Observation of Molten Slag Surface under Gas Impingement by X-ray Computed Tomography

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Observation of molten slag at 1 673 K was carried out by X-ray Computed Tomography (X-ray CT) to make clear the shape of slag surface where gas was downward blown. X-ray CT scanning of molten slag heated in an electric furnace was conducted to take an image of its cross section. In order to examine the effects of gas momentum supplied on the surface shape, three kinds of inert gases, Ar, He and N₂, were employed as the blowing gas under the several conditions of gas flow rate and gas pipe diameter.

The obtained X-ray CT images successfully visualized the cross section of molten slag. The boundary line between gas and slag in the image was concave under the gas blowing, indicating a formation of depression on the slag surface by gas impingement. The concave boundary is completely different from the parabolic shape conventionally evaluated. The depression became larger, not only in depth but also in width, with increasing gas flow rate, whereas drastically smaller with increasing gas pipe diameter. In addition, larger depth was brought by impingement of larger molecular (atomic)-weight gas. These results were well explained by the conservation law of momentum between gas and slag. It was also revealed that the increment in the boundary line caused by formation of depression, which corresponds to an increase in the interfacial area, is in proportion to the depression depth in the range of more than 2 mm, and was independent of the pipe diameter and gas species.

KEY WORDS: molten slag; gas impingement; depression formation; X-ray CT; high temperature.

1. Introduction

Recently, the authors have proposed a process for heat recovery from molten slag by using chemical reactions. In the proposal, reactants of endothermic reactions, such as methane and steam, are supplied to the surface of molten slag. The reactions proceed on the surface of slag which plays a role of heat source as well as catalyst. As a consequence, the sensible heat of the slag can be recovered as chemical energy of product gases, such as hydrogen and carbon monoxide. An appropriate contact of supplied gases with the slag could bring about high conversion, in other words, high efficiency of heat recovery. Therefore, an evaluation of the interfacial area between the gas and slag is needed. One of the simple methods for the contact is gas blowing downward to the slag surface.

Top gas blowing is a common operation employed in steel-making processes such as basic oxygen furnaces and electric arc furnaces, in which gas jet deforms the initially horizontal surface of molten slag, leading to a vigorous stir of the melt. At the interface between the gas and melt, mass and heat transfer progresses, followed by reactions of gas with impurities in the metal such as carbon, silicon, manganese, sulfur and phosphorus. For the purposes of analyzing and optimizing of the operation, researchers have paid much attention to the interfacial shape and fluid flow around the field of gas impingement. And then, several model experiments have been carried out by using substitutes for molten slag (and molten metal) such as water, alcohol–water, mercury, and so on. Cheslak et al. employed fast-setting cement as the substitute to permanently record the surface shape created by gas impingement, and concluded that the surface is deformed in a parabolic shape.

Muchi et al. applied a parabolic curve to the description of the depression shape on the melt surface in their numerical simulation of an oxygen top blowing converter. However, these results have never been verified by an experiment using molten slag (and metal) itself although significant difference in the physical properties such as viscosity, surface tension and density were found between the slag and substitutes. This is obviously due to a difficulty in direct observation of the slag surface where the temperature is higher than 1 600 K.

One of the promising methods to overcome the difficulty is to utilize X-ray. In particular, X-ray Computed Tomography (X-ray CT) can provide a cross-sectional image of an object, and thus visualize its internal condition without any disturbance from the surroundings. This causes that X-ray CT has recently come into wide use in the field of industry as well as in that of medicine. In the fields of iron- and steel-making, some studies have been conducted by actively employing X-ray CT to clarify the sinter-
ing process where complicated changes in the structure of iron ore packed bed take place.

Hence, the aims of this study are to visualize the shape of molten slag surface by X-ray CT and to examine effects of gas flow rate and gas pipe diameter on the surface shape under the impingement conditions of three inert gases; Ar, He and N₂, in which the depth of depression and length of boundary line between gas and slag were mainly examined.

