Uniformity and Activity of Blast Furnace Hearth by Monitoring Flame Temperature of Raceway Zone

Dongdong ZHOU, Shusen CHENG,* Ruixuan ZHANG, Yan LI and Tian CHEN

School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, 30 Xueyuan Road, Haidian District, Beijing, 100083 P. R. China.

(Received on February 17, 2017; accepted on April 26, 2017; J-STAGE Advance published date: July 11, 2017)

With the effective volume of the blast furnace is upsizing in recent years, the effective volume and the hearth diameter of largest blast furnace are reached to 5 800 m³ and 15 m in China, respectively. The numbers of raceway zones are increased from one dozen to several dozens, the hearth uniformity and the activity become more important for large blast furnaces. The uniformity and activity of hearth are very crucial to produce the high quality hot metal and prolong the campaign life of blast furnace, it also could influence the stability state and operation indexes of a blast furnace. Currently, there is still no effective evaluation system for estimating whether the hearth is uniformity and activity or not. In this paper, the Uniformity Index and Activity Index in the peripheral direction and local regions were proposed to evaluate the hearth condition by measured the flame temperature of raceway zones in 2 000 m³ and 2 500 m³ blast furnaces. The established uniformity and activity evaluation system for blast furnace hearth, not only has academic value in understanding the formation of raceway zone and combustion mechanism, but also has tremendous application values to estimate work state of hearth and maintain a stable state of the blast furnace.

KEY WORDS: blast furnace hearth; uniformity; activity; evaluation system.

1. Introduction

The hearth of the blast furnace is the starting and ending point of the smelting process, the work state of hearth could influence the campaign life, stable state and hot metal quality of blast furnace.1) It’s hardly to monitor the work state of hearth by direct way, so the auxiliary monitoring method such as thermocouple temperature,2–4) hot metal and slag tapping,5,6) hot metal temperature were used to estimate the work state of hearth.7) With the effective volume of the blast furnace is upsizing in recent years, the effective volume and the hearth diameter of largest blast furnace are reached to 5 800 m³ and 15 m in China, respectively. The numbers of raceway zones are increased from one dozen to several dozens, the amount of hot blast and coal injection rate are different in the various tuyere,8) causing the combustion conditions of coke and coal are different for various raceway zones. Consequently, the flame temperature of raceway zones are different. According to the calculation model of raceway zone,9,10) the gas pressures in different tuyere are also various, causing the size of raceway zones are different, affecting the first gas distributions in the blast furnace hearth.

The uniformity and activity of blast furnace hearth are very crucial to produce the high quality hot metal and prolong the campaign life of blast furnace, it also could influence the burden descend rate in the peripheral direction. Indirectly influence the utilization rate of CO, production cost, operation indexes and energy consumption of a blast furnace. If the uniformity and the activity of the blast furnace hearth are worsening, the permeability index of blast furnace will be decreased, the blast pressure will be increased, then the BF cooling water temperature will be increased, and the fuel rate per one ton hot metal will also be increased, while the tapping time will be decreased, the amount of tapping hot metal and slag in different tapping turn will be also unequal. On this account, some researches on uniformity and the activity of the blast furnace hearth has been made in recent decades.

Sasaki investigated the quenched No. 2 blast furnace at Kokura works, and found that the depths of various raceway zones were different. And the shapes and positions of cohesive zones for different tuyere were also different.11) Baosteel has proposed an active index to reflect the work state of blast furnace hearth,12) but it could just suitable to use in the Baosteel blast furnaces. Chen developed a new index to evaluate activity index of blast furnace hearth based on the flowing resistance coefficient of slag and hot metal,13) which is hardly being used to estimate the work state of blast furnace hearth because the calculated parameters are not easy to gain. Dai has modified the activity index of blast furnace hearth based on the Chen’s model,14) however, it also has the problem in obtaining the calculated parameters. Xu has

* Corresponding author: E-mail: shusencheng@hotmail.com

DOI: http://dx.doi.org/10.2355/isijinternational.ISIJINT-2017-091
established the activity index of blast furnace hearth based on the pressure difference and temperature of deadman, but it's also hard to get those two parameters.

