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Development of New Technique for Continuous Molten Steel Temperature Measurement

Masato SUGIURA*[1] Tsuyoshi YAMAZAKI*[2]
Ryuji NAKAO*[3] Tomoaki TANAKA*[4]
Seiji NAGATA*[1] Hiroyuki KUMAZAWA*[5]
Eiji TSUBOTA*[5] Wataru NAGAI*[5]

Abstract

In the production of steel in a smelting furnace such as a converter, to measure molten steel temperature is extremely important to both process control and metallurgical quality. Generally, sublance method is only utilized for direct measurement of the steel temperature. A disposable thermocouple probe attached at the tip of the sublance is intermittently inserted the steel. Nippon Steel developed a new continuous temperature measurement technique using 2-dimensional radiation thermometry. The molten steel is observed through a tuyere nozzle at the bottom of the furnace. Experiments were carried out on a laboratory steel bath, a stainless steel converter AOD and a scrap melting furnace. Efficiency of this continuous thermometry was clarified.

1. Introduction

At the refining stage of steelmaking, high-temperature molten steel is refined in a furnace lined with refractory material to prescribed chemical composition and temperature. Because the refining process consists of a series of chemical reactions and the reaction velocities depend on the temperature of steel, it is necessary to know the temperature accurately during the process. Temperature is very important also from the viewpoint of process control for judging the timing of the end of refining as steel temperature changes every moment. In a converter, for instance, oxygen gas is blown to molten steel and, as a result of exothermic oxidation reactions, carbon and other impurities are removed and steel temperature rises at the same time. 100 t or more of molten steel is processed in one heat of a large-capacity converter, but the time required for the proc-ess is only a fraction of an hour; steel temperature rises by approximately 200°C during the time period.

According to a method widely practiced at present, steel temperature is measured intermittently using a thermocouple probe mounted on a lifter called a sub-lance, and the temperature transition between the measurements with the probe is estimated using a mathematical model. In this method, which was developed in the 1960's, a consumable thermocouple is immersed in molten steel and its temperature is measured during the short period until the thermocouple is fused. While accurate and reliable temperature measurements are possible by this method, because of restrictions due to the change of probes, their costs and so forth, temperature can be measured only a few times during a process cycle. Problems of not hitting target chemical composition and/or prescribed end-point temperature may sometimes occur for this reason.

In the above background, a technology to continuously measure the molten steel temperature has long been awaited. A method in which a temperature-sensing element such as a thermocouple is immersed directly in molten steel is not suitable for the continuous tem-

*[1] Environment & Process Technology Center
*[2] Hirohata R&D Lab.
*[3] Hikari R&D Lab.
*[4] Hikari Works
*[5] Hirohata Works

perature measurement because materials having such a high thermal resistivity are not available. Therefore, radiation thermometry to measure thermal radiation not contacting the object is promising. There have been some reports on the methods of radiation thermometry by which the measurement is done through an observation nozzle that is provided through the bottom of a refining furnace [1,2].

This paper discusses, first, the technical problems related to the measurement of thermal radiation from molten steel in a furnace and then presents a newly developed technique of radiation thermometry for molten steel to solve the above problems [3,4]. The new technology, wherein 2-dimensional radiation thermometry is combined with an image processing technique to automatically detect molten steel, is capable of continuously measuring temperature as accurately as the thermocouple method and has a practical advantage of being little influenced by the change of a field of view.

2. Difficulty in Measuring Thermal Radiation of Molten Steel in Furnace

The radiation thermometry is a method of measuring the temperature by measuring the intensity of thermal radiation emitted from an object. Since the method enables non-contact, high-speed and remote measurement, it has been practiced in various fields of industry including the steel industry.

When an object can be considered to be an ideal radiator which is called a blackbody, its spectral intensity is expressed according to Planck's low of radiation by the following equation:

$$L_b(\lambda, T) = C_1\lambda^{-5}\frac{1}{\exp(C_2/\lambda/T) - 1} \quad (1)$$

where, λ is wavelength,
T is the temperature (K) of the object, and
C_1 and C_2 are the first and second constants, respectively, of blackbody radiation.

