Continuous Temperature Measurement of Liquid Iron and Slag Tapped from a Blast Furnace

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Abstract: Temperature measurements of liquid pig iron coming out of a blast furnace are essential for estimating the thermal condition in the hearth. The temperature is generally monitored by a disposable thermocouple on a runner. This paper proposes radiometric temperature measurement that targets an iron-slag-mixed stream in front of a taphole. It enables non-contact continuous thermometry. Liquid iron and slag are spatially separated on a thermal image obtained by a CCD camera with a high-speed electronic shutter. Molten iron temperature is calculated from the iron radiance detected automatically by means of histogram processing of the thermal image. Regarding optically semitransparent molten slag, its radiance varies as a function of the thickness. Slag temperature is determined from the highest radiance, presuming that the emittance of sufficiently thick slag converges on a constant. The authors performed an on-site test at a blast furnace in ordinary operation. It was confirmed that both iron and slag temperatures were continuously monitored. The temperature data obtained from the test showed findings such as unsteady temperature difference between the two liquids and discontinuous temperature fluctuation. This imaging thermometry technique is expected to be used in a new sensor for blast furnace operation.

Key Words: radiation thermometry, high temperature, thermal image, blast furnace, iron.

1. Introduction

In an integrated steel plant, a blast furnace (BF) produces molten iron as the initial step of the steel-making process. Thereafter, steel, which is refined from molten iron, is supplied to various types of product lines. Because the BF, known as the typical mass production process, is operated around the clock and manufactures more than 10000 metric ton of pig iron a day, well-controlled stable BF operation is extremely important for the steel plant. Although a large number of sensors such as thermocouples and pressure gauges are placed at the furnace body to predict the thermal conditions inside the BF, it is essentially difficult to insert a sensing device directly into the reaction field because of high temperature. Thus, the temperature of tapped molten iron is always monitored carefully as one of the few means of knowing the thermal conditions in the hearth of the BF.

The liquid iron is accompanied by molten slag, a by-product composed of several molten oxides, when flowing out at a tap-hole. The temperature of the liquid, roughly 1500°C, is intermittently measured with a disposable immersion-type thermocouple on a runner. To enable rapid and frequent measurement, another contact-type thermometry using optical fiber, which is directly immersed into the molten iron, was proposed by Yamada et al. [1],[2]. We developed a temperature measurement method using a CCD camera calibrated as a two-dimensional pyrometer for liquid metal in a smelting furnace [3],[4], and thereafter the authors conducted feasibility studies on its application to iron-slag-mixture stream tapped from a BF [5],[6]. Iron and slag can be distinguished on a thermal image of the tapped stream. The radiance emitted from molten iron depends only on the temperature. On the other hand, for molten slag, its radiance is related to not only temperature but also layer thickness because of its semitransparent optical property.

This paper presents the authors’ recent practical study on the simultaneous temperature measurements of iron and slag spouting from a BF. First, in Chapter 2, a situation of observing the high-temperature liquid discharged from a taphole is outlined, and the thermal radiation property of the liquid, including the semitransparent slag, is described. In Chapter 3, a radiation thermometry system comprising CCD cameras and an image processing PC developed for an on-site test is illustrated. In addition, temperature calculation algorithm such as recognition of representative radiances of iron and slag on a thermal image is explained. Finally, in Chapter 4, we discuss the experimental results that include findings about the liquid temperature behavior.

2. Measurement Object

A BF is a so-called huge chemical reactor. The inner volume of a large-size BF exceeds 5000 m³. A reductive reaction between iron ore sinter (Fe₂O₃) and coke (carbon), both charged from the top of the BF, occurs in the wake of hot-air injection through tuyeres. As shown in Fig. 1, high-temperature liquid comprising molten iron and slag falls in drops from the upper reaction zone and forms a pool at the hearth of the BF.

The taphole, which has a diameter of about 100 mm, is a horizontally drilled hole on the side wall of the BF to discharge the iron-slag-mixed liquid. The liquid has a temperature between 1400°C and 1600°C. Tapping continues for a few hours until
the liquid level inside the BF descends, and then the taphole is closed by a mud gun. The molten iron and slag flow through a runner, and the slag is separated from the molten iron at a skimmer located tens of meters downstream of the runner from the taphole. The temperature measurement of molten iron is generally performed by a factory worker at the skimmer using a disposable immersion thermocouple.

Radiation thermometry targeting the stream adjacent to the taphole is attractive because it enables continuous temperature measurement avoiding the influence of heat loss at the runner. However, this was considered difficult because of the mixture of iron and slag which have different emissivities. The mixing rate of iron and slag varies during tapping, and we have no knowledge of the mixing rate in real time; i.e., the effective emissivity required for precise pyrometry is unknown when utilizing an ordinary spot-measurement radiation thermometer.

