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# Study on the early warning mechanism for the security of blast furnace hearths

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**Abstract:** The campaign life of blast furnace (BF) hearths has become the limiting factor for safety and high efficiency production of modern BFs. However, the early warning mechanism of hearth security has not been clear. In this article, based on heat transfer calculations, heat flux and erosion monitoring, the features of heat flux and erosion were analyzed and compared among different types of hearths. The primary detecting elements, mathematical models, evaluating standards, and warning methods were discussed. A novel early warning mechanism with the three-level quantificational standards was proposed for BF hearth security.

**Keywords:** blast furnaces; hearths; erosion; heat flux; warning

## 1. Introduction

Blast furnaces (BF) will still play an important leading role for a long time owing to its advantages, such as large production capacity, high efficiency, low cost, high energy utilization, and mature technology. The problem of hearth safety is always the limiting factor for the long-life campaign and smooth operation of BF, in which the refractory always faces scouring by hot metal and slag with high temperature, erosion, and thermal stress damage. The burn through of hearths will directly lead to blowing-out as the BF campaign life ends. For the critical link between the campaign life and the condition of hearths, researches on prolonging hearth life have been done. For example, from the material preparation point of view, the refractory resistance to erosion by slag and hot metal is promoted [1-2]; from the heat transfer point of view, the design and refractory collocation are optimized [3-7]; from the operation point of view, the flow pattern of hot metal in hearths is controlled [8-11]. However, the problem of hearth safety is still increasingly prominent under the conditions of poor raw materials, frequent burden changes, and increased smelting intensity. Recently, many BFs at home and abroad have severe hearth erosion and even safety accidents of burn through. How to accurately monitor hearth erosion and establish a reasonable and effective early-warning mechanism of BF hearths has become a difficult problem for BF operators. The simplex or empirical warning standard is hard to satisfy multiple demands for security early warning of various hearths with different refractory, structure, and operational features. The requirement on monitoring hardware and the mechanism diagnosis model are still not unified. The warning standards and security mechanism for hearths are not yet clear. In order to solve this problem, in this article, based on the heat transfer calculations and online monitoring of heat flux and erosion for various hearths, the features of heat flux and erosion for different types of hearths were compared and analyzed. The primary detecting elements, mathematical models, evaluating standards, and warning methods for hearth security were discussed. An early warning mechanism of hearth security was proposed for modern BFs.

## 2. Analysis on the characteristics of heat flux and erosion for different types of BF hearths

BFs with different volumes always have different hearth types, which can be divided basically into three kinds. The principle feature of large-scale BFs is mainly

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the use of high-conductivity hot-pressed small carbon bricks or "thermal resistive" composite hearth with a low-conductivity ceramic cup and high-conductivity carbon bricks. Middle and small BFs mainly adopt the hearth using a ceramic cup with small moulded carbon blocks or micro-porous alumina carbon bricks with middle thermal conductivity. Some small BFs adopt all alumina-brick hearth with lower thermal conductivity. The total heat transfer performances of different types of hearths are obviously different. For the above-mentioned hearths, the online monitoring system is developed and applied, which contains the wireless hardware system for detecting the water temperature differences and heat flux of cooling staves at the hearth, the flexible thermocouple for detecting the brick temperature, and the mathematical model for diagnosing the 3D inner wear profile and skull layer in the hearth and bottom. Based on the actual monitoring results, it is found that the characteristics of heat flux and erosion are also different for different types of hearths.

Hot-pressed small carbon bricks with high thermal conductivity are mainly adopted at the sidewall of the "heat transfer method" hearth. The hearth sidewall is about 1.2 m thick, which consists of NMD bricks with 45-55 $W \cdot m^{-1} \cdot K^{-1}$ thermal conductivity near cooling staves and NMA bricks with 18-22 $W \cdot m^{-1} \cdot K^{-1}$ thermal conductivity near the hot face. During online monitoring of the hearth water temperature difference and total wear profile, it is found that the highest water temperature difference reached above 1.3°C corresponding to the heat flux above 30000 $W \cdot m^{-2}$ four years after blowing-in, which is much higher than the traditional heat flux warning standard (12000 $W \cdot m^{-2}$), even higher than the blowing-out standard (18000 $W \cdot m^{-2}$). However, the residual brick thickness of this "heat transfer method" hearth sidewall was still in control because of its high thermal conductivity. As shown in Fig. 1(a), the residual brick thickness at the most severe erosion region is about 750 mm corresponding to 30000 $W \cdot m^{-2}$ heat flux. It means that the "heat transfer method" hearth with higher thermal conductivity has the larger upper limit of safe working heat flux. However, attentions should be paid to the control of deadman state and circulation flow in the hearth to form a "self-protecting" skull layer, or else, a larger heat loss and a faster erosion speed will occur. By further calculating the temperature field, it is found that the 1150°C erosion line can be pushed away from the hot face of carbon bricks when the residual thickness is 750 mm if the circulation flow in the hearth is effectively controlled. The effects of hearth maintenance on the wear profile and skull formation can be directly monitored by the online model. As shown in Fig. 1(b), the skull layer has been formed by adopting some effective maintaining measures, when the water temperature difference of hearth cooling staves is about 0.4-0.6°C, corresponding to the low heat flux about 9300-14000 $W \cdot m^{-2}$.