When the observed wavelength λ is fixed, Equation (1) becomes a function of the temperature T only and therefore, the spectral intensity $L_b(\lambda, T)$ increases monotonously as the temperature T rises. Thus, temperature can be calculated accurately from the spectral intensity measured with a radiometer.

However, no material of the real world is a blackbody, and the spectral intensity L_λ of a real material measured with a radiation thermometer is given as:

$$L_\lambda = \varepsilon_\lambda L_b(\lambda, T) + \beta(1 - \varepsilon_\lambda) L_b(\lambda, T_s) \quad (2)$$

where, ε_λ is the spectral emissivity of the surface of the object,
β is a coefficient expressing the ratio in which back ground radiation from surrounding materials reflected at the surface of the object is detected, and
T_s is the temperature (K) of the surrounding.

From the above, it is necessary to know the value of the spectral emissivity of an object beforehand. In addition, if the temperature T_s of the surrounding materials is higher than that of the object, then a stray light noise error occurs where the background radiation from the surroundings is observed together with the radiation from the object. The coefficient β varies depending on the positions of the background radiation sources, their sizes and the reflection characteristics of the object surface, and it is usually extremely difficult to accurately quantify it.

The authors examined the application of the radiation thermometry to molten steel in a steelmaking furnace in consideration of the above. **Fig. 1** schematically illustrates a steel refining furnace such as a converter. An observation method through the furnace top opening with a radiation thermometer corresponds to the situation expressed by Equation (2). The emissivity of molten steel in a wavelength band of red to near infrared, which is suitable for radiation thermometry, is approximately 0.4 [5], but the value is influenced by the fluctuation of emissivity and stray light noise. A high-temperature combustion point is formed by the top-blown oxygen gas and this, among others, is considered to constitute a source of violent stray light noise. In addition, slag, which is a mixture of molten oxides, floats on the molten steel surface in most cases, and the emissivity of slag is known to be different from that of molten steel. Further, because much dust is generated inside a furnace, the radiation from molten steel is attenuated in its path to a radiation thermometer. Owing to these problems related to the principle of measurement, accurate radiation thermometry through the furnace top is considered impracticable.

As an effort to solve the above problems, the authors employed a method of radiation thermometry wherein a nozzle is provided through the bottom of a furnace and the measurement is done while an inert gas is blown through the nozzle. The inert gas is blown from outside the furnace at a prescribed pressure and let go into the molten steel. Such gas injection through a furnace bottom nozzle has long been practiced in steel refining. When the flow rate of gas is sufficient for preventing molten steel from coming into the nozzle, the gas blowing out from the nozzle forms a gas column in molten steel, and the height of the gas column is kept equal to or more than a certain value. Then, conveniently, thanks to the multiple reflection of emitted light within the gas column, the portion of molten steel to be observed forms a pseudo-blackbody called a cavity blackbody. Thus, a condition theoretically ideal for radiation thermometry is realized, where emissivity is kept stably high and there is no stray light noise.

There are, however, difficulties in practicing this measurement method. The situation of observing molten steel through a nozzle is illustrated in **Fig. 2**. While the thickness of the refractory lining is 500 mm or more even in a small-size furnace, the inner diameter of the nozzle should not exceed 20 mm in consideration of the costs of the injected inert gas, which is lost into the molten steel, and its supply system. As a consequence, the observation has to be done through a pipe having a very large length/inner diameter ratio. The nozzle is