2. Experimental

2.1. Slag Sample

A slag sample modeled into a blast-furnace slag was employed. Chemical compositions of the sample are listed in Table 1. Pure oxides except CaO were mixed in an alumina crucible with an inner diameter of 82 mm and a height of 72 mm. Ca(OH)₂ was used as a raw material of CaO. Slag sample was prepared by heating the mixture in a muffle furnace at 1 773 K for an hour. Phase diagram indicates the liquidus temperature of the slag as about 1 650 K, and the density estimated was around 2 680 kg/m³ within a temperature range of 1 610 to 1 720 K.²²) Although the surface tension of the slag employed was not clear, that of the synthetic blast furnace slag of CaO (44.5 mass%), SiO₂ (40.3) and Al₂O₃ (14.9) was reported to be about 0.52 N/m at 1 673 K by Boni and Gerge.²³)

2.2. Apparatus and Procedure

Figure 1 shows a schematic diagram of the X-ray CT device used. This is classified in so-called the 3rd-generation type of X-ray CT scanner; that is, an X-ray tube and a detector continuously rotate around an object, simultaneously. This device is mainly composed of three parts; one of “scanner” where X-ray is irradiated and received, another of “bed” where the position and inclination of the object is adjusted, and the other of “console” where the operation of the device, reconstruction of a 2-dimensional CT image, and visualization and save of the image are conducted.

A cylindrical electric furnace schematically shown in Fig. 2 was employed with an outer diameter and a height of 380 and 450 mm, respectively. A 100 mm i.d. alumina tube was vertically put at the center of the furnace. A crucible containing slag was settled on a thermal insulator within the tube and was heated by a graphite heater surrounding the tube. The outer frame and thermal insulator were made of aluminum and alumina fiber, respectively. The outer frame was cooled by flowing water to prevent overheat.

The furnace was placed on the head of a bed, and was moved into the central space of the scanner, where the slag sample was heated up to 1 673 K. Slag temperature was measured by a thermocouple inserted to a height of a few millimeters below the slag surface through an alumina tube. An inert gas was blown onto the slag surface through an alumina pipe inserted from top of the furnace. In order to examine the effects of gas momentum supplied on the shape of slag surface, Ar, He and N₂ gases, the atomic (molecular) weights of which are 39.95, 4.003 and 28.02, respectively, were employed as the inert gas. The pipe diameter and gas flow rate were also varied in respective ranges of 3 to 6 mm, and 5×10⁻² to 23.3×10⁻² m³/s, which was controlled by a mass flow controller. Preliminary experiments were performed to examine the effects of the height of pipe end above the slag surface on the shape of slag surface at an Ar gas flow rate of 16.7×10⁻² m³/s through a 6 mm i.d. pipe, and then revealed that the shape of slag surface was insignificantly affected by the height ranging from 5 to 25 mm. Therefore, the experiments were carried out at a fixed height of 5 mm above the slag surface.

A central cross-sectional image of the object (molten slag) was taken with the X-ray CT scanner under the conditions of an X-ray tube voltage and a current of 120 kV and 250 mA, respectively, and the scanning time of 4 s. The slice thickness was set at 1 mm. CT values were calculated assuming that the CT value of water is 0 and that of air is −1 000. An X-ray CT image was reconstructed in a round field, which has 512 pixels in diameter. This was the average image for the phenomena during the scanning time of 4 s. One pixel in the image visualized a part of the object, the size of which was 0.2×0.2 mm. Thus, the minimum detectable length in the present experiments was 0.2 mm. For each run, more than three X-ray CT images were taken to analyze the surface shape of molten slag. The average of the standard deviations for the measured lengths was around 0.33 mm.
3. Results and Discussion