Some BF in SHOUGANG achieves a long campaign life of 16 years and high-level unit production of 13000 t pig iron. It adopts a ceramic cup with all NMA bricks at the hearth sidewall. By online monitoring the water temperature difference and heat flux of cooling staves, calculating and analyzing the temperature field and erosion, it is known that the water temperature difference is low from 0.1 to 0.3°C, and the heat flux is from 2300 to 7000 $W \cdot m^{-2}$ in the early period of the campaign life. By heat transfer calculation, as shown in Fig. 2, the isothermal lines from 350 to 1350°C all get together in the ceramic cup because, at the early period, the thick ceramic cup has high heat resistance.

With the extension of service time, the ceramic cup is eroded gradually, so the water temperature difference and heat flux all increase. Especially when the residual bricks are only NMA bricks, the rising speed of heat flux starts to increase due to low heat resistance. However, a "self-protecting" skull layer begins to form when NMA bricks are eroded to some thickness, the hot face temperature is below 1150°C, and then, the heat flux falls back and becomes stable. The relationship between hearth residual thickness and heat flux was calculated by a mathematical model of the hearth temperature field, considering that the latent heat of hot metal solidification. The calculated results are shown in Table 1; while the actual detected historical highest heat flux value is 23746 $W \cdot m^{-2}$, and the average heat flux value one year before blowing-out is 14967 $W \cdot m^{-2}$.

By comparing the calculated values with the online monitor data of heat flux in the middle and late stages of this BF's campaign life, it is known that, when the most severe erosion happens, the residual thickness of the hearth sidewall is about 600-650 mm. The calculated temperature field shows that the 1150°C erosion line can be pushed away from the hot face of bricks when the thickness is 600 mm, as shown in Fig. 3, which means that the residual NMA bricks have reached heat transfer balance, and a "self-protecting" skull layer will be formed stably. This conclusion is proved by the actual monitoring results that, at the later stage of the BF's campaign life, the heat flux falls back and stably remains lower than the historical highest value.

Based on this monitoring practice and analysis, it can be concluded that the control standard of heat flux changes at different erosion states for a composite hearth. The key point for hearth safety is to form a dynamically balanced "self-protecting" skull layer when the heat resistance of the hearth decreases to some level, which should be defined by online heat flux monitoring data and calculated residual thickness and skull formation. That is, to establish the security early warning mechanism of a BF hearth, both accurate detecting hardware and a mechanism erosion model are essential.

