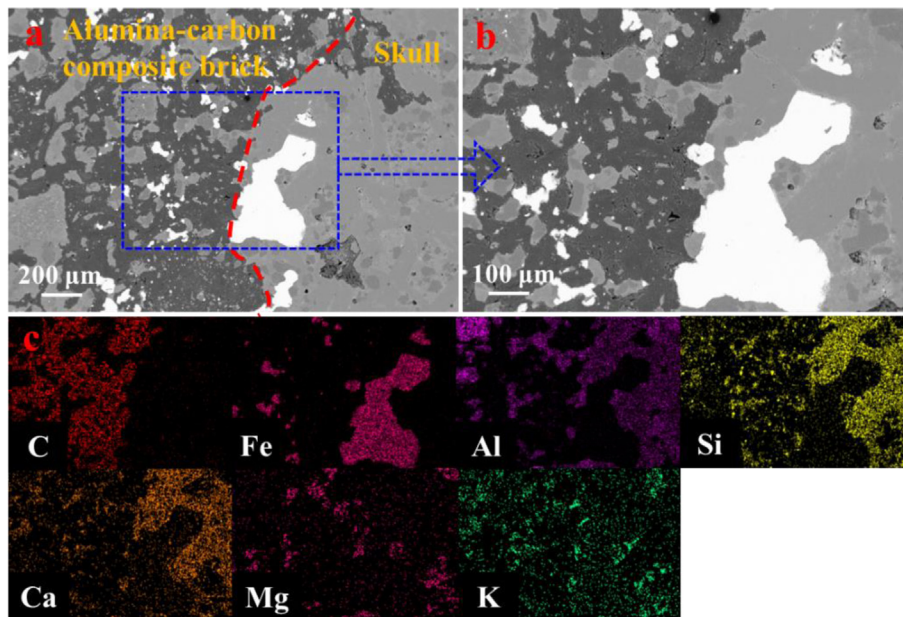


Fig. 14. SEM-EDS results of alumina-carbon composite brick and skull composite.

front slag-iron-coke, hearth slag-iron-coke, and cohesive zone coke were analyzed for illustrating the relationship between the erosion resistance and the thermal conductivity of alumina-carbon composite brick. The key conclusions were summarized as follows,

- The continuous decrease in the thermal conductivity of alumina-carbon composite brick detected by the new device method with increasing temperature correlates to that detected by the laser flash method, which proves the feasibility of the new device method for thermal conductivity measurement. However, the thermal conductivity measured by the new device method is lower than that measured by the laser flash method.
- The thermal conductivity of alumina-carbon composite brick decreases from 500 °C to 850 °C of the heating temperature of heating furnace, increases from 850 °C to 1500 °C. When the heating temperature is a constant, the thermal conductivity decreases with the increase in the temperature of the alumina-carbon composite brick itself, except for that at 500 °C, which is mainly resulted from the difference in heat flux intensity of cooling water and the heating temperature.
- The thermal conductivity of alumina-carbon composite brick increases from 900 mL/min to 1200 mL/min of the cooling water flow, then decreases from 1200 mL/min to

1500 mL/min. When the cooling water flow is a constant, the thermal conductivity decreases with the increase in the temperature of the alumina-carbon composite brick itself.

- The thermal conductivity of carbon brick, alumina-carbon composite brick and corundum brick at 1200 °C of the heating temperature of heating furnace and 1500 mL/min of the cooling water flow follows the reduction order:  $\lambda_{\text{carbon brick}} > \lambda_{\text{alumina-carbon composite brick}} > \lambda_{\text{corundum brick}}$ . However, the thermal conductivity of the alumina-carbon composite brick is not much lower than that of carbon brick, although the alumina-carbon composite brick possesses high  $\text{Al}_2\text{O}_3$  content up to 73.05 wt.%.
- The high thermal conductivity and erosion resistance to slag and hot metal of alumina-carbon composite brick benefits from, (a) reasonable composition combination of  $\text{Al}_2\text{O}_3$ , C,  $\text{SiO}_2$ , SiC et al, (b) dense structure, small pore diameter, and uniform distribution of the pores, (c) the generated SiC whiskers and  $\text{Al}_6\text{Si}_2\text{O}_{13}$ , which can fill in the pores and reduce the porosity.
- The analysis on alumina-carbon composite brick in a dissected blast furnace reveals that the SiC is almost completely vanished, the  $\text{Al}_2\text{O}_3$  and C contents are lower than that of the original brick, and harmful elements of K, Na, S invades the brick, which will influence the thermal conductivity of alumina-carbon composite brick in service.
- The hot surface of alumina-carbon composite brick is a slag-rich layer, higher  $\text{Al}_2\text{O}_3$  and C contents contribute to maintaining the stability of thermal conductivity of the brick and protecting the brick from further erosion, higher  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  contents indicate the transfer pathway of alkali metal, that is first enriched in the skull, then continued to erode into the alumina-carbon composite brick.

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