3.1. X-ray CT Image of Molten Slag

X-ray CT scanning was conducted for slags without gas blowing and with Ar blowing through a 4 mm i.d. pipe at a flow rate of $11.7 \times 10^{-3} \text{m}^3/\text{s}$. The images 3(a) and 3(b) in Fig. 3 show the X-ray CT images obtained, respectively. For both the images, a bright gray figure is clearly seen at the lower part. It corresponds to molten slag contained in an alumina crucible. On the contrary, the part visualized with dark grays shows the gas phase. From a comparison of both the images, we can find the different shapes of the boundary line between the gas and slag. The boundary line in the image 3(a) is almost horizontal whereas that in 3(b) is concave. This result clearly shows that a depression forms on the slag surface by gas impingement. In Fig. 4, X-ray CT images show the depressions created from Ar, He and $N_2$ blowing at a flow rate of $16.7 \times 10^{-3} \text{m}^3/\text{s}$ through a 4 mm i.d. pipe. Obviously, the shapes of the depression differ from one another. In particular, the distortion of the boundary line for He is much smaller than that for the others. Therefore, the X-ray CT can be a powerful tool to evaluate the surface shape of molten slag with gas impingement, quantitatively.

3.2. Thresholding of X-ray CT Image

To clearly visualize the boundary line between gas and slag, X-ray CT images were subjected to thresholding processing. As mentioned above, an X-ray CT image consists of pixels. Each of the pixels has a pixel value into which the CT value detected from the scanning is transformed. A pixel value, to which one of the whole numbers from 0 to 255 is assigned, has a meaning of one of the gray colors gradated from black (0) to white (255). Thresholding processing is conducted by transforming the pixel values smaller than a prescribed value to 0, and those greater than the value to 255. Consequently, a binary image expressed by black and white is obtained. The boundary value is called a thresholding level.

Figure 5 shows a histogram of pixel values for the X-ray CT image shown in Fig. 3(a). The number of pixels drastically increases from the pixel value of about 30, reaches a maximum at 70, and then steeply decreases (Region 1). A gradual decrease in the number follows in a pixel value range from ca. 95 to 130 (Region 2). In the further range of pixel value, the number of pixels increases again, and decreases via another maximum at around 175 (Region 3). As mentioned in the previous section, slag is visualized in an X-ray CT image with bright grays and gas in dark ones. Corresponding to this fact with the distribution of pixels in the histogram, the pixels in Region 1 make visualization of gas, and those in Region 3 do that of the others (slag, alumina crucible, and so on). The pixels in Region 2 are ambiguous parts in the image mainly due to noises. In this study, the boundary value between Regions 2 and 3 was given to a thresholding level.

X-ray CT scanning was conducted to the solid slag at the center of which a cylindrical depression was mechanically prepared. The obtained X-ray CT image is shown in Fig. 6(a). Images 6(b) and 6(c) were obtained after thresholding of this image at different thresholding levels. For the image 6(b), the boundary value between Regions 1 and 2 was given to the thresholding level. For 6(c), the level was determined according to the above-mentioned method. A photograph 6(d) shows the cross section of the solid slag which
was cut into halves after the X-ray CT scanning. From the comparison of the images with one another, the shape of depression in (b) is not clear, while that in (c) is in good agreement with that in (d). Hence, the thresholding used in this study is revealed to be valid for the separate representation of gas and slag in an X-ray CT image.

3.3. Changes in Depression Shape with Gas Flow Rate

Figure 7 compares the boundary lines of depressions created by Ar blowing at four different flow rates through a 4 mm i.d. pipe. Evidently, depression becomes larger with gas flow rate not in depth but also in width. In addition, the slope is quite steep for the depressions created at more than 11.7×10⁻² m³/s. This means that the depression has a shape of column rather than cone. In the same figure, a parabolic curve is drawn by a dotted line. As mentioned above, the parabolic shape is very often applied to the conventional description of the depression shape. However, the shapes of boundary lines are visibly far from the parabolic one. This result reveals that the conventional assumption based on the parabolic curve is not appropriate for the description of the depression shape on the slag surface.