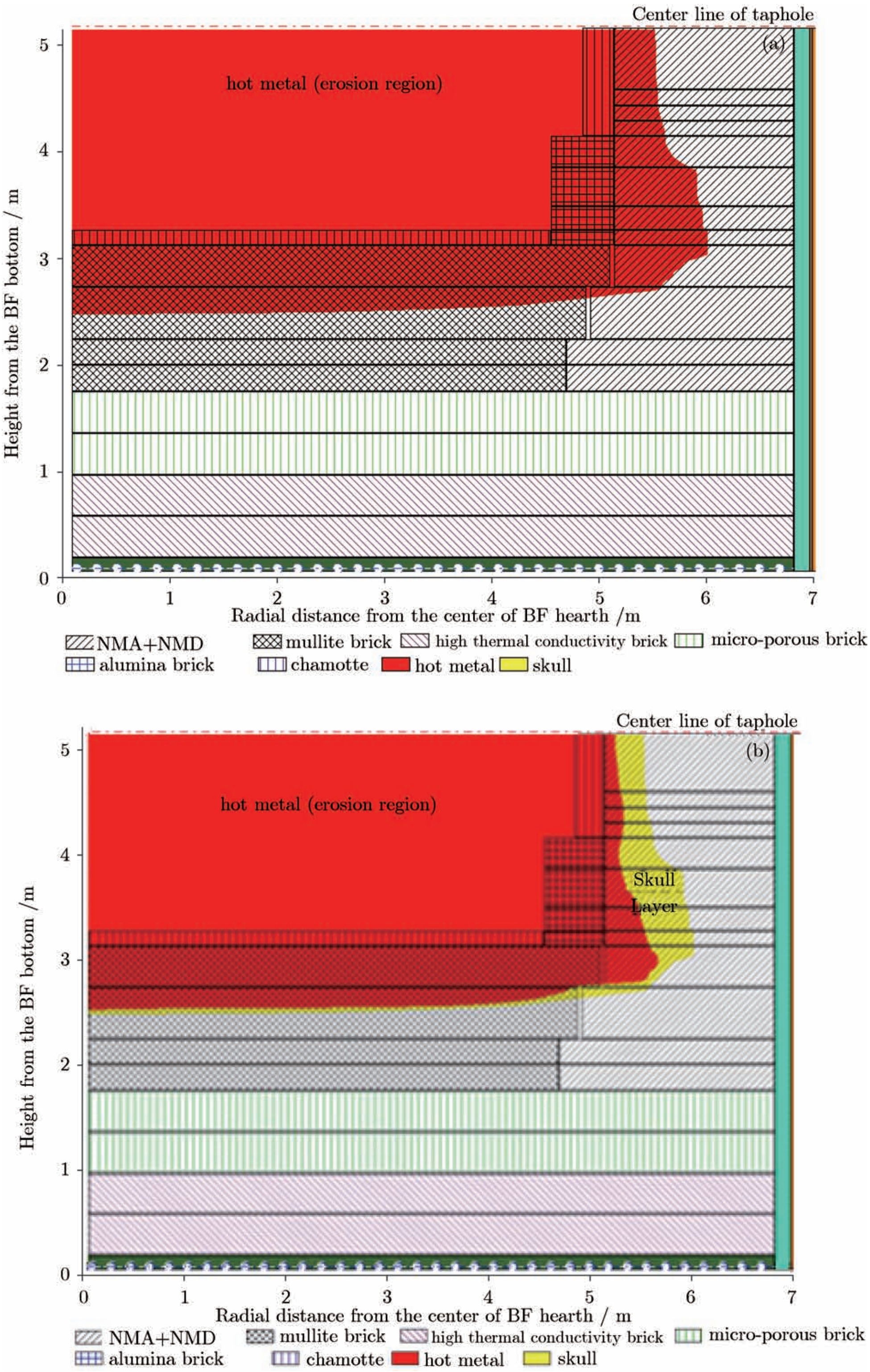

**Fig. 1. Wear profiles and skull changes of a "heat transfer method" hearth with different heat fluxes: (a) wear profile when the heat flux is 30000 W·m$^{-2}$; (b) erosion and skull profile when the heat flux is 12000 W·m$^{-2}$.**

Some middle or small scale BFs always adopt a ceramic cup with moulded carbon blocks or micro-porous alumina carbon bricks with the middle thermal conductivity of 8-12 W·m$^{-1}$·K$^{-1}$. Based on the monitoring data of heat flux and brick temperature, combined with erosion calculation, it is found that cooling water can hardly per-

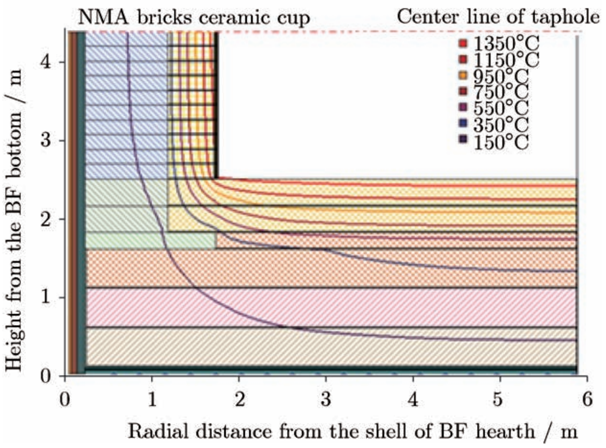

**Fig. 2. Temperature field of some BF hearth using the ceramic cup with NMA bricks at the early period.**

**Table 1. Calculated heat fluxes according to different erosion stages for some BF hearth using the ceramic cup with NMA bricks**

| Structures of the hearth sidewall at different erosion stages | Heat flux / (W·m$^{-2}$) |
|---|---|
| Original design | 2066 |
| Ceramic cup fully eroded | 12773 |
| Residual NMA bricks of 1000 mm | 15849 |
| Residual NMA bricks of 800 mm | 19749 |
| Residual NMA bricks of 600 mm | 25883 |