From the above description, it is clear that the effective work state evaluate systems for the blast furnace hearth are still not established at present. It is necessary to establish the practical and effective system to obtain the evaluation system for the blast furnace hearth. The flame temperature of raceway zone could directly influence the melting slag and iron as well as heat transfer and mass transfer of furnace, which has a direct relationship with the work state of the blast furnace hearth. In this paper, the Uniformity Index and Activity Index in the peripheral direction and local regions were proposed to evaluate the work state of the hearth by measuring the flame temperature of raceway zones in 2 000 m³ and 2 500 m³ blast furnaces. Therefore, the digital imaging system based on the color CCD (Charge Coupled Device) is one of the effective methods applying in the temperature measurement field. The characteristic parameters of the flame radiations could be obtained from images which are captured by a vision-based radiation monitoring system. Then the temperature distribution of radiation images could be calculated. In this paper, the temperature of raceway zones of 2 000 m³ and 2 500 m³ blast furnaces was detected through a peephole in front of the blowpipe by the application of digital imaging and image processing techniques. In addition, the two-color method and partial least square method were used in the calculation model to improve the accuracy and the calculation speed. The results agreed well with the other measured temperature. The study will contribute to predict the work state of blast furnace hearth, improve the quality of hot metal and maintain the stable state of a blast furnace.

2. Theory

2.1. Temperature Calculation Method

The flame of raceway zone radiation is described by the Wien radiant law

\[ M_\lambda (\lambda, T) = C_1 \varepsilon(\lambda, T) \lambda^{-5} e^{-\frac{C_1}{\lambda T}} \] ........................ (1)

For the color CCD camera, the relationship of flame temperature and the gray level of the image is given by

\[
\begin{align*}
H_R &= N_R \varepsilon(\lambda_R, T) \frac{C_1}{\lambda_R^5 e^{\frac{C_1}{\lambda_R T}}} \\
H_G &= N_G \varepsilon(\lambda_G, T) \frac{C_1}{\lambda_G^5 e^{\frac{C_1}{\lambda_G T}}} \\
H_B &= N_B \varepsilon(\lambda_B, T) \frac{C_1}{\lambda_B^5 e^{\frac{C_1}{\lambda_B T}}}
\end{align*}
\] ........................ (2)

While the combustion flame of raceway zone is pulverized coal and coke, which could be assumed as graybody. The two-color method was used to calculate the temperatures of each pixel in the radiation images of raceway zones (T), and the expression can be written as

\[ T = -C_2 \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \ln \left( \frac{H_A}{H_B} - \ln \frac{N_M}{N_B} + 5 \ln \frac{\lambda_1}{\lambda_2} \right) \] ........................ (3)

In Eq. (3), the wavelengths of R, G and B are already known. The gray level of the two wavelengths can be obtained from the radiation images. The coefficients in the calculation model can be calibrated with a blackbody furnace. Then the temperature distribution and average temperature of raceway zone could be calculated.

2.2. Definitions of Uniformity Index and Activity Index

The 2 000 m³ and 2 500 m³ blast furnace has 26 and 30 tuyere, respectively. The two adjacent tuyere were assumed as one region, so that the 2 000 m³ blast furnace was separated into 13 regions in the peripheral direction, and 2 500 m³ one was separated into 15 regions, as shown in Fig. 1. Since the temperature distributions in various regions are completely different, in order to describe the hearth uniformity in i region, which is changed from 1 to 13 for 2 000 m³ blast furnace and 1 to 15 for 2 500 m³ one, as well as to compared the hearth uniformity between in different regions, the local Uniformity Index \( U_I \), of hearth can be written as

\[ U_I = \left\{ \begin{array}{ll} 100; & T_i - 1 \leq T_i \leq T_i + 1 \\
100 \sqrt{\frac{(T_i - T)^2}{n}}; & \text{other} \end{array} \right. \] ........................ (4)

While the Uniformity Index in the peripheral direction of the hearth is given by

\[ U_I = \frac{100}{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_i - T)^2}} \] ........................ (5)

Similarly, the local Activity Index in the peripheral direction of hearth gives

\[ A_I = \frac{T_i}{T_A} \] ........................ (6)

According to the temperate data measured in the actual blast furnace of 2 000 m³ and 2 500 m³, when the mean temperature in i region in the one period (T_i) of most regions is larger than that of 2 000°C, the permeability index, descending rate of burden and the hot metal temperature as well as surfer content were found under on good state. Consequently, the required temperature for the active state of the blast furnace hearth (T_A) is equal to 2 000°C in this paper. It must be appointed that T_A might change with burden conditions and operating parameters for different blast furnaces, especially for those of larger effective volume ones.