3.4. Changes in Depth of Depression

Effects of gas flow rate and pipe diameter were examined on the depth of depression, D, for Ar, He and N₂ impingements. Figures 8 and 9 show changes in D with gas flow rate through a 4 mm i.d. pipe, and those with the pipe diameter at a gas flow rate of 11.7×10⁻² m³/s, respectively. From Fig. 8, it is found for Ar and N₂ that D’s increase with gas flow rate in the same manner, while that for Ar is slightly larger. The gas of He also gives a similar change. However, the increment is much smaller than those for the others. In contrast, as is shown in Fig. 9, D for all the gases drastically decreases with increasing pipe diameter from 3 to 4 mm, followed by a slight decrease to 6 mm. From both the figures, larger D is brought about by impingement of the gas having larger atomic (molecular) weight under the same conditions. These tendencies were also observed for other series of experiments.

From the conservation law of momentum between gas and slag, the depth of depression can be expressed in the following equation;24–26)
where $g$ is gravitational acceleration (m/s$^2$), $k$ is a constant (—), $v_0$ is the gas velocity at the exit of a pipe (m/s), and $\rho_g$ and $\rho_l$ are the gas and slag densities (g/m$^3$), respectively. This equation indicates that $D$ would change in direct proportion to the square of the gas velocity, $v_0^2$. In Fig. 10, all the $D$'s obtained for Ar, He and N$_2$ are re-plotted against $v_0^2$. Here, an average gas velocity was applied to $v_0$, namely,

$$v_0 = \frac{Q}{A} \tag{2}$$

where $A$ is the cross-sectional area of the gas pipe (m$^2$) and $Q$ (m$^3$/s) is the volumetric gas flow rate at standard temperature and pressure. The results show, as expected, that $D$ straightly increases with increasing $v_0^2$ for all the gases. Equation (1) further explains that deeper depression is created from greater gas density, $\rho_g$, when gas is blown at the same velocity. Since gas density is directly associated with atomic (molecular) weight of gas, $D$ should be larger for the gas impingement with larger atomic (molecular) weight at the same gas velocity. The experimental results well reflect this explanation, as is shown in Fig. 10.

### 3.5. Changes in Length of Boundary Line with Formation of Depression

Interfacial area between gas and slag is an important factor to discuss the phenomena at the interface. An increase in the area might correspond to that in the length of the boundary line, $L$. Therefore, effects of gas flow rate and pipe diameter on $L$ were examined for Ar, He and N$_2$ blowing. Figure 11 shows the results. For the 3 mm i.d. pipe, $L$ drastically increases with increasing gas flow rate larger than $5.0 \times 10^{-3}$ m$^3$/s for all the gases. In contrast, $L$ for a 6 mm i.d. pipe slightly increases without significant difference among the gases. For the 4 mm i.d. pipe, the trends of $L$ increase differ from one another. For Ar, $L$ rises moderately with gas flow rate above $8.3 \times 10^{-3}$ m$^3$/s whereas that for He is still insignificant at $16.7 \times 10^{-3}$ m$^3$/s. For N$_2$, $L$ increases in a manner between Ar and He. Figure 12 depicts plots of $L$ against the depth of depression, $D$. For $D$ less than 2 mm, increment of $L$ is insignificant against $D$. However, interestingly, $L$ increases with $D$, and the plots converge on a straight line in the further range of $D$. In addition, the change is independent of the pipe diameter, and also of the gas species. Hence, it is indicated that the increase in the interfacial area with gas impingement can be predicted once the depth of depression is obtained.

### 4. Conclusions

Molten slag surfaces with gas impingement under different blowing conditions at 1673 K were observed by using an X-ray CT scanner. Three different gases of Ar, He and N$_2$ were employed for the blowing gas. The results are summarized as follows:

1. Formation of depression on the molten slag surface due to gas blowing is clearly visualized by the X-ray CT.
2. Depression becomes larger; not only in depth but also in width, with increasing gas flow rate.
3. The shape of depression is like a column; indicating that the parabolic shape is far from the expression for the cross-sectional shape of the depression.
(4) The depth of the depression increases with increasing the gas momentum supplied.
(5) The length of the boundary line between gas and slag increases with formation of depression, and the increment is in proportion to the depth of the depression in the range of more than 2 mm without depending on the pipe diameter and gas species.

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