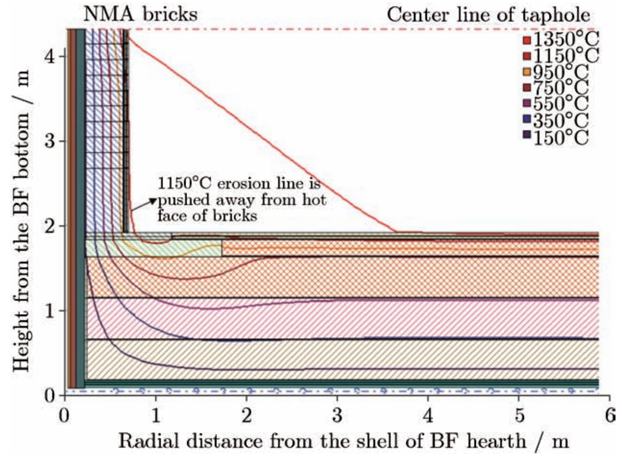

**Fig. 3. Temperature field of some BF hearth when the thickness of NMA bricks is 600 mm.**

form at the early period due to the thick ceramic cup with high heat resistance, corresponding to a very low water temperature difference below 0.1°C. The erosion of the ceramic cup is irreversible. When the ceramic cup is fully eroded, the 1150°C erosion line is still hard to be away from the hot face of carbon bricks because the residual bricks still have large heat resistance. Moreover, the 870°C brittle line is also deep into carbon bricks, so the hearth erosion is still aggravated, and the temperature of thermocouples in sidewall bricks also rises. The temperature of corner bricks arrives above 800°C just two years after blowing-in. The thinnest brick thickness at the hearth sidewall is only about 500 mm by erosion model calculation, while the water temperature difference is only 0.4°C, and the heat flux is 8720 W·m$^{-2}$. The sensitivity of heat flux to hearth erosion is low because this BF has some low thermal conductivity bricks and a thick padding layer. By temperature calculation, it is known that a skull layer can build up until the total thickness of bricks is smaller than 500 mm. Based on the online accurate monitoring of small heat flux, erosion diagnosis and in-time maintenances, the water temperature difference of this BF hearth decreases from 0.4°C to 0.2°C; also, the heat flux drops below 5800 W·m$^{-2}$ and becomes stable.

Some BFs adopt too thick padding layers (for example, the thickness of some designed padding layers is 150-200 mm) or padding materials with too low thermal conductivity (for example, the conductivity of some actually used padding materials is only 0.85 W·m$^{-1}$·K$^{-1}$ at 20°C and 1.36 W·m$^{-1}$·K$^{-1}$ at 300°C). The design disadvantages lead to insufficient heat transfer and quick erosion speed, while the water temperature difference is low and has response lag. Under this condition, the temperature of thermocouples in bricks should be basic data, and an erosion model must be used to monitor the changes of residual thickness and the skull layer.

The ring crack at the hearth sidewall often occurs after blowing-in by water ingress, large thermal stress, high load of alkali metal, and gas penetration into the wall. Once the ring crack forms, not only the water temperature difference of cooling staves at the hearth sidewall becomes insensitive but also the temperature of thermocouples in bricks becomes inaccurate, while the erosion in the hearth is aggravated. Under this condition, an online erosion model with knowledge base is built to judge the position of the ring crack and calculate the wear profile, which is verified by actual BF dissection, as shown in Fig. 4.

Air gaps will form between cooling staves and carbon bricks or between stave bodies and water pipes due to some reasons; for example, the moisture and volatile in padding materials are removed, the padding layer is not compacted, and the cooling stave deforms. Once the seemingly minor air gaps form, it will become the limit factor to heat transfer of the hearth and lead to severe erosion. The reason for this is that the thermal conductivity of air is only about 0.025 W·m$^{-1}$·K$^{-1}$, which is about 1/1000 of the cast iron stave or 1/100 of the ceramic cup. Under this condition, to realize accurate calculation and judgment of hearth erosion, whether and where air gaps exist must be judged according to heat flux and brick temperature changes, and then, an erosion model including knowledge base for abnormal conditions should be built for effective safety warning.

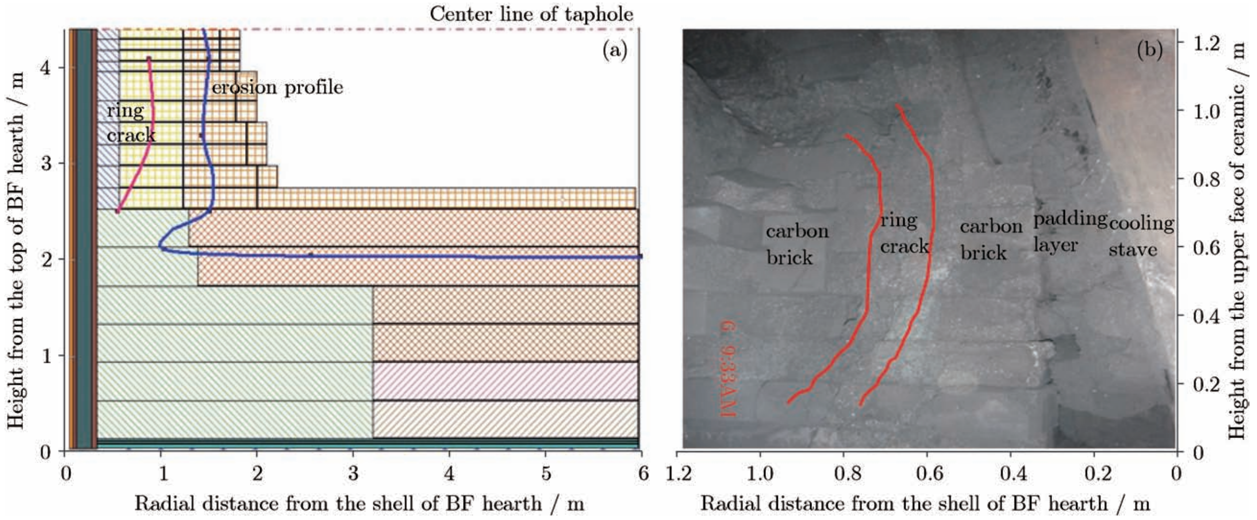

**Fig. 4. Diagnosed results (a) and dissection results (b) of the ring crack and wear profile in the hearth for some BF.**