The Activity Index in the peripheral direction of hearth

Fig. 1. The division regions of 2 000 m³ and 2 500 m³ blast furnaces.
Above those definitions of Uniformity Index and Activity Index in the peripheral direction and local regions, the uniformity and activity evaluation system of the blast furnace hearth were established.

3. Experiments

3.1. Digital Imaging System Setup

The test environment of blast furnace has characteristics of high temperature and dust. Thus, the digital imaging system consisted by tuyere stocks with heat-resistant and dustproof functions, image acquisition system, data transmission system and image storage and data processing system. And the image acquisition system consisted of a lens and a DAHENG MER-125-30UC color CCD camera, its main parameters are shown in Table 1.

3.2. Calibration for Digital Imaging System

A blackbody furnace with temperature range from 1 000 to 3 000°C (with temperature errors within ± 2°C) was used to calculate the calibration coefficients, as shown in Fig. 2. A blackbody furnace was used to supply the radiation intensities at different temperatures, over the temperature range 1 500°C to 2 000°C, with steps of 100°C. The blackbody furnace consisted by furnace body, vacuum system, water cooling system, temperature control cabinet. The argon gas was used when the temperature of blackbody larger than 1 000°C, and the photoelectric pyrometer, which has calibrated by the National Institute of Metrology China, was used to calibrate the temperature of cavity temperature in the blackbody furnace. Table 2 gives the comparison of the calculated temperatures with setting ones of the blackbody furnace. The measurement errors are within 0.53%.

3.3. Monitoring of Flame in Blast Furnace Raceway Zone

The digital imaging system within heat-resistant and dustproof is installed in the front of the tuyere peephole of 2 000 m³ and 2 500 m³ blast furnaces, as shown in Fig. 3. The main parameters of those two blast furnaces are shown

Table 1. Main parameters of color CCD camera.

<table>
<thead>
<tr>
<th>Type</th>
<th>MER-125-30UM/UC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image resolution</td>
<td>1 292 (H) × 964 (V)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 fps</td>
</tr>
<tr>
<td>Sensor</td>
<td>1/3' Sony ICX445 CCD</td>
</tr>
<tr>
<td>Pixel size</td>
<td>3.75 μm × 3.75 μm</td>
</tr>
<tr>
<td>Spectrum</td>
<td>Color</td>
</tr>
<tr>
<td>Data interface</td>
<td>Mini USB2.0</td>
</tr>
<tr>
<td>Lens mount</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 2. Comparison of the calculated temperature with those of the blackbody furnace.

<table>
<thead>
<tr>
<th>Setting temperature/°C</th>
<th>Calculated temperature/°C</th>
<th>Error/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 500</td>
<td>1 497.186</td>
<td>−0.18</td>
</tr>
<tr>
<td>1 600</td>
<td>1 608.291</td>
<td>0.52</td>
</tr>
<tr>
<td>1 700</td>
<td>1 691.062</td>
<td>−0.53</td>
</tr>
<tr>
<td>1 800</td>
<td>1 799.723</td>
<td>−0.01</td>
</tr>
<tr>
<td>1 900</td>
<td>1 902.035</td>
<td>0.11</td>
</tr>
<tr>
<td>2 000</td>
<td>2 004.447</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Fig. 2. The sketch map of calibration process for digital imaging system.

Fig. 3. The diagram of blast furnace and the digital imaging system in the raceway.
in Table 3. When pulverized coal injected by lance and coke particles encounter with the hot blast, the combustion process will be occurred. Then the beam radiated by combustion flame will be projected to the tuyere peephole, which could be captured by digital imaging system. Since the temperature of raceway zone is about 2 000°C, and the combustion processes of coal and coke particles are occurring in the limited area of raceway zone, causing the radiation intensity is too high, which could lead the CCD camera oversaturated. In our study, the shutter speed, aperture size and gain of digital imaging system were considered, and the suitable combination of those parameters was chosen to ensure the CCD camera is not oversaturated.