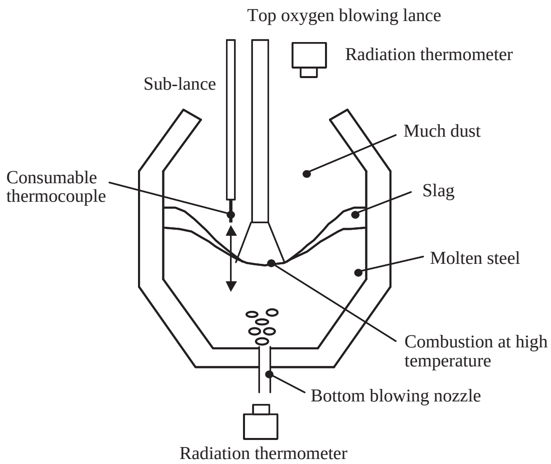

Fig. 1 Schematic illustration of refining furnace such as converter

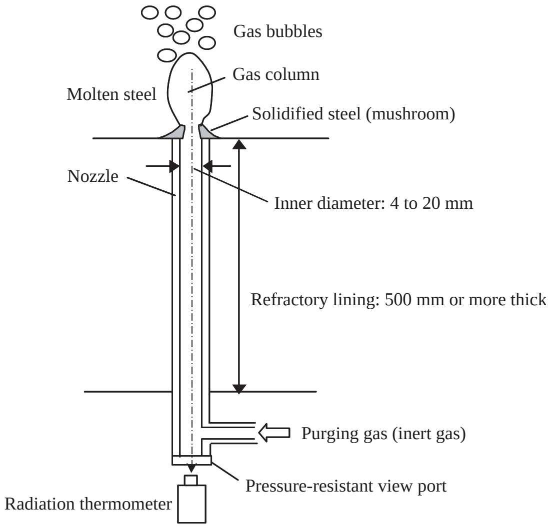

Fig. 2 Outline of nozzle for molten steel observation

likely to undergo gradual deformations due to thermal and mechanical reasons as the charging and discharging of high-temperature molten metal to and from the furnace are repeated. In addition, steel solidifies to form what is called a mushroom at the inside end of the nozzle where the inert gas at room temperature contacts molten steel and as a result, the field of view may be narrowed.

Supposing that a common radiation thermometer for spot measurement is used, it has to be trained across a large distance to aim accurately at a small measurement area and thus the alignment of its optical axis is not easy. Specifically, this is done gropingly by delicately shifting the measurement direction of a radiation thermometer to find out the direction in which its output signal hits a maximum, or the direction in which the thermometer is, most probably, looking at the molten steel straightly. During furnace operation it is impossible for operators to come close to the thermometer installed at the furnace bottom, and if the measurement direction of the thermometer is shifted by only a small angle by any reason, it ends up catching indirect light reflected and attenuated at the inner wall of the nozzle or its field of view is partially obstructed by the mushroom. The radiation intensity measured in such a situation is smaller than the true intensity of molten steel and the thermometer outputs a temperature signal lower than the true temperature, but it is impossible to know whether the molten steel temperature is actually low or the thermometer is not trained correctly at the molten steel.

3. New Technique for Measuring Thermal Radiation of Molten Steel

3.1 Measurement principle of 2-dimensional observation of nozzle inside

As a measure to solve the problems in the thermometry through a long and small-diameter nozzle, the authors worked out image observation of the nozzle inside using a radiation thermometer equipped with a 2-dimensional light detector. Here, the view angle of a 2-dimensional radiation thermometer has to be so adjusted that its field of view covers the whole inner diameter of the nozzle at its furnace inside end. By so doing, the molten steel at the far end of the nozzle can be included, as shown in **Fig. 3**, in an observed image, in which high-temperature molten steel shows as a light area against a darker area corresponding to the lower-temperature inner wall of the nozzle.

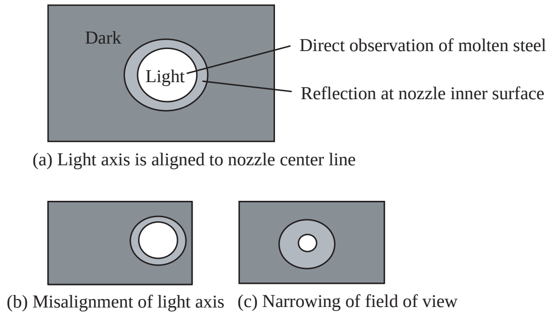

Fig. 3 Appearance of thermal image

If object molten steel is monitored in the form of an image as shown in the figure, the optical axis of the thermometer can be adjusted easily at the time of its installation. Even if the image of molten steel is not exactly at the center, there is no problem as far as it is within the field of view; thus a precise optical axis adjustment as in the case of a spot measurement type radiation thermometer is not required. In the case where shifting of the optical axis (Fig. 3 (b)) or narrowing of the field of view by a mushroom (Fig. 3 (c)) occurs during measurement, although the position or size of the molten steel image changes, its intensity remains unchanged. A reliable and stable radiation thermometry method was worked out by adding to the above an image processing system to automatically detect a molten steel image.