## 3. Performance requirements for hardware and models of a hearth warning system

Based on the practice of erosion monitoring and safety warning for different types of BF hearths, it is found that both the heat flux of cooling staves and temperature of thermocouples in bricks are essential to be detected online. Meanwhile, an online 3D erosion diagnosis model must be built to calculate the wear profile and skull layer changes so as to clearly master the inner state of the hearth and the effectiveness of hearth maintenances. Furthermore, the knowledge base should be established in the erosion model to automatically judge possible abnormal situations during BF campaign such as ring cracks and air gaps. Performance requirements for hardware and models for a hearth safety warning system are discussed as follows.

### 3.1. Performance requirements for accurate detection hardware

The selection and layout of thermocouples in the hearth and bottom are listed as follows. (1) The layout of thermocouples should be optimized to satisfy the monitoring demands for the full campaign life, especially the key demands for taphole erosion, elephant foot erosion at the hearth corner and hearth activity, as shown in Fig. 5. (2) In order to improve the sensitivity of thermocouple temperature on inner erosion change, the radial insertion depth and the circumferential interval of thermocouples in bricks are decided by the thermal conductivity of hearth bricks, which means the larger thermal conductivity of bricks, the shallower radial insertion depth and the larger circumferential interval for thermocouples. (3) In order to reduce the damage of inbuilt thermocouples in the brick lining and to ensure the security and normal work of thermocouples during the whole campaign life, flexible N-type thermocouples are selected, which have a higher precision, a wider range, and a higher security than K-type. (4) In order to ensure long-term normal and stable work as well as the security of data transmission under the BF onsite conditions of dusts and high temperature, the technologies of concentrated extraction, anti-jamming highly integrated design, and bus transmission are adopted, as shown in Fig. 6.

The selection and layout for the monitoring system of water temperature difference and heat flux at the hearth are listed as follows. (1) In order to guarantee the sensitivity and accuracy of water temperature difference to erosion and skull changes in the hearth, especially for the monitoring requirements of a “heat insulation method” hearth, digital temperature sensors are selected, which have high precision and high stability. The measurement accuracy is recommended to be better than 0.05°C because the maximum error of water temperature difference is twice of the sensor precision. The accuracy of traditional temperature elements is only 0.1°C, and the error of water temperature difference is 0.2°C, corresponding to the error of heat flux above 2000 $\mathrm{W \cdot m^{-2}}$, while the change of water temperature difference for a “heat insulation method” hearth is always less than 0.1°C during operation fluctuation, even the highest water temperature difference is below 0.2°C in the whole service of some actual BFs. (2) It is suggested that a wireless transmitter acquisition of all the measured point data be built with a single communication bus of high-temperature resistance and high security under the conditions of much water vapor, high temperature, and lots of dusts on the BF site, as shown in Fig. 7. Using practice of this wireless monitoring system in more than 50 BFs has proved that the security and stability of this wireless system are significantly higher than a wired temperature measurement system. In addition, the construction and maintenance are much more convenient.