Because the blast furnace has long smelting period and rapid variation with smelting conditions, the three different periods were chosen to gather the radiation images of the raceway zone in various regions. The interval time for each period are 8 hours, there has 5 images were chosen to calculate the mean temperature of each region $T_c$, while the sampling cycle of the image is 1 second. Then the mean temperature of all regions $T_c$ could be obtained, consequently, the local Uniformity Index (UI) and Activity Index (AI) for each region could be calculated according to the Eqs. (4) and (6). Similarly, the Uniformity Index (UI) and Activity Index (AI) in the peripheral direction of hearth could be calculated according to the Eqs. (5) and (7).

### 4. Results and Discussion

#### 4.1. Calculation of Flame Image Temperature in Blast Furnace Raceway

The flow chart to calculate the temperature distribution of raceway zone radiation images is shown in Fig. 4, the radiant image of flame was photoed by digital imaging system, the noises and distortion were eliminated by image processing techniques, and the brightness of radiation could be represented by the gray level of the image. Then the radiation level was obtained by optical model, blackbody temperature were calculated by Planck law and calibration process. Eventually, the temperature distribution of radiation images could be gained by graybody assumption. In order to reduce the errors, the two-color and partial least square methods were applied in the temperature distribution calculation process.

**Figure 5** shows the radiation images and temperature distributions of the raceway zones in different regions of 2 000 m$^3$ blast furnace in the first period of one image. The brightness of radiation images in different regions are distinct, the black area in the center of the image is the coal cloud which was formed by the pulverized coal injection, and its areas are different in various regions. Those phenomena could be explained by the combustion conditions in various regions are different. As we know, the distances of main blast pipe to tuyere stocks of each region are different, leading to the blast volumes of various regions are not equal. Moreover, the distances of the coal injection system to lances of each region are also different, causing the quantities of pulverized coal for various region are not equal.

In order to improve the accuracy of the calculated temperature, the black areas in the center of the images were removed. It also could be observed that the temperature distributions of the raceway zone in different regions are different, the temperature ranges of raceway zone is from 1 600°C to 2 450°C, and the average temperature of raceway zone is about 2 000°C. The results agreed well with the other measured results.$^{16,21–23}$ While the radiation images and temperature distribution of raceway zones in different regions of 2 500 m$^3$ blast furnace in the first period of one image is shown in Fig. 6. The black areas of coal cloud are larger than that of 2 000 m$^3$ blast furnace. Similarly, the radiation images and temperature distributions of raceway zones in second and third periods of 2 000 m$^3$ and 2 500 m$^3$ blast furnaces were also obtained.

#### 4.2. Local Uniformity Index and Local Activity Index

The local uniformity indexes were proposed to evaluate the uniformity of hearth in local regions, which could benefits to adjust the blast distribution and pulverized coal distribution of distinct regions in the hearth. **Figure 7** shows the local activity indexes of 2 000 m$^3$ and 2 500 m$^3$ blast furnaces in three different periods. The local uniformity indexes in three periods are different, the highest local uniformity indexes of 2 000 m$^3$ blast furnaces are 22.66 and 90.41, respectively. For 2 000 m$^3$ blast furnace, the local uniformity indexes of No. 8 to No. 13 regions are...
larger than that of No. 1 to No. 7 regions, it indicated that the uniformity of hearth in No. 8 to No. 13 regions are better than that in No. 1 to No. 7 regions. While for 2 500 m³ blast furnace, the local uniformity indexes of No. 1 to No. 8 regions are larger than that of No. 9 to No. 15 regions. From the above analysis, it is clear that the local uniformity indexes are different for different hearth regions, while the local uniformity indexes in various times are different for the same hearth region. It could be explained that the combustion conditions of various hearth regions in different time are different, because of the blast volumes and the quantities of pulverized coal which were changed over time, leading to the combustion conditions in the tuyere zone at various moments being different. Moreover, the local uniformity indexes of 2 500 m³ blast furnace are larger than that of 2 000 m³ blast furnace. That may be explained by the hearth diameter of 2 500 m³ blast furnace is larger than that of 2 000 m³ one, causing the differences of the blast volume and pulverized coal quantities of 2 500 m³ blast furnace are smaller than that of 2 000 m³ one. The conclusion that the local uniformity index of large effective volume blast furnace is better than that of small one.

The local activity index in various regions could benefit to judge the activity state of blast furnace hearth, which could affect the quality of hot metal and camping life of a blast furnace. Figure 8 shows the local activity indexes of 2 000 m³ and 2 500 m³ blast furnaces in three different periods. For the same hearth region, the local activity indexes in various times are different. For different hearth regions, the local activity indexes of all hearth regions in different time are also different. Most of the local activity indexes in two adjacent regions shown different tendency.

