

# A Measuring System for Burden Surface Temperature Field of Blast Furnace <sup>\*</sup>

Jian-Qi An<sup>\*</sup> Min Wu<sup>\*</sup> Bo Wang<sup>\*</sup> Yong He<sup>\*</sup>

<sup>\*</sup> School of Information Science and Engineering, Central South  
University, Changsha, Hunan 410083, China  
(e-mail: min@csu.edu.cn)

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**Abstract:** It is important to measure the burden surface temperature of blast furnace (BF) since it can indicate the gas flow distribution and provide instruction for BF operation. The measuring system configuration based on multi-source information fusion is given in this paper to solve the problem of temperature field measuring in BF. As a result, the multi-source information feature extraction and fusion methods are proposed. Finally, the methods proposed have been applied to a 2200 m<sup>3</sup> BF. Real runs of the measuring system show that the proposed measuring strategy can give good and visible measuring for burden surface temperature field, which would be an effective method for controlling and monitoring in complicated metallurgy process.

*Keywords:* Information fusion; Blast Furnace; Burden surface temperature field

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## 1. INTRODUCTION

The steel industry which has significant effect on sustainable development is one of national key industry, but it is also with great resource, energy consumption and environmental pollution, see Wang et al. (2005) and Rasul et al. (2007).

Blast furnace (BF) is the key equipment in steel industry, and its steady running has great influence on the economic benefits of steel enterprises, see Cheng et al. (2003). However, BF is a typical 'black box' together with high temperatures, high pressure and dust, which leads that its inner state can not be measured directly.

The gas flow distribution in BF is one of the most important factors to influence BF production (Xue et al. 2008), and mainly reflected by the burden surface temperature field. So, the burden surface temperature field measuring is a critical process for gas flow development forecasting and BF operation optimization.

At present, many works have been done for burden surface temperature field distribution in BF. Jiao (2006) and Tu et al. (2004) have given some research on burden surface temperature distribution based on contacted crossing temperature device; and Ishimaru et al. (2005) and Gao et al. (2002) have described a non-contacted measuring method based on the infrared camera. But these studies only considered single measuring equipment, which can not fully reflect the real burden surface temperature distribution. For example, the crossing temperature device and BF wall thermocouple can only give the discrete information of temperature distribution and can't provide continuous information. Similarly, the infrared camera can

give continuous information but still has dead-zone in space. We can see that, the single measuring equipment can not provide the global information of the temperature distribution.

The multi-sources information which reflects the burden surface temperature field is fully used to improve the measuring accuracy, reduce measuring cost, and overcome the problems above. So a temperature field measuring system for BF based on all the available measuring equipments and information is developed in this paper. The system has been applied to a 2200 m<sup>3</sup> BF. The application results show that our method can accurately reflect the temperature distribution of burden surface, determine the abnormal BF status and give guidance for charge and other optimal operation.

## 2. PROCESS DESCRIPTION AND SYSTEM ARCHITECTURE

This section describes the burden surface temperature field measuring process and the configuration of the measuring system.

### 2.1 Measuring process

Blast furnace smelting is a process where charging is in the top and blowing is in the bottom. The ore and coke make an oxidation-reduction reaction with the warm air blow in the bottom so as to obtain the molten iron. The distribution of gas flow is very important in that process because it has an important influence on quality of the pig iron, utilization rate of the coke, and the status of the BF, see Yamamoto et al. (2007).

The temperature distribution of the BF burden surface is the direct embodiment of the gas flow distribution. It is shown in the BF process that the temperature is high where the gas flow is strong and the temperature is low

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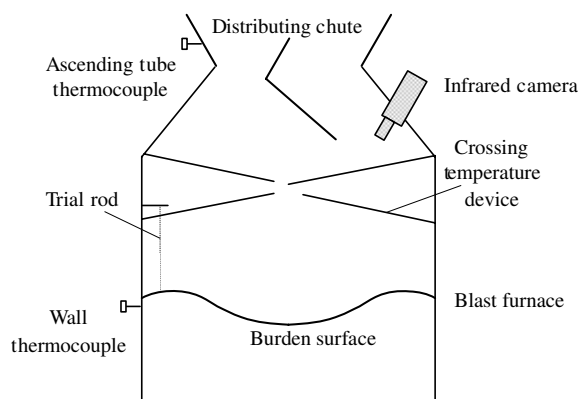


Fig. 1. The devices of burden surface temperature field

where the gas flow is weak. So the distribution of the gas flow can be described by the burden surface temperature field.