3.2 Configuration of radiation thermometry system

Fig. 4 schematically illustrates the configuration of the 2-dimensional radiation thermometry system developed by the authors. Since molten steel emits red components of visible spectrum in the temperature range of a steel refining process, a CCD camera can be used as a two-dimensional light detector. It was anticipated that huge cooling equipment would be required if an electronic device, such as a CCD camera, designed for use in a temperature range near room temperature was to be installed directly at a nozzle on a furnace shell, which was heated to 400°C or higher in normal operation. As a countermeasure, a heat-resistant fiberscope (image transmission fiber) was fitted to the nozzle and the image was led through it to a CCD camera installed at a remote and cooler location. The fiberscope was encased in a protection tube and its inside was cooled by air.

A special fiberscope equipped with an objective lens designed for the observation through a nozzle was manufactured. A monochrome CCD camera was used, and an optical bandpass filter having a central transmission wavelength of 0.6 μm was fitted to it. The exposure time of the CCD camera was controlled by a camera controller for the purpose of correlating the spectral intensity of an ob-

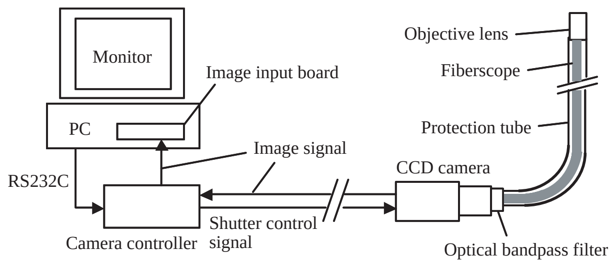

Fig. 4 2-dimensional radiation thermometry system

ject with the intensity of an image. An image signal from the CCD camera was sent to a personal computer (PC) via an image capture board. It was possible to use economical general-purpose products available in the market for the PC and the image processing board thanks to the latest remarkable price reduction and technical advancements.

The PC carries out image processing calculations to extract a molten steel image from the image signal from the CCD camera and calculate the temperature of observed molten steel in real time. Since a molten steel image represents the part having the highest luminanceintensity in a whole view image, it can be extracted comparatively easily through a simple binalization. The threshold for the binalization is determined based on the maximum luminance intensity of a whole view image. Then, the position and size of the molten steel image are determined in terms of the coordinate of the center of gravity and the number of pixels, respectively. The position information tells if or not the observation direction of the CCD camera is correctly aligned to the centerline of the nozzle, and the size information if or not the narrowing of the field of vision is occurring. In the event that such a large misalignment that a molten steel image goes out of the field of view or a significant narrowing of the field of view is detected, the system holds the processing and issues an alarm. Next, the molten steel image is cut out, its average intensity is calculated, and the temperature is calculated referring to calibration data prepared beforehand through actual measurements. The above series of image processing steps are repeated at a rate approximately of 5 images a second to measure the molten steel temperature continuously until a measurement end signal is given. The temperature reading thus obtained is shown on a monitor screen and is stored together with image processing information such as the position and size of the molten steel image.

3.3 Temperature calibration

Temperature calibration is a procedure to determine the calibration curve of the temperature of an object and the output of a radiation thermometer through experiment beforehand. The authors did this off-line using a blackbody furnace as in the cases of common radiation thermometers. A blackbody furnace is an apparatus to provide a thermal radiation reference by keeping temperature of a cavity heat generator, which emissivity can be regarded as 1. The higher the temperature of a blackbody furnace, the larger its thermal radiation intensity becomes and also the stronger the intensity of its image, which corresponds to the output from a radiation thermometer. The intensity of an image is processed in a PC in the form of a digital signal in 256 gradations, but the range of the intensity of an image effective for stable image processing is rather limited. Empirically, when the intensity of a molten steel image is as low as 40 or less, the image extraction processing becomes unstable and, when the intensity is 220 or more, on the other hand, saturation of the light sensing elements of a CCD camera begins and their sensitivity is lowered. The 180 gradations between the above two figures corresponds to a temperature range of approximately 200°C, which is insufficient for covering the whole range of molten steel temperature change in actual refining operation.