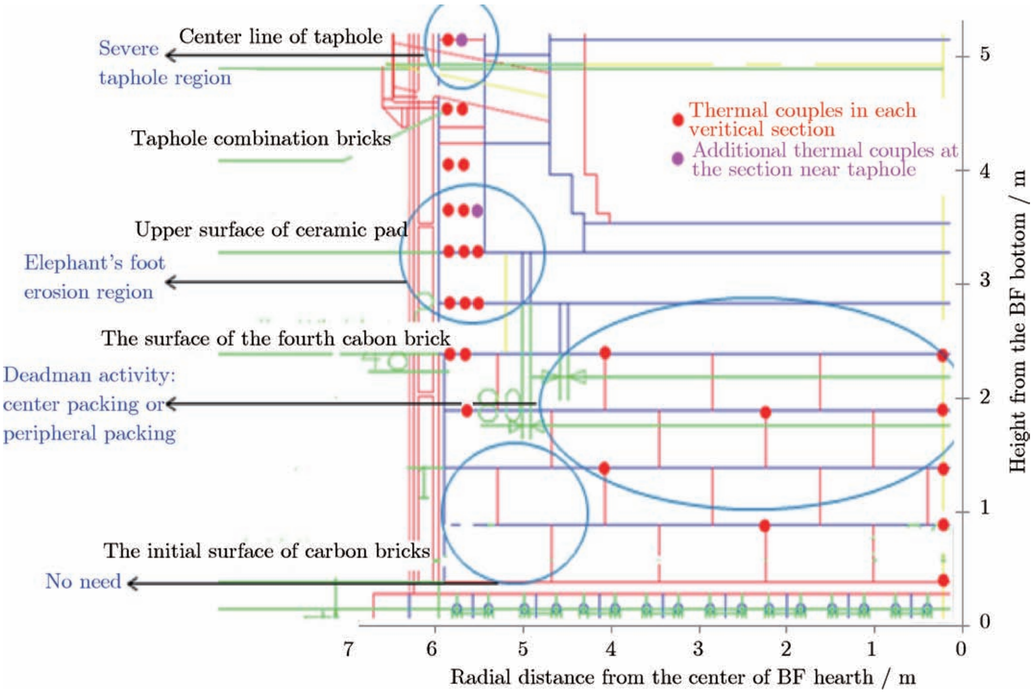

Fig. 5. Optimization for the layout of thermocouples in the BF hearth and bottom.

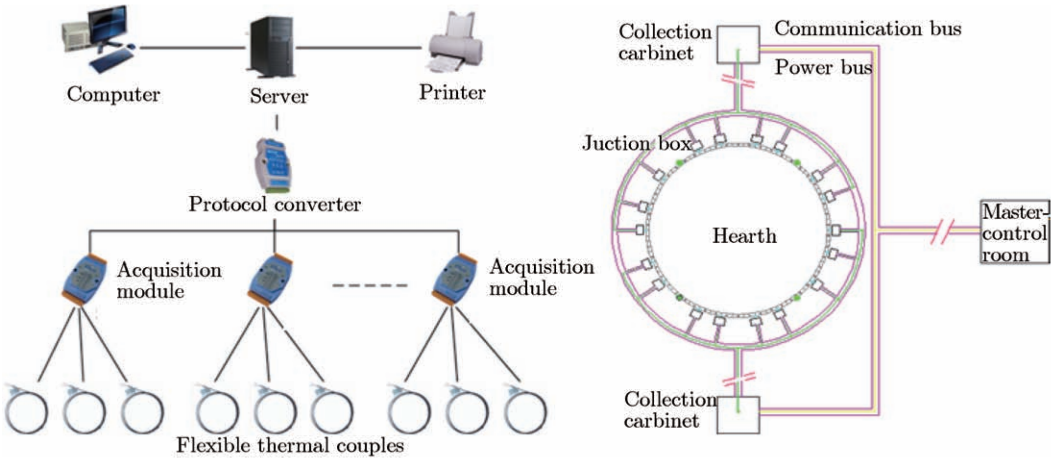

Fig. 6. Acquisition and communication system of brick temperature in the BF hearth and bottom.

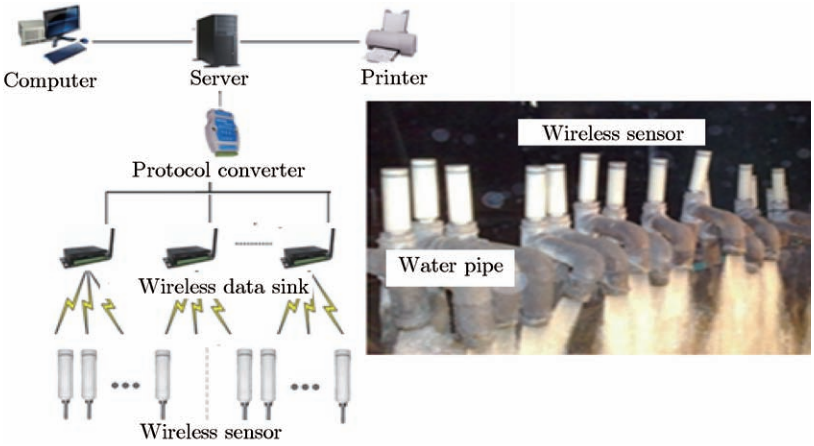

Fig. 7. Wireless acquisition and communication system of heat flux at the hearth.

Wireless surface temperature measuring devices attached on the BF shell are used at the "poor cooling" region and "monitoring blind" region of the BF hearth. The "poor cooling" region is the certain space between adjacent cooling staves at the BF hearth, where the sensitivity of water temperature difference to erosion change is low. Unfortunately, some BFs have severe erosion even burn-through just at this "poor cooling" region. In addition, the number of thermocouples in the hearth and bottom is usually limited, especially in the late period of BF campaign, a "blind zone" will form when thermocouples in this region are damaged. Therefore, temperature monitoring on BF shell temperature should be executed in order to achieve the overall monitoring of the hearth. An infrared temperature gun is mostly used to periodically detect shell temperature when the erosion of the BF hearth is severe, but this method has disadvantages of low detecting frequency, large error, and potential safety hazard for BF operators. Therefore, it is suggested that high-precision wireless attached temperature measuring devices should be installed in the "poor cooling" zone and "monitoring blind" zone. The accuracy of the devices is 1°C. The shell temperature can be detected automatically, and data can be transmitted wirelessly every minute. The devices can be used as important auxiliary security monitoring tools for the security of the BF hearth.

