Heat Transfer between Bubbles and Molten Wood's Metal

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In refining processes for steel and some other metals, gas is blown into molten metal from the top, the bottom or simultaneously from the top and bottom of the vessel to promote mixing and chemical reactions. Since the gas is usually injected at a temperature lower than the molten metal temperature, knowledge about the heat transfer between gas and molten metal is required to predict precisely the mixing effect. Present authors previously carried out cold model experiments for bottom injection to investigate the mechanism of convective heat transfer between bubbles and liquid, using cooled gas and water and proposed an empirical correlation for the Nusselt number. In this paper, the mechanism of convective heat transfer between bubbles and molten metal was investigated using molten Wood's metal. The functional relationship between the Nusselt number and the Peclet number was the same as that for water models although the Prandtl numbers of water and Wood's metal were much different with each other.

KEY WORDS: steelmaking; injection; bubbling jet; heat transfer; Nusselt number; Peclet number; microthermocouple; Wood's metal.

1. Introduction

In the steelmaking and refining processes, bottom gas blowing is a method widely utilized to homogenize the temperature of molten metal and chemical concentrations in the bath, and to accelerate the chemical reactions. In an examination of the efficiency of these methods of operation most previous investigations¹⁻⁴⁾ have been made under isothermal condition. That is, gas was injected into liquid of the same temperature. There are many advantages to this approach, but under real conditions, gases such as Ar and oxygen are blown into molten iron, for example, from the bottom of the vessel at a temperature lower than the molten iron temperature and hence convective and radiation heat transfer takes place between bubbles and liquid as shown in Fig. 1. The

radiation heat transfer becomes significant as the temperature difference becomes large.

Present authors previously pointed out that convective heat transfer between bubbles and liquid would be evaluated using water models, and reported⁵⁾ the effect of the convective heat transfer on the bubble characteristics such as gas holdup and bubble frequency. Very little research, however, has been carried out on how the difference in temperature affects the formation of bubbles. In addition, it is necessary to confirm whether or not the mechanism of convective heat transfer for aqueous systems is the same for molten metals because the Prandtl number of water is much larger than those of molten metals. Consequently, molten Wood's metal was used in this study to investigate the latter subject.

2. Experiment

2.1. Experimental Apparatus

Figure 2 shows a schematic diagram of the experimental apparatus. The gas temperature of compressed nitrogen was measured with a thermocouple and its flow rate was adjusted using a regulator and a mass flowmeter. The nitrogen, at a temperature of 18°C, was blown into a cylindrical vessel through a single-hole nozzle located at the center of the bottom plate. The vessel, made of carbon steel, had an inner diameter of 200 mm and a height of 300 mm, and the temperature of molten Wood's metal inside the vessel was kept at approximately 105°C by means of an electric heater and a thermo-controller. The molten metal bath has a depth of 150 mm. The nozzle, made of fluororesin whose commercial name

Fig. 1. Schematic illustration of injected bubble phenomenon.

is Teflon, has an inner diameter of 1 mm. The Wood's metal has a melting point of 47°C.

2.2. Measurement of Bubble Temperature

Under the present temperature difference (87°C), the ratio of radiation heat transfer to convective heat transfer is less than 5% because the emissivities of liquid and gas are considered to be 0.1 and 0.001, respectively. Therefore it is sufficient to consider the convective heat transfer.

According to the previous work,⁵⁾ change in the temperatures of bubbles was measured directly using a microthermocouple.⁶⁾ Figure 3 illustrates a schematic of the microthermocouple together with a diagram of the signal processing system. In this measurement, a bare thermocouple with a hot junction diameter of 12.5 μm was employed to measure as small a bubble as possible.

As the heat capacity of gas inside the bubble is very small, the heat capacity of the thermocouple wire around the hot junction is also required to be small. In addition, to increase the area of heat transmission, the wire adhered to the inverse Y-shaped holder should be bare. The holder is made of heatproof plastic resin. To improve signal quality, the wire and holder were sprayed with silicone. According to Hasatani,⁷⁾ the response time of this thermocouple is considered to be less than a few ms.