In the initial stage of this study, it was clarified that two liquids, molten iron and slag, were spatially separated and made a marble-like pattern on the thermal image. This finding hinted the possibility of radiation thermometry using a two-dimensional radiometer. We utilized a commercially available camera with a visible-light CCD detector to obtain the thermal image for the following reasons. Figure 2 denotes blackbody spectral radiance at high temperatures exceeding 1400°C. The temperature dependence of the spectral radiance is significantly larger in visible light range than in long wavelength used by a commercial infrared camera; namely, the visible-light camera is suitable as a pyrometer for red-hot objects. Furthermore, the CCD camera has useful electronic control functions such as short exposure time and brightness adjustment.

The thermal radiation model of the stream is schematically illustrated in Fig. 4. In the case that the radiation source is an optically opaque iron surface, the emissivity is substance-specific constant, about 0.4 [7], and radiance $I$ is simply expressed as follows.

$$I = \varepsilon_i \times I_b$$

where $\varepsilon_i$ denotes emissivity of molten iron and $I_b$ denotes spectral radiance of a blackbody given by Planck’s law as follows:

$$I_b = \frac{2c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1} \ (W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1})$$

where $c_1 (W \cdot m^{-2} \cdot \mu m^{-3} \cdot sr^{-1})$ is the first radiation constant, $c_2 (\mu m \cdot K)$ is the second radiation constant, $\lambda (\mu m)$ is wavelength and $T (K)$ is temperature.

Regarding the semitransparent slag surface, combined two radiances are observed. One ($I_{iron}$) is emitted from the iron interface beneath the slag and penetrates the slag layer with attenuation. Lambert-Beer’s law is applicable to inner slag transmissivity. The other ($I_{slag}$) arises inside the slag. Inner slag emissivity is derived from Kirchhoff’s law, which states that the sum of the transmissivity and the emissivity is equal to one. Accordingly, the total radiance ($I$) is expressed in the Equation (2) as a function of the slag thickness.

$$I = I_{slag} + I_{iron} = (1 - r) \times (1 - e^{-kd}) \times I_b + (1 - r) \times e^{-kd} \varepsilon_i \times I_b = (1 - r) \times (1 - e^{-kd} + e^{-kd} \varepsilon_i) \times I_b$$

Fig. 1 Schematic structure of a blast furnace and high-temperature liquid tapping.

An example of the steam thermal image is shown in Fig. 3. The gray level of each pixel corresponds to radiance. The difference in emissivity between molten iron and slag causes spatial brightness distribution on the stream. The dark area of the pattern, i.e., lower emissivity material, is the molten iron. The gray level profile on the dotted line drawn on the thermal image indicates the following. While the gray level of the iron region is approximately constant, the gray level of slag fluctuates.

Fig. 2 Wavelength dependence of thermal radiation at high temperature.

Fig. 3 Thermal image of the stream.
where $k$ denotes absorption coefficient, $d$ denotes slag thickness and $r$ denotes slag-interface reflectance given by Fresnel equation as follows:

$$r = \frac{(n - n_0)^2}{(n + n_0)^2}$$

where $n$ and $n_0$ are refractive indexes of slag and atmosphere, respectively.

The slag absorption coefficient is essential to evaluate the thickness dependence of slag emittance. A solid specimen in the shape of a tablet was prepared to estimate the slag absorption coefficient at room temperature. The experimentally obtained absorption coefficient was $0.37 \, \text{mm}^{-1}$. The slag refractive index was supposed to be 1.5, by referring to similar elemental glass. Substituting these optical constants into Equation (2), the effective emittance of the semitransparent slag was calculated (Fig. 5). Depending on slag thickness, the effective emittance rises from 0.4, the emissivity of the iron surface, to 0.96. In the range exceeding a thickness of 10 mm, the effective emittance is stable at almost 0.96. Needless to say, the absorption coefficient of molten slag at around 1500$^\circ$C must not be the same. However the non-uniformity of the slag radiance in Fig. 3 can be explained qualitatively by this optical model.

### 3. Experiment

#### 3.1 Imaging Thermometry System

The authors performed a measurement test at a commercially-operating BF. As shown in Fig. 6, the BF has three tapholes (TH1, TH2, and TH3), which are located every 90$^\circ$ in the circumference direction of the BF body. Each taphole was monitored by a monochromatic CCD camera. The camera was placed at least a few meters away from the taphole and protected by an air-cooling jacket from harsh environments such as high ambient temperature and molten iron splash. The stream moves at a high velocity of roughly 5 m/s; thus the camera took the thermal image with a short exposure time of $1/10000$ s to avoid blurring. An optical bandpass filter, with a central wavelength of 650 nm, was attached to the camera lens. The distance between the cameras and image processing PC installed in the operating room is hundreds of meters, and hence the digitalized thermal image is transmitted to the PC via optical communication link. Each camera was individually calibrated as a pyrometer in advance. The temperature calibration was conducted utilizing a blackbody furnace. Figure 7 shows an example of the calibration curve. The 8-bit gray level of each pixel on the thermal image indicates the blackbody temperature of the object. The gray level rises exponentially with the temperature according to Planck’s law. The calibration curve is approximated by a polynomial approximate formula and memorized in the PC. The image processing software, which was developed for this test, calculates the iron and the slag temperatures in real time. The temperature readings obtained are displayed on a monitor as continuous temperature data and saved in the PC.