The measuring equipments of burden surface temperature field are shown in Fig. 1. The key equipments are crossing temperature device, infrared camera, ascending tube thermocouple, trial rod, wall thermocouple, and so on.

The infrared camera can film the gray-scale images of the burden surface which can reflect the temperature of the burden surface. However, the infrared camera can only film the central and middle area of the burden surface because of the dead-zone in space.

Crossing temperature device can measure the four directions radical temperature of the gas flow including the central area, middle area, and edge area. However, the value of measuring has the deviation contracted to the real value because the gas migrates when rising in the BF.

Many wall thermocouples are installed around the wall to measure the various wall temperatures. But it is hard to obtain the edge temperature by heat conduction calculation because it needs precise dimensions, coefficient of heat conduction, convection coefficient, and other parameters.

## 2.2 Measuring System Configuration

As shown in the former section, the burden surface temperature field can not be completely and accurately measured by using single equipments such as infrared images, crossing temperature, and wall thermocouples. This paper makes full use of the measuring information in the usual BF and builds the burden surface temperature field so as to fix the device of the single device. The measuring System Configuration is shown in Fig. 2.

First of all, infrared images and BF process multi-sources information are obtained from infrared camera and OPC sever based on PLC control module respectively, such as crossing temperature, BF wall temperature, ascending pipe temperature, gas composition, burden surface level, and distributing chute angle.

Secondly, feature extraction of measuring information is done, including feature of infrared images, ore-coke-ratio based on burden model, feature of radial temperature based on crossing temperature, and feature of edge temperature are acquired from feature calculating. Various

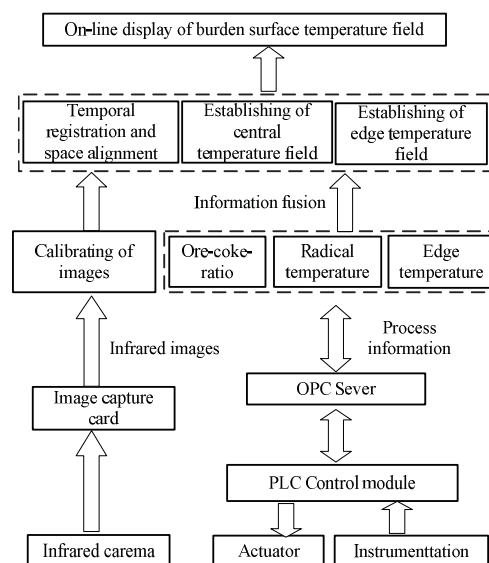


Fig. 2. Illustration of burden surface temperature field measuring System configuration

data feature are unified to the same detection time period by the least square method.

Third, temporal registration and space Alignment are done before fusion. Then central temperature field is acquired by fusing infrared images, crossing temperature, and ore coke ratio. In addition, edge temperature field is obtained by fusing crossing edge temperature, BF wall temperature, and ore-coke-ratio.

Finally, the whole temperature field model is acquired by composing the central temperature field and edge temperature field.

## 3. FEATURE EXTRACTION OF MULTI-SOURCE INFORMATION

Feature extraction is done with infrared images and process multi-source information. It contains that temperature calibrating, calculating of ore-coke-ratio based on charging parameters, radical temperature distribution based on crossing temperature, and edge temperature distribution based on wall temperature.

### 3.1 Image processing and temperature calibrating

Infrared images captured by infrared camera are the direct embodiment of thermal state in BF throat. However, the noise exists in infrared images because of hostile environment in BF. So the infrared images must be processed before used.

The partial noise can be eliminated from a group of infrared images by mean filtering based on time scale. Meanwhile, remaining noise can be effectively removed by mean filtering based on space scale because the adjacent pixels have a strong relevancy with each other, see Wiczorek. (2010).