This type of structure is often used for rapid temperature fluctuation measurement in high speed gas flow

in a compressor, an internal combustion engine or a wind tunnel.⁷⁾

The filtered signal was A/D-converted at a sampling frequency of 1 kHz or 2 kHz. Using these instruments, a change in the bubble temperature on the center line was measured at an axial position located between $z = 30$ and 80 mm, where z was measured from the nozzle exit.

2.3. Measurement of Bubble Rising Velocity

In order to determine the Reynolds number of a rising bubble $Re_B (= \bar{u}_B \bar{d}_B / \nu_g, \text{ or } \bar{u}_B \bar{d}_B / \nu_L)$, measured values of the mean bubble rising velocity $\bar{u}_B$ and mean bubble diameter $\bar{d}_B$ are necessary. These quantities $\bar{u}_B$ and $\bar{d}_B$ were measured with a two-needle electro-resistivity probe at an axial position of $z = 30$ mm for a bath depth of 150 mm. The mean bubble diameter $\bar{d}_B$ was calculated from the relation, $\bar{d}_B = 1.5 \bar{L}_B$, where $\bar{L}_B$ is the mean bubble chord length. This relation can be derived by assuming that bubbles are spherical in shape. Bubble frequency f_B and gas holdup α also were obtained together with $\bar{u}_B$ and $\bar{L}_B$. The output signal of the probe was A/D-converted at a sampling frequency of 10 kHz and a total of 2400 bubble signals were processed to determine the bubble characteristics mentioned above.

3. Experimental Results and Discussion

3.1. Bubble Characteristics at $z = 30$ mm

The experimental results of bubble rising characteristics on the center line at $z = 30$ mm are shown in Table 1. At this location the gas holdup α was less than 50% for all gas flow rate values. The mean bubble rising velocity $\bar{u}_B$ and mean bubble chord length $\bar{L}_B$ increased as the blowing gas flow rate Q_g increased.

3.2. Change in Bubble Temperature

Figure 4 shows examples of the bubble temperature data measured using a microthermocouple. In this

Fig. 2. Experimental apparatus.

Fig. 3. Microthermocouple and schematic diagram of signal processing system.

Q_g (cm ³ /s)	42.0	84.0	126.0
f_B (1/s)	33.7	52.0	58.3
α (%)	26.2	38.4	47.0
$\bar{u}_B$ (m/s)	0.78	0.89	0.96
$\bar{L}_B$ (m)	0.0116	0.0132	0.0176

Fig. 4. Temperatures of gas and molten Wood's metal measured using a microthermocouple ($z = 30$ –80 mm).

Fig. 5. Temperatures of gas and molten Wood's metal measured using a microthermocouple ($z=30$ mm).

measurement, the microthermocouple was pulled up by every 10 mm intervals and at each measurement position the temperature was measured for 2 sec. This figure means that the convective heat transfer between bubbles and molten Wood's metal mainly takes place in the region just above the nozzle because the bubble temperature rapidly approaches the Wood's metal temperature there as z increases. Figure 5 shows the temperature data at $z=30$ mm under the same experimental condition as shown in Fig. 4. The abscissa was magnified to show the history of temperature change more clearly. In Fig. 5, the parts of decreased temperature indicate bubble signals. The bubble signals having flat part at the bottom were selected to determine the bubble temperature. That is, the mean value of the bottom temperatures was regarded as bubble temperature. The liquid temperature, gas temperature inside bubbles and even bubble frequency can be obtained from this chart. Bubble frequency, however, was approximately one third of the value determined from the electro-resistivity probe. This is because the microthermocouple cannot detect the temperatures of small bubbles. Furthermore, this chart revealed that the liquid temperature around the bubble surface was almost the same as the temperature of the bulk liquid.