### 3.2. Performance requirements for intelligent diagnosis models and warning software

As mentioned above, safety warning standards are different for various hearths of different structures, refractory materials, and operational characteristics. Therefore, it is not reliable to solely rely on detection of hardware data to judge hearth security. In order to establish a reasonable and effective security warning mechanism of the BF hearths, a professional diagnosing model should be established on the basis of the erosion mechanism and heat transfer in the hearth and bottom. The intelligent diagnosing models and warning software should contain some functions listed as follows. (1) Real-time data transmitted from hardware is automatically acquired and filtered to ensure the accuracy of erosion calculation. (2) The hearth and bottom are automatically meshed, and the 3D non-steady-state temperature field and erosion are calculated considering the influence of the latent heat of hot metal solidification. (3) The erosion images of different cross-sections and the vertical sections in the hearth and bottom are reconstructed and displayed. (4) Abnormal conditions in the BF hearth and bottom are diagnosed automatically, such as ring cracks, iron penetration, and air gaps. (5) Intelligent diagnosis and maintenance measures are proposed based on different reasons for hearth erosion. (6) The location, thickness, and shape of the skull layer in the hearth and bottom are automatically calculated and displayed. (7) The most severe eroded parts of the hearth and bottom are alarmed to prevent hearth burn-through accidents.

## 4. Suggestions on the safety criteria and early warning mechanism for BF hearths

By erosion mechanism study and online monitoring of heat flux, thermocouple temperature, wear profiles, and skull change for lots of BFs, it is known that the monitoring values of different types of hearths are obviously different both at the burn-through stage and the ideal operation stage. However, the essence of realizing the long campaign life for different kinds of BFs is the same, and the 1150°C erosion line is pushed away from the hot face of bricks and the 870°C brittle line away from carbon bricks. Then, a "self-protecting" skull layer can build up and achieve the dynamic balance of formation-fall off-formation, leading to lower heat loss and stable heath flux and thermocouple temperature. Based on this, the safety criteria and early warning mechanism for BF hearths are listed as follows.

(1) According to the initial design of BF hearths and refractory properties, the eroding process of bricks at the hearth and bottom is simulated by heat transfer calculations. When the 1150°C erosion line and the 870°C brittle line are away from the hot face of bricks by analyzing the temperature filed, the criteria are established, which are called "balanced standards", including "balanced residual thickness", "balanced heat flux" and "balanced temperature of thermocouples".

(2) The heat flux and brick temperature are calculated and set as the "warning standards" when the thickness of residual bricks at the hearth sidewall is 350 mm, since the burn through of the BF hearth will probably happen with thin bricks due to some operational fluctuations or abnormal situations although a skull layer forms.

(3) The layouts of thermocouples in bricks, digital sensors of water temperature difference, and shell temperature detecting devices are optimized according to the BF hearth's structure and the erosion mechanism. N-type flexible thermocouples and wireless acquisition and communication systems for heat flux and shell temperature are suggested to be selected.

(4) An online 3D mathematical model with knowledge base and considering the latent heat of solidification is built to realize the intelligent diagnosis on possible abnormal situations, such as air gaps and ring cracks, to reconstruct a 3D image of the wear profile in the hearth and bottom, to judge the formation and fall off of the skull, and to draw the different isothermals.

(5) After BF blowing in, the "balanced standards" and the "warning standards" will be automatically modified by the erosion model when the abnormal conditions are judged by the knowledge base.

(6) The monitor data of thermocouple temperature and heat flux of cooling staves will decline with the formation of a skull layer after reaching the "balanced standards" and will gradually be stable. The stable values are defined as the "work standards".

Three-level quantificational standards can be set as the control criteria of hearth security, including "work standards", "balanced standards" and "warning standards" by erosion model calculating and monitoring. The changes of hearth monitor data during the campaign life of a BF are shown in Fig. 8. The online monitor data will rise in the early period because the erosion has not reached balance. Some measurements should be done when the monitor data come near the "balanced standards", such as the control of water quality and stabilization of smelting intensity. Then, after reaching the "balanced standards" in the middle period, the monitor data may decline due to the balance of heat transfer and the formation of a skull layer. The monitor data may also continue to rise due to some reasons. Then, in case of abnormal situations, the targeted measurements can be adopted by the diagnosed results of the erosion model, or adjustments for activating the hearth, improving the permeability, and restraining the circulation flow in the hearth are suggested without abnormal situations. The decline of monitor data can be expected by the adjustments. In the late period, if the monitoring values are obviously larger than the "balanced standards" due to erosion aggravation, maintenance, such as addition of Ti-compounds, proper production rate reducing, and coke load reduction are suggested, also the effects of maintenances can be judged by monitoring the position and thickness of the skull layer in the hearth and bottom. If the monitoring values are near the "warning standards", the enforceable maintenances are suggested, such as blocking the tuyere, greatly reducing the production rate, and even blowing-out to avoid safety accidents.