The noise can be well restrained after the filtering based on time and space scale. Moreover, stationary of images is

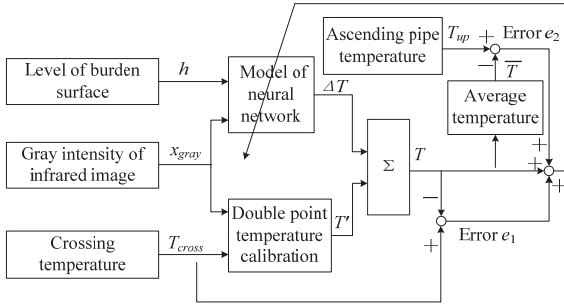


Fig. 3. Illustration of temperature calibration based on BP neural network

well maintained so as to establish burden surface temperature field.

Though infrared camera can film the gray images of the BF burden surface, it can not directly acquire the temperature value. So the relationship between the gray intensity and temperature must be established to transform the gray images to temperature images. In other words, temperature calibration of infrared images must be done.

Though the method of dynamic temperature calibration based on two points is easy, it is not accurate enough. Error compensation can be done to the dynamic temperature calibration based on the BP neural network. What's more, not only can the calibration accuracy be improved, but also it is easy enough and has a high convergence rate. Therefore, the method of temperature calibration based on two points and BP neural network is used to realize the transformation of temperature-gray in this paper, and the structure is shown in Fig. 3, see Liu et al. (2008).

Error compensation  $\Delta T$  of the temperature-gray can be obtained by training the BP neural network, and  $T'$  can be easily acquire by the method of temperature calibration based on two points. So the temperature of discretionary point in the BF burden surface temperature field can be figured out. The dynamic temperature calibration and on-line measuring of BF burden surface temperature field is realized according to the method of temperature calibration based on two points and BP neural network.

### 3.2 Ore-to-coke ratio calculation

BF burden surface temperature has the direct relation to the distribution of whole radical ore-to-coke ratio that can't be detected directly. Therefore, it is necessary to build the charging model to calculate the ore-to-coke ratio for the purpose of building the accurate burden surface temperature field, see Xu et al. (2005).

The paper has built a model with some 2200 m<sup>3</sup> BF on the basis of burden flowing theory. Firstly burden distribution model is calculated according to BF experimental data and charging experience. The function of BF burden surface can be described as

$$\begin{cases} z = a_0 + a_1x + a_2r^2, 0 \leq r < X_1 \\ z = b_0 + b_1r, X_1 \leq r < X_2 \\ z = c_0 + c_1r + c_2r^2, X_2 \leq r < X_3 \\ z = d_0 + d_1r, X_3 \leq r \leq X_w \\ r^2 = x^2 + y^2 \end{cases} \quad (1)$$

where,  $x$ ,  $y$ , and  $z$  is the horizontal, longitudinal and vertical coordinate of the burden curve respectively,  $a_0$ ,  $a_1$ ,  $a_2$ ,  $b_0$ ,  $b_1$ ,  $c_0$ ,  $c_1$ ,  $c_2$ ,  $d_0$ , and  $d_1$  are undetermined coefficients,  $X_w$  is the distance between BF center and BF wall,  $X_1$ ,  $X_2$ , and  $X_3$  can be fixed by experiential equation.

Secondly, curve function and undetermined coefficients can be obtained partly on the basis of material balance theory and BF running data. Then the function  $f(x, y)$  of burden surface curve can be acquired.

Finally, following Xu et al. (2005), the ore-to-coke ratio of point  $(x, y)$  in BF horizontal coordinate can be obtained based on the burden surface curve

$$OCR(x, y) = \sum_{i=1}^N \frac{(\Delta L_O)_i}{(\Delta L_C)_i} = \sum_{i=1}^N \frac{[f'_O(x, y) - f_C(x, y)]_i}{[f'_C(x, y) - f_O(x, y)]_i} \quad (2)$$

### 3.3 Burden surface radical temperature distribution

The Crossing temperature device is a bracket used to detect gas temperature in BF throat. Burden surface radical temperature distribution can be obtained by extracting the feature of the every crossing temperature point.

As shown in Fig. 4, the crossing temperature is mapped to the burden surface on the basis of space registry algorithm.

Since the circular cycle is adopted in BF charging system, the points that have the equidistant from the origin nearly have the same temperature in  $xy$  plane. Therefore, this paper adopts the algorithm as follow to fix every point of burden surface, and it can be explained by the example of the temperature of point  $(x, y)$  in Fig. 4. The steps are:

(1) In the radial direction of the crossing temperature, calculate the temperature between every two points by interpolation method. The interpolated temperature  $T_x$  that is near to  $t_i$  between the points  $t_i$  and  $t_{i+1}$  is given by:

$$T_x = t_i - (t_i - t_{i+1})/n, i \leq x \leq i + 1 \quad (3)$$

where  $n$  is the interpolation parameter.