3.3. Convective Heat Transfer Coefficient between Bubble and Molten Wood's Metal

In this discussion, a bubble is assumed to be spherical in shape, its mean diameter being denoted by $\bar{d}_B$. The mean Nusselt number is represented as a function of the Reynolds number and the Prandtl number. Hijikata *et al.*⁸⁾ pointed out that the vibration and deformation of a bubble promote heat transfer at the bubble-liquid interface due to the breaking of the stream lines in the bubble, which exhibits a similar effect of turbulence. Therefore, the heat and mass transfer coefficient obtained theoretically by Kronig and Brink,⁹⁻¹¹⁾ for a Hadamard-type fluid flow inside a sphere, should be less than that for a bubble mentioned here.

An attempt was made to determine the convective heat transfer coefficient by using the concept of the overall heat transfer coefficient in the previous work.⁵⁾ The convective heat transfer coefficient between bubbles

and water was confirmed to be much larger than the theoretical solution of Kronig and Brink's equation. Determination of the convective heat transfer coefficient between bubbles and molten Wood's metal is made in the same manner as employed for the water model experiment.

The overall heat transfer coefficient U_m between bubbles and molten Wood's metal can be represented as follows:

$$U_m = 1/(1/h_L + 1/h_g) \quad \text{.....(1)}$$

where $h_L = Nu_{mp,L} \lambda_L / \bar{d}_B$: heat transfer coefficient from liquid to a bubble sphere, and $h_g = Nu_{mp,g} \lambda_g / \bar{d}_B$: heat transfer coefficient from gas inside the bubble to liquid.

The process of bubble expansion is modeled by Eqs. (2) and (3), on the basis of the hypotheses that the temperature change in molten Wood's metal is negligible and the bubble shape is spherical.⁵⁾

$$c_g \rho_g V_B (d\theta_g / dt) = U_m A_B (\theta_L - \theta_g) \quad \text{.....(2)}$$

$$dV_B / d\theta_g = V_{B,0} / \theta_{g,in} \quad \text{.....(3)}$$

where, $V_{B,0}$ is the initial bubble volume and $\theta_{g,in}$ is the gas temperature at the nozzle exit.

Here U_m can be determined utilizing the change in bubble temperature between $z=30$ and 80 mm measured using a microthermocouple. Since bubbles generate at the nozzle exit in the presence of convective heat transfer, the expansion of a bubble consists of two parts if we neglect the contribution due to static pressure change; one is associated with the bubble generation and the other is the thermal expansion due to heat transfer. Consequently, discrimination of the two expansions should be made to determine the heat transfer coefficient between the bubble and liquid by focusing on the thermal expansion.

In the previous study,⁵⁾ gas was also injected into the bath at the same temperature as the bath temperature. The volumetric gas flow rate was equated with that for cold gas injection. The diameter of a bubble generated under this condition was measured at an axial position just after the release of the bubble from the nozzle exit using an electro-resistivity probe. This diameter was used as the initial bubble diameter for numerical calculation of Eqs. (2) and (3) to remove the effect of the expansion associated with the generation and take only the effect of the thermal expansion into consideration.

Although this is actually an approximate method, the same method is employed for the present Wood's metal system because we can not find any other adequate method of determining the heat transfer coefficient at the present stage. According to electro-resistivity probe measurements, the mean bubble rising velocity was almost constant in the axial direction. The lapse of time from the release of the bubbles at the nozzle exit to each measurement location was determined according to the measured value of the mean bubble rising velocity. A part of the data on $\bar{u}_B$ are listed in Table 1 shown in the previous section.

Figures 6 and 7 show the relationship between the change in the bubble temperature and the overall heat

Fig. 6. Relation between temperature change of bubble and overall coefficient of heat transmission U_m ($Q_g = 126 \text{ cm}^3/\text{s}$).

Fig. 7. Relation between temperature change of bubble and overall coefficient of heat transmission U_m ($Q_g = 84 \text{ cm}^3/\text{s}$).

transfer coefficient. The experimental conditions are shown in the figures. The solid lines represent the numerical solutions of Eqs. (2) and (3). The overall heat transfer coefficient can be estimated by fitting the data obtained from the microthermocouple measurement with one of numerical lines. The value U_m was found to be about $170 \text{ W/m}^2 \text{ K}$ in Fig. 6 and $120 \text{ W/m}^2 \text{ K}$ in Fig. 7.