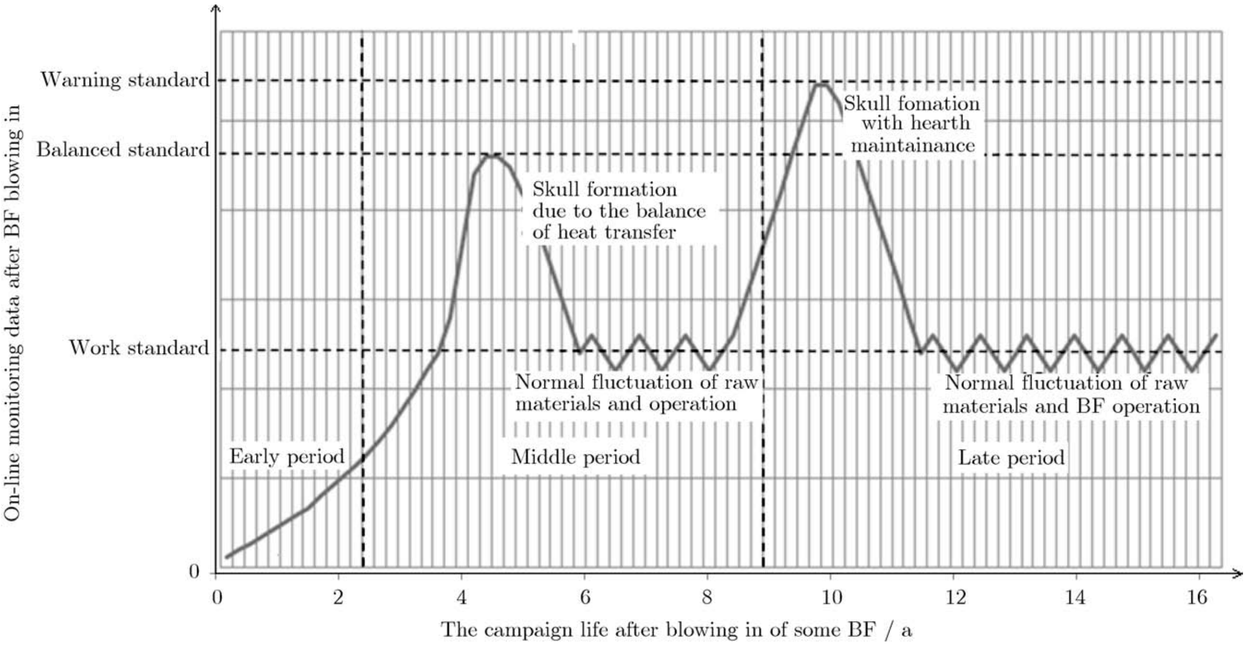

**Fig. 8. Schematic diagram of changes of hearth monitoring data during the campaign life of some BF.**

## 5. Conclusions

(1) The control standards and early warning criteria for various hearths are various because the actual maximum and the stable values of monitoring data are all obviously decided differently by different designs and refractory collocations.

(2) A reasonable early warning mechanism should be built not only based on the heat transfer characteristic of BF hearths but also on the judgments of abnormal situations, such as ring cracks and air gaps.

(3) The requirements of a hearth warning system for detection hardware are as follows. The layout of thermocouples in bricks should be optimized according to the erosion mechanism and monitoring demands, using N-type flexible thermocouples with high precision and long life. The wireless acquisition and communication systems for monitoring the water temperature difference and heat flux at the hearth should be adopted, which has high precision, high security, strong stability, and very convenient for construction and maintenance. Wireless surface temperature measuring devices attached on the BF shell should be added to ensure the safeties of the "poor cooling region"

and “monitoring blind region”.

(4) Due to the different heat transfer characteristics of various hearths, an online 3D mathematical model with knowledge base should be built to calculate and display the temperature field, wear profile, and formation and fall off of the skull in the hearth and bottom, so as to provide accurate and quantificational guidance on early warning for the security of BF hearths.

(5) The early warning standards should contain heat flux, thermocouple temperature, erosion thickness, and the skull. The three-level quantificational standards can be set as the control criteria of hearth security, including “work standards”, “balanced standards” and “warning standards” by erosion model calculating and monitoring. Different adjustments and maintenances can be adopted by comparing the online monitoring data with the three-level standards to realize the long campaign life and high efficiency of BF.

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