#### 3.2 Iron Temperature Calculation

Focusing on the gray level of the iron region on a thermal image, the iron temperature can be measured as mentioned below. Initially, the image processing PC calculates gray-level histogram. Figure 8 illustrates three examples of thermal images and their histograms. A gray level distribution lower than 60 on the histogram arises from dark background area. The
distribution of the bright stream is composed of partially overlapped gray levels of iron and slag. Although the histogram shape varies depending on the iron/slag mixture rate, the gray level distribution of molten iron consistently has a clear peak. The iron peak is considered to be the reliable representative value of the radiance of the iron. Automatic detection of the iron peak is not easy because the histogram sometimes has another confusing peak such as the slag peak shown in Fig. 8 (c). Here we utilize a empirical knowledge that the ratio of the iron peak and the maximum gray level ranges from 0.4 to 0.55. The iron peak can be unfailingly found in this limited scope. The brightness temperature is provided from the iron peak, and then, the iron temperature is obtained by means of emissivity correction. The constant emissivity of molten iron is set to be 0.4.

3.3 Slag Temperature Calculation

The same procedure for the iron temperature calculation cannot be applied for the slag temperature measurement because the emittance of slag is not constant, as mentioned in the previous chapter, and slag distribution on the histogram always has no explicit peak. The slag temperature was calculated from the maximum gray level on the stream image, by assuming that a part of the slag layer is optically thick. Because of the deficiency of high temperature data, we use the presumed slag emittance of 0.96 shown in Fig. 5, which is defined by optical constants at room temperature.

4. Results and Discussion

Figure 9 shows the comparison between intermittent thermocouple measurements, which were conducted at roughly 1-h interval during tapping, and the temperature readings obtained simultaneously by the imaging thermometry. There is a clear correlation in Fig. 9. The reason why the two temperatures do not agree absolutely is chiefly considered to be a discrepancy of the measurement locations. Because a plant operator manually immerses a disposable thermocouple probe in molten iron, the thermocouple measurement is made at the downstream runner, which is tens of meters from the taphole, to avoid danger of the splash of molten materials and poisonous gas leak. Meanwhile, the imaging thermometry observes the stream close to the taphole. The liquid flowing along the runner might be influenced by the heat loss. On the other hand, it is desirable to doubt iron emissivity. If iron emissivity is higher than 0.4, which is the value set in this test, the imaging thermometry temperature comes close to the thermocouple temperature. Therefore, the accurate estimation of iron emissivity will be a future task.

An example of continuous temperature data measured for a day by switching the three tapholes is shown in Fig. 10. Tapping schedule is decided by the situation of the BF operation such as the estimation of hearth liquid level, tapping flow rate, and runner refractory repair. The stream temperature fluctuates in each tapping. The instantaneous temperature drops in the data were caused by the optical obstacle with smoke generated near the taphole. The stream temperature typically increases with the descent of the liquid level in the hearth during tapping. This is because the hearth has vertical thermal gradient. However, various temperature patterns are observed. For example, the stream temperature monotonically decreased from 6.5 h to 8.5 h for unexplained reason.

In this study, slag emittance is suppositionally given by solid-state optical property. Even so, instantaneous fluctuation of slag temperature is not seen in Fig. 10. This fact implies that slag layer corresponding to the maximum gray level is optically thick and has a stable emittance.

The iron and slag temperatures are always similar to each other because of the heat exchange between the two liquids in turbulence flow. However, unsteady temperature difference, up to nearly 30°C, is confirmed as a newly found fact. In this case the two liquids might exist separately before being discharged.

Discontinuous large temperature drops are observed when switching the taphole from TH2 to TH1 at around 12.5 h and 19.5 h. The taphole TH1 and TH2 are located on the opposite
side of the BF body. This phenomenon implies that there are more than one regions with different temperatures in the hearth.

5. Conclusion

This paper presents radiation thermometry targeting a high-temperature liquid stream tapped from a BF and its on-site test. The newly developed imaging thermometry, which utilizes a thermal image taken with a visible-light CCD camera, features continuous temperature measurements of both iron and slag. The iron temperature is calculated by means of histogram processing. The slag temperature measurement is performed considering the radiation property of optically semitransparent slag. An on-site test was conducted in an operating BF. The temperature of the stream flowing out at three tapholes was successfully measured. The result shows previously unknown facts such as the fluctuating temperature difference between the two liquids and discontinuous change of the temperature. This imaging thermometry technique is expected to be the new information source for understanding the thermal conditions in the hearth of the BF.

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References


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