(2) Give a distance  $R$  and find the nearest two points  $T_{xr}$  and  $T_{yr}$  on the  $x$  axis and  $y$  axis, respectively, that  $R = \sqrt{x^2 + y^2}$ .

(3) Calculate  $T_{xy}$  by:

$$T_{xy} = xT_{xr}/(x + y) + yT_{yr}/(x + y) \quad (4)$$

Radical temperature of every point in the BF burden surface temperature field can be obtained by the above method with crossing temperature.

### 3.4 Feature extraction of edge temperature

Since the modern large capacity BF has a big diameter, the infrared camera can not film the edge of BF burden surface, but it is closely concerned by the BF operators, see An et al. (2006).

The edge temperature of burden surface can be calculated by extracting the BF shaft wall temperature in the throat according to the BF shaft wall thermocouples and the theory of heat conduction. Suppose the BF shaft wall

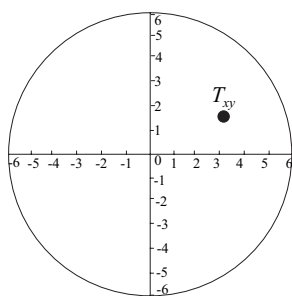


Fig. 4. Device of crossing temperature

conducts the heat from inside to outside by the style of one-dimensional conduction, and the BF shaft wall only is impacted by the conductivity of cooling water density and temperature. So the function of heat conduction can be described as

$$u_t - a^2(\rho, t) \frac{\partial^2 u}{\partial x^2} = f(x, t) \quad (5)$$

where  $u_t$  is the inside temperature of the BF,  $a(\rho, t)$  is the thermal conductivity of water,  $x$  is the radical offset of BF wall, and  $f(x, t)$  is the BF wall radical temperature distribution. The inside corresponding temperature  $u_t$  can be obtained from the above equation. Then the inside temperature can be converted to the burden surface temperature based on the difference between the level of burden and temperature point. It can be described as

$$u = u_t + (l_1 - l_2) \frac{du}{dx} \quad (6)$$

where  $l_1$  is the charging level of the BF, and  $l_2$  is the level of temperature measurement point.

#### 4. ALGORITHM OF MULTI-SOURCE INFORMATION FUSION

This section gives a detailed description to the algorithm of multi-source information fusion.

##### 4.1 Temporal registration

Multi-source information must be unified to the same temporal period before fusion because every feature of measurement information has different sampling period. The sampling period of the infrared images and charging model is 5 seconds, but that of other process data is 500 milliseconds. Other feature information can be registered to the same period by the least square method with the standard of sampling period of infrared images and charging models, see Han et al. (2006).

##### 4.2 Space Alignment

Since various feature information related to the BF burden surface detection have different angle and direction in space, they must be aligned to the same space for the information fusion. Infrared images need to be corrected to the burden surface plane based on the standard of burden surface in this paper because the angle is exist when the infrared camera films.

As shown in Fig. 5, the  $ABCD$  plane can be defined as the  $xy$  plane, and the corresponding coordinate system is

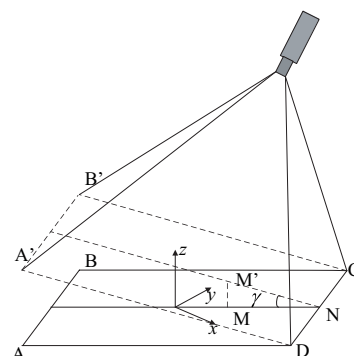


Fig. 5. Dimensional registration of images

$xyz$ . Meanwhile,  $A'B'CD$  can be defined as the  $x'y'z'$  plane, and the corresponding coordinate system is  $x'y'z'$ .  $x'y'z'$  can be obtained by rotating the  $xyz$  plane with the axis  $CD$ .

