Oxidation of Molten Steel by the Air Permeated through a Refractory Tube

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Refractory tubes such as a shrouding nozzle and a submerged entry nozzle are employed for molten steel transferring from a ladle to a tundish, and a tundish to a mold, respectively, to prevent molten steel from being oxidized. When the cross-sectional area in the molten steel flow channel is suddenly contracted and subsequently enlarged, a negative pressure is generated at the area. Thereby air is permeated into the molten steel flow through the refractory tube and oxidizes the molten steel.

The permeability of a submerged entry nozzle was predicted from measurement of the gas permeated through the refractory tube by a dipping test. Using the predicted permeability and the pressure analysis in fluid flow, we calculated the oxidation rate by the permeated air during molten steel transferring. As a result, the concentration decrease rate of aluminum in molten steel is estimated 0.35 ppm per hour and this oxidation formed by the permeated air does not attribute to alumina build-up in the submerged entry nozzle.

KEY WORDS: submerged entry nozzle; sliding nozzle gate; oxidation; permeability; nozzle clogging; diffusion air.

1. Introduction

In continuous casting process molten steel is transferred from a ladle to a tundish, and a tundish to a mold by using a refractory tube such a shrouding nozzle and a submerged entry nozzle (later abbreviated as SEN). A pressure in molten steel flow passing through the refractory tube is decreased below a sliding nozzle gate that the cross-sectional area suddenly changes. When the pressure of molten steel is reduced lower than the atmospheric pressure, air possibly is permeated into an inside of the refractory tube through its wall and oxidizes aluminum in molten steel.

Yokoya et al.¹¹ have studied air suction between sliding nozzle gate plates with a water model and a numerical simulation of fluid flow during molten steel transferring from a tundish to a mold. They showed that the pressure on inner surface of the sliding nozzle gate is decreased lower than the atmospheric pressure.

Hofer et al.¹² have investigated steel cleanliness during continuous casting and showed that a negative pressure, i.e., a pressure lower than the atmospheric pressure, of molten steel is generated just below a sliding nozzle gate set between a tundish nozzle and a SEN. Resultantly air is sucked and oxidizes molten steel and deteriorates steel cleanliness. They have prevented the air suction by improving the shape of sliding nozzle gate and SEN.

One of mechanisms of the SEN clogging is considered that the permeated air oxidizes aluminum in molten steel, and alumina formed is deposited on the inner surface of the SEN. Resultantly the SEN clogging may be formed. However, this mechanism has not yet investigated quantitatively.

Since very few studies have been conducted on oxidation of molten steel flow by air permeated through the refractory tube, in this study we measured the flow rate of the air permeated through the SEN and predicted the permeability and the amount of oxidation of molten steel formed by the permeated air. Also we checked if the oxidation caused by the permeated air is a cause of alumina build-up or not.

2. Experimental

An experimental apparatus is shown in Fig. 1. A 2-kg of steel was induction melted in a chamber under argon gas atmosphere. After the temperature of molten steel was maintained constant at 1853 ± 10 K, a cylindrical shape refractory test piece made of SEN material was dipped into molten steel in Fig. 1(a). The refractory test piece assembly is shown in Fig. 1(b). The test piece had a hole with 13 mm in diameter and 110 mm in depth. A high alumina tube of 13 mm in outer-diameter and 9 mm in inner-diameter was inserted into the inlet of hole as shown in Fig. 1(b). A small high alumina tube with 6 mm in outer-diameter and 4-mm in inner-diameter was also set into the alumina tube to a position of 10 mm away from bottom of the hole. High alumina cement was coated on outer surface of the test piece in a portion of 40 mm from the top of test piece in order to prevent gas from being permeated through the portion, where was not dipped into the molten steel.

A gas was introduced to the inner alumina tube at a con-
stant flow rate, \(Q_{in}\), and then to a gap between surface of the hole and the inner tube, and discharged to outside of the chamber.

The pressure in the inside of the chamber was adjusted to a certain pressure lower than the atmospheric pressure, and resultantly a pressure difference, \(P_{in}-P_{out}\), was generated between in inner and outer surfaces of the test piece.

The test piece was dipped into the molten steel for an aimed dipping time, \(t_{dip}\), and subsequently pulled out. The inlet and outlet gas flow rates, \(Q_{in}\) and \(Q_{out}\), were measured with two mass-flow meters set at an inlet and an outlet sides of gas supplier line. Since a difference of the flow rates, \(Q_{in}\) and \(Q_{out}\), can be considered equal to the gas permeated through refractory, the permeated gas volume, \(Q_{G}\), is expressed by

\[
Q_{G} = Q_{in} - Q_{out} \quad \text{(1)}
\]

Steel sample for chemical analysis was taken from the molten steel in a crucible before and after dipping test, and the chemical composition was analyzed.