As a measure to solve this problem, the exposure time of the CCD camera was changed in stages at predetermined exposure values to find an exposure time at which the intensity of a whole view image was confined within the range from 40 to 220; thus it became possible to cover a wider temperature range. 5 different exposure times were selected: 1/125, 1/250, 1/500, 1/1,000 and 1/2,000 s. Because the upper limit temperature of the blackbody furnace available to the authors was 1,700°C, it was decided that the calibration curve for an exposure time of 1/2,000 s be extrapolated for measuring a molten steel temperature higher than 1,700°C. As a result, the radiation thermometry system was made to cover a temperature range from 1,200 to 1,750°C.

4. Verification Tests Using Small Laboratory Steel Bath

Fundamental tests were carried out, first, using a laboratory steel bath having a capacity for 1.5 t for the purpose of evaluating basic characteristics such as measurement accuracy and operability. A stainless steel contained 1.5% carbon was used for the tests. The temperature of the steel bath was controlled by means of an induction heater and natural cooling. A steel pipe 4 mm in inner diameter was installed vertically at the bottom of the furnace as the observation nozzle. The distance from the top end of the nozzle contacting the steel bath to the fiberscope was 800 mm. In this arrangement, molten steel covers 1,000 or so pixels on a CCD camera image of 600 × 480 pixels. Argon was used as the inert gas.

An example of measurement results is shown in **Fig. 5**. In this example, molten steel was left to cool naturally for 13 min after it was charged into the furnace, then heated by induction heating up to 30 min after the charging and left to cool again thereafter. The steel bath temperature was measured, for comparison purposes, by manual measurement using consumable thermocouples at an interval of 3 min. The flow of the purging inert gas was changed during the process from 6 to 10 Nm^3/h.

It was made clear as a result that the measurement by radiation thermometry agreed well with the measurement with thermocouples, and the fluctuation of the data during the course of the tests was as small as $\sigma = 2°C$. The height of the gas column was estimated at approximately 80 mm from the nozzle inner diameter and the gas flow [6], and an optical diffused surface was presumed to form at the top end of the gas column where small gas bubbles were formed continuously; from these, it was presumed that the gas column formed a cavity blackbody stably. The above change of the gas flow did not disturb the formation of the cavity blackbody. With respect to operability, the optical axis of the fiberscope was aligned at its installation work comparatively easily to the centerline of the nozzle 4 mm in inner diameter, and the advantages of the image observation method were confirmed.

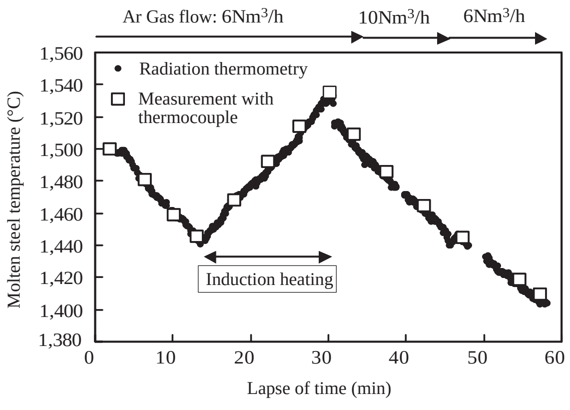

Fig. 5 Example of temperature measurement on 1.5-t laboratory steel bath

5. Applications to Commercial Production

5.1 Stainless steel refining furnace (AOD furnace)

Having confirmed the effectiveness of the image observation method of radiation thermometry, the authors carried out temperature measurement tests on the commercial 60-t AOD furnace of Hikari Works, which was actually used for producing stainless steel. An optical system for the fiberscope observation was installed at one of the bottom nozzles (13 mm in inner diameter) of the furnace for blowing gas for steel refining. The distance from the top end of the nozzle contacting molten steel bath to the fiberscope was roughly 1,500 mm. The same kinds of gas used for the refining process were blown through the nozzle by the same amounts: a mixed gas of O_2 and N_2 in the first half of refining, and single N_2 or Ar in the second half.