![Radiation images](image1)

![Temperature distributions](image2)

**Fig. 5.** The radiation images and temperature distributions of raceway zones in different regions of 2 000 m³ blast furnace in first period of one image. (Online version in color.)
According to the definition, the hearth activity in particle region is under active state when the local activity index larger than 1. Therefore, there has four active regions for 2,000 m$^3$ blast furnace and almost three active regions for 2,500 m$^3$ one. And the active regions concentrate upon No. 1 to No. 7 regions for 2,000 m$^3$ blast furnace and No. 8 to No. 14 regions for 2,500 m$^3$ one. The conclusion that the local activity index of small effective volume blast furnace is better than that of large effective volume one.

4.3. UI and AI

Compared to the local uniformity index and activity index, the UI and AI could represent the uniformity and activity state of the blast furnace hearth in the peripheral direction. Figure 9 represents the UI and AI of 2,000 m$^3$ and 2,500 m$^3$ blast furnaces in three different periods, the UI and AI are different in different time. It can be observed that the UI of 2,500 m$^3$ blast furnace is larger than that of 2,000 m$^3$ one, while AI of 2,500 m$^3$ blast furnace are smaller than that of 2,000 m$^3$ one. It indicated that the 2,500 m$^3$ blast furnace hearth in the peripheral direction is more uniform than that of 2,000 m$^3$ one, and the 2,000 m$^3$ blast furnace hearth in the peripheral direction is more active than that of 2,500 m$^3$ one. The conclusion that the uniformity in the peripheral direction of large effective volume blast furnace is larger than that of small effective volume one, and the activity in the peripheral direction of small effective volume blast furnace is larger than that of large effective volume one could be obtained.
5. Conclusions

Based on previous studies, the uniformity index and activity index in the peripheral direction and local regions were proposed to evaluate the hearth condition by measured the flame temperature of raceway zones in 2000 m³ and 2500 m³ blast furnace. The conclusion that the uniformity in the peripheral direction and local regions of large effective volume blast furnace is larger than that of small effective volume one, and the activity in the peripheral direction and local regions of small effective volume blast furnace is larger than that of large effective volume one could be obtained. The established uniformity and activity evaluation system for blast furnace hearth, not only has academic value in understanding the formation of raceway zone and combustion mechanism, but also has tremendous application values to estimate work state of hearth and maintain a stable state of the blast furnace.
Acknowledgement

The authors would gratefully acknowledge the financial support from the National Natural Science Foundation of China (No. 61271303, 61571040).

Nomenclature

\( M_\lambda (\lambda, T) \): spectral power of \( \lambda \) wavelength \((\text{W/m}^3)\)  
\( \varepsilon (\lambda, T) \): the effective spectral emissivity of radiation \((-)\)  
\( T \): temperatures of each pixel in the radiation images of raceway zones \((\text{K})\)  
\( C_1 \): first radiation constants of Planck \((\text{W·m}^2)\)  
\( C_2 \): second radiation constants of Planck \((\text{m·K})\)  
\( H_R, H_G, H_B \): the gray levels of R, G, B wavelength \((-)\)  
\( \lambda_R, \lambda_G, \lambda_B \): the wavelengths of R, G, B wavelength \((\text{m})\)  
\( N_R, N_G, N_B \): the calibration coefficients of the calculation model \((-)\)  
\( \varepsilon_R, \varepsilon_G, \varepsilon_B \): the emissivity of R, G, B wavelength \((-)\)  
\( U_{Ii} \): the local Uniformity Index of i region \((-)\)  
\( T_i \): mean temperature of five radiation images in i region in the one period \(\left(\text{°C}\right)\)  
\( T_c \): mean temperature of all regions in the one period \(\left(\text{°C}\right)\)  
\( UI \): the Uniformity Index in the peripheral direction of hearth \((-)\)  
\( n \): the number of the separated region for blast furnace hearth \((-)\)  
\( AI_i \): the local Activity Index of i region \((-)\)  
\( T_d \): the required temperature for active state of blast furnace hearth \(\left(\text{°C}\right)\)  
\( AI \): the Activity Index in the peripheral direction of hearth \((-)\)  

REFERENCES