According to the water model experiment, the term $(1/h_L)$ on the right hand side of Eq. (1) was negligible since the measured value of the overall coefficient, from about $100\text{--}200 \text{ W/m}^2 \text{ K}$, was relatively small compared with the liquid side heat transfer coefficient of $3.3 \times 10^4 \text{ W/m}^2 \text{ K}$, being estimated from an empirical correlation of Clift *et al.*¹⁰⁾ The following relations, therefore, were obtained:

$$h_g \cong U_m \quad (4)$$

$$Nu_{mp} \cong h_g \bar{d}_B / \lambda_g \quad (5)$$

These relations also were found to be valid for the molten Wood's metal system.

Figure 8 shows the relation between the experimental values of Nu_{mp} and $Pe/(1+\kappa)$, where $Pe (= Re_{B,g} Pr_g)$ is the Peclet number and κ is the viscosity ratio (viscosity of fluid inside the fluid sphere/viscosity of fluid outside

Fig. 8. Relation between Nu_{mp} and $Pe/(1+\kappa)$.

it). The experimental values are well correlated in Fig. 8 in spite of significant differences in the physical properties of the liquids. This is explained by the fact that the heat transfer from gas inside a bubble to liquid is a rate determining step. In other words, the physical properties of liquid exert a negligible effect on the heat transmission. The following expression, originally derived for an air-water system and drawn by a solid line in Fig. 8, was confirmed to be valid for an N_2 -Wood's metal system.

$$Nu_{mp} = 1.1 [Pe/(1+\kappa)]^{0.7} \quad (6)$$

Recently Kawakami *et al.*^{12,13)} derived an empirical correlation of Nu_{mp} for an N_2 -Tin system. Its functional relationship was the same as Eq. (6) but its coefficient was much smaller than 1.1

$$Nu_{mp} = 0.58 [Pe/(1+\kappa)]^{0.68} \quad (7)$$

The reason for this difference must be left for a future study.

4. Summary and Conclusions

Nitrogen gas was blown into a molten Wood's metal bath in a cylindrical vessel. The convective heat transfer coefficient between bubbles and molten Wood's metal was examined. The radiation heat transfer was very small compared with the convective heat transfer. The coefficient of heat transmission U_m ranged from approximately 100 to $200 \text{ W/m}^2 \text{ K}$ under the present experimental conditions. The heat transmission was governed by the heat transfer between the gas inside the bubble and the molten Wood's metal. This result was the same as obtained for an air-water system. Consequently, Eq. (6) was found to be valid for predicting the mean Nusselt number between bubbles and molten Wood's metal though the Prandtl number values for water and molten Wood's metal were much different with each other.

Nomenclature

- A_B : interfacial area between bubble and molten Wood's metal (m^2)
- c : specific heat of gas (J/kg K)
- $\bar{d}_B$: mean bubble diameter (m)
- d_n : inner diameter of nozzle (m)
- f_B : bubble frequency ($1/\text{s}$)
- $\bar{L}_B$: mean bubble chord length (m)
- Nu_{mp} : Nusselt number ($-$)
- Pe : Peclet number of bubble ($Pe = Re_{B,g} \cdot Pr_g$) ($-$)

Pr : Prandtl number (—)
 Re : Reynolds number (—)
 t : time (s)
 $\bar{u}_B$: mean bubble rising velocity (m/s)
 V_B : volume of bubble (m³)
 α : gas holdup (%)
 θ : temperature (K)
 κ : viscosity ratio, defined by (viscosity of fluid inside the fluid sphere)/(viscosity of fluid outside the fluid sphere) (—)
 λ : thermal conductivity (W/m K)
 ν : kinematic viscosity (m²/s)
 ρ : density (kg/m³)

Subscripts

B : bubble
 cl : value on the center line
 g : gas
 L : liquid
 m : spatial mean value

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