Equation (7) displays that point  $M'$  with the value of  $(x'_M, y'_M, z'_M)$  in  $x'y'z'$  plane can be aligned to point  $M$  with the value of  $(x_M, y_M, z_M)$ . So every pixel point of infrared images in spatial coordinate can be acquired.

$$\begin{cases} x_M = x_N - (x'_N - x'_M) \cos \gamma \\ y_M = y_N - (y'_N - y'_M) \cos \gamma \\ z_M = 0 \end{cases} \quad (7)$$

##### 4.3 Establishment of central temperature field

The central temperature field is the zone where the infrared images can be filmed. The factors that can reflect the burden surface temperature field are infrared images, crossing temperature, and charging model.

Since the detection dead zone of the infrared images that result in all black and all white zones, the accurate temperature distribution can not be obtained.

Fig. 6 is the model structure of central temperature filed distribution. The establishment of central temperature field in this paper can be described as follow: firstly, all black and all white zones are corrected by the radical temperature extracted based on the crossing temperature. Secondly, every gray intensity  $G(x, y)$  of the points in the BF temperature field can be obtained easily. Finally, every temperature  $T(x, y)$  of the points in the temperature field can be acquired by temperature calibration.

Since the charging model can reflect the status and tendency of temperature field, the central temperature filed distribution can be figured out by the ore-to-coke ratio  $OCR(x, y)$  and temperature  $T(x, y)$  of every point based on the algorithm of fuzzy information fusion.

##### 4.4 Establishment of edge temperature field

The distribution of edge temperature field is closely related to the burden loading, gas distribution, and utilization ratio of gas. However, the infrared camera can not film the edge of the large BF. So the temperature and the width of the edge temperature field are firstly calculated by fusing the temperature of edge thermocouples, crossing temperature, and the curve of ore-to-coke ratio. Then

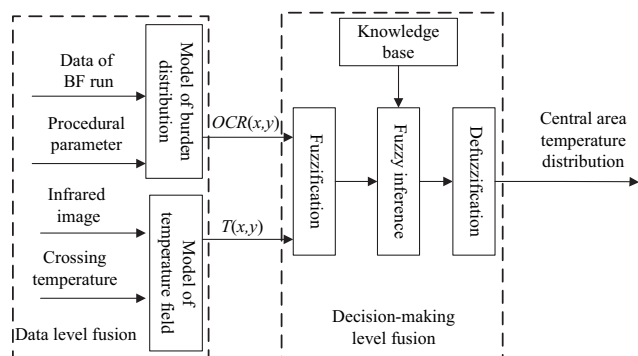


Fig. 6. Structure diagram of central area temperature distribution

the BF edge temperature field is obtained by fitting. Its specific handling method is shown in Fig. 7.

The temperature of the burden surface can be acquired by fusing the edge crossing temperature, charging level, and other multi-source information based on the methods such as neural network, fuzzy inference, and expert rules.

The width of the edge temperature field can be acquired by calculating the width of break over region on the ore-to-coke ratio curve based on the charging model.

Finally, the BF burden surface temperature field based on multi-source information fusion can be obtained by composing the central temperature field and the edge temperature field.

## 5. SYSTEM IMPLEMENTATION AND INDUSTRIAL APPLICATION

The method of measuring system implement and industrial application are described this section. The results of actual runs have demonstrated the validity of this method.

### 5.1 System implementation

According to the model of the burden surface temperature field, the measuring system is established by employing Visual C++ software. In addition the data is stored by SQL sever database to provide data to the system. Moreover the measuring system exchanges data to the process control system by OPC communication technology so as to make the measuring system become a part of the control system and realize on-line measuring of burden surface temperature field. The structure of the system implement is shown in Fig. 8.

The workstation computer of burden surface temperature field is the platform for realizing the measuring system. It is connected to the BF PCS7 control system by industrial ethernet and obtains the real-time process data. In addition the capture card OK-C30A of the computer can capture the infrared images for the measuring system.