An example of measurement results is shown in **Fig. 6**. It was impossible to measure the temperature in the first half of a refining process because combustion occurred at the steel/gas interface of the gas column by the mixed gas containing oxygen. Facing this situation, radiation thermometry was tested by temporarily stopping the oxygen during a short period at each of the measurements with thermocouples mounted on the sub-lance. After 15 min of the commencement of refining, the injection gas was switched to the single N_2 or Ar, and the temperature shift could be measured continuously thereafter. The temperature measurement results by the developed method agreed very well with the results of the sub-lance + thermocouple method. It has to be noted, however, that the reading of the radiation thermometry was always lower than that of the measurement with a thermocouple by 140°C and for this reason, the results of radiation thermometry were adjusted by adding the difference. The main reason for this is presumably that molten steel was cooled by the injected gas at the steel/gas interface of the gas column. Continuous temperature measurement of molten steel is expected to significantly improve the accuracy in the control of a refining process compared with the conventional operation based on the temperature measurement using a sub-lance and the complementary calculation using a mathematical model. Application of the developed technology to the commercial operation of the furnace is now being carried forward.

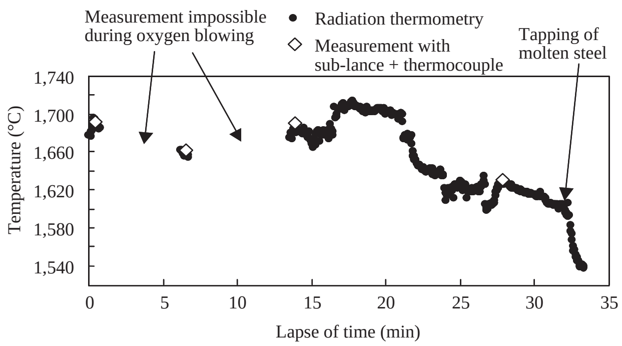

Fig. 6 Example of temperature measurement on commercial AOD furnace

5.2 Scrap-melting Furnace

The developed method of radiation thermometry was tested also at Hirohata Works using its scrap-melting furnace, which melts steel scrap by top and bottom blowing of O_2 gas and carburizes molten steel by injecting pulverized coal. A sub-lance cannot be used in an early stage of the furnace process because scrap not completely melted obstructs its immersion, and consequently it has been difficult to accurately grasp the temperature shift pattern of a steel bath. One of the bottom-blowing nozzles of the furnace was used for continuous radiation thermometry, and N_2 gas was injected through it at a prescribed flow rate. Temperature measurement was commenced at the time when cold scrap was added to an initial small molten steel bath and the process of temperature rise was observed as the melting proceeded. The readings of the radiation thermometry were compared with those of the sub-lance + thermocouple measurements, at the stages where such was possible; the difference between the two methods was roughly ±10°C or less. This was the first time that a temperature shift pattern of the process was measured in the scrap-melting furnace. The measurement was repeated under different operating conditions and as a result, the relationship between the charging amounts of scrap and other auxiliary materials, timing of their charging, etc. and the shift pattern of bath temperature was clarified. This contributed to the stabilization of the melting process and the reduction of damage to the refractory lining.

6. Summary

Nippon Steel developed a new technique of radiation thermometry applicable to molten steel in a steelmaking process. Thermal radiation of molten steel is observed 2-dimensionally through a nozzle at the bottom of a refining furnace, and the thermometry is carried out with image processing. The developed technology enables continuous temperature measurement of molten steel during its refining process, and can replace the conventional intermittent temperature measurement method using consumable thermocouples. In addition, the new technique has significant practical advantages such as being little influenced by a misalignment of a optical axis or a change in the size of a field of view. A hardware system for the radiation thermometry was developed and tested on a 1.5-t laboratory steel bath, a commercial 60-t stainless steel refining furnace (AOD) and a commercial scrap-melting furnace. As a result, good measurement results well agreeing with the measurements using consumable immersion thermocouples were obtained, and thus effectiveness of the developed technique was confirmed. Actual application of the new technique to commercially operated AOD furnaces and converters are programmed.

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