According to the process data and infrared images in the BF, the paper establishes a measuring system based on information fusion so as to measure the burden surface temperature field accurately. Meanwhile, the system stores the associated data to the local SQL database to analysis and query. Therefore, the system can provide effective bur-

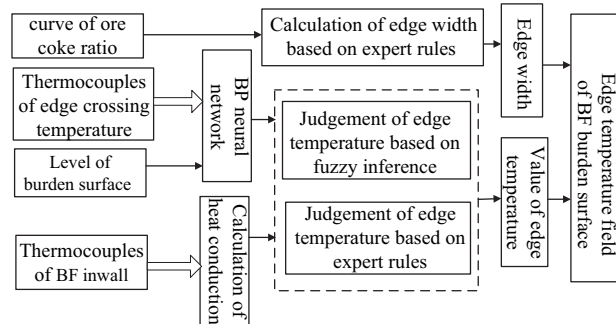


Fig. 7. Flow diagram of intelligent extraction to edge temperature field on BF burden surface

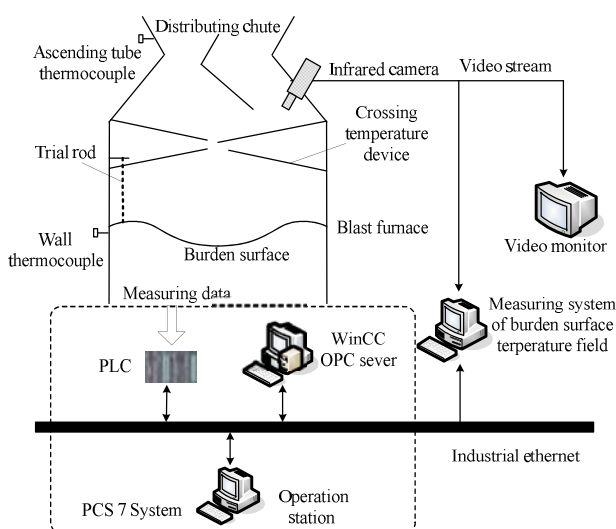


Fig. 8. Structure diagram of system implement

den surface temperature field information to BF operators by simple interface.

### 5.2 Industrial application

The on-line detecting system of BF burden surface temperature field is established in the 2200 m<sup>3</sup> BF in some iron-making enterprise based on the algorithm of this paper. The results of actual runs demonstrate that the system can accurately reflect status and trend of BF burden surface temperature distribution which can easily illustrate the gas flow distribution in the BF. Moreover, it can also help BF operators find abnormal BF status timely and guide the charging operation, which are necessary for the BF operation. The main interfaces of the measuring system are shown in Figs. 9 and 10.

The Fig. 9 is the crossing-shape interface of the measuring system, and the image in the top right corner is the original image of the BF. Besides, the Fig. 10 is the radical curve of burden surface temperature field.

It is shown that the system based on the information fusion not only compensates all black and all white zones of the infrared image but also adds edge temperature distribution to the temperature field. Moreover, it can reflect the radical temperature distribution easily. So the

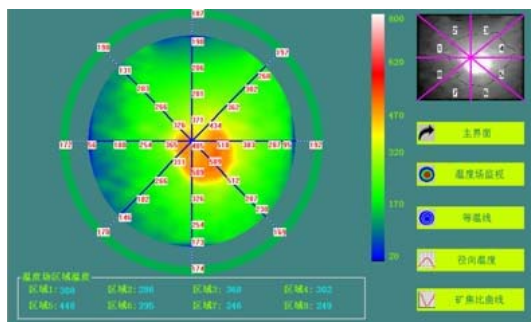


Fig. 9. Measuring results of burden surface temperature field

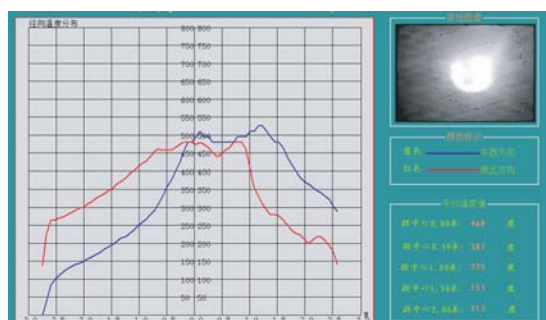


Fig. 10. Radical curve of burden surface temperature field system can truly measure the burden surface temperature field to guide the BF operation.

## 6. CONCLUSION

A measuring system for burden surface temperature field of blast furnace has been proposed in this paper. Multi-source information related to temperature field have been fully utilized and the information features have been extracted effectively. Besides, intelligent algorithms have been used to establish the burden surface temperature field. The system can provide an accurate detection of the burden surface temperature distribution, and it also can help BF operators discover the abnormal BF status and guide the BF optimal operation.

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