Two kinds of SEN materials were used for the experiment: \(\text{Al}_2\text{O}_3\)-\(\text{SiO}_2\)-graphite type (test piece-A) and \(\text{ZrO}_2\)-\(\text{CaO}\)-graphite type (test piece-Z), which are used for casting practice. The chemical composition of the refractory test pieces is listed in Table 1. Porosity of the test piece-A and the test piece-Z were 12.9% and 19.7%. The thickness of the test piece was 10 mm. Gas species were \(\text{Ar}+20\%\text{O}_2\) and pure oxygen for the experiment. The pressure in the chamber was adjusted 2.7 \(\times 10^4\) to 6.1 \(\times 10^4\) Pa. The test piece was dipped for 60 min. The steel grade for the dipping test was a low carbon aluminum killed steel. We adjusted the initial concentration of Al about 0.5 mass% by adding aluminum into the molten steel before dipping the test piece.

The dipping test conditions are summarized in Table 2.

### Table 1. Chemical composition of refractory test piece.

| Refractory | Test piece-A | Test piece-Z |
|------------|--------------|--------------|
| \(\text{Al}_2\text{O}_3\) | 25.0 | - |
| \(\text{SiO}_2\) | 45.7 | - |
| \(\text{CaO}\) | - | 22.1 |
| \(\text{ZrO}_2\) | - | 59.0 |
| C | 28.1 | 17.7 |
| Apparent porosity(%) | 12.9 | 19.7 |

### Table 2. Dipping test conditions and the aimed chemical composition of molten steel.

| Refractory | Materials | Thickness | Gas species | Pressure | Dipping time |
|------------|-----------|-----------|-------------|----------|-------------|
| Test piece-A | \(\text{Al}_2\text{O}_3\)-\(\text{SiO}_2\)-C | 10 mm | \(\text{Ar}+20\%\text{O}_2\) and pure \(\text{O}_2\) | 2.7 \(\times 10^4\) - 6.1 \(\times 10^4\) N/m² | 60 min |

### 3. Results and Discussion

#### 3.1. Observation of Refractory Test Piece after Dipping Test

Appearance and transverse cross-section of the test pieces-A and -Z are shown in Figs. 2 and 3 under a pressure of \(4.7\times10^4\) Pa in the chamber and \(\text{Ar}+20\%\text{O}_2\) gas mixture. Transverse cross section is shown at a position of 40 mm away from the bottom of the test piece in these figures. We can see deposition on outer surface of the both test pieces.

Figure 4 shows SEM images of deposition on outer surfaces of the test piece-A [Fig. 4(a)] and the test piece-Z [Fig. 4(b)]. The both deposition in the test piece-A and the test piece-Z were composed of a little alumina and almost solidified steel.

The air permeated through refractory oxidizes aluminum in molten steel and leads to formation of alumina, but the alumina seems not to be deposited on the surface of the test piece in this dipping test.

#### 3.2. Flow Rate of Gas Permeated through Refractory

##### 3.2.1. Relationship between Flow Rate of Permeated Gas and Pressure Difference

The gas flow rate was controlled to be \(5\times10^{-6}\) m³/s at the inlet. The flow velocity of the gas in the inner alumina tube is predicted to be 0.4 m/s, and the remaining time of the gas is about 0.18 s in the dipped part. The flow velocity of the gas is about 0.048 m/s in the ring area between the outer and inner tubes in Fig. 1(b). Accordingly the gas is
Fig. 2. Appearance and microstructure of cross section of the refractory test piece-A at a 40 mm distance away from its bottom after dipping test [test conditions: \( P_{\text{in}} = 0.47\times10^6 \) Pa, \( t_{\text{dip}} = 60 \) min and Ar+20%O\(_2\) gas]

Fig. 3. Appearance and microstructure of cross section of the refractory test piece-Z at a 40 mm distance away from its bottom after dipping test [test conditions: \( P_{\text{in}} = 0.47\times10^6 \) Pa, \( t_{\text{dip}} = 60 \) min and Ar+20%O\(_2\) gas]

Fig. 4(a)  Fig. 4(b)

Fig. 4. SEM images of deposit on the surfaces of (a) test piece-A and (b) test piece-Z.
heated for about 1.5 s on passing through dipping zone. Thus the gas is heated totally for about 1.7 s. Accordingly the gas temperature seems to be attained the same temperature on the inner surface of the test piece hole. Since the temperature of dipped part of the test piece is thought to be as same as the molten steel temperature, the gas temperature is equal to approximately the molten steel temperature. Accordingly, the gas volume seems to be expanded 6.2 times in the dipping part of the test piece.

The flow rate of permeated gas was defined from which the permeated gas volume, \(Q_G\), is converted to a gas flow rate per second and unit area (m\(^2\)), and calculated at 1853 K. The flow rate of permeated gas is shown in Fig. 5 against the pressure difference between the inside and the outside of the chamber for a 10-mm thick test piece. The flow rate of permeated gas is proportional to the pressure difference. The flow rate of permeated gas for the test piece-A is smaller than that of the test piece-Z. On the other hand, for a test piece coated on the whole inner surface with an anti-oxidation reagent, its flow rate of permeated gas is decreased about one-thirds in comparison with that of the test piece without an anti-oxidation reagent.

### 3.2.2. Estimation of the Permeability of Submerged Entry Nozzle Materials

We will estimate the permeability, \(\kappa\), of the SEN material from measurement of the flow rate of permeated gas. Figure 6 shows the flow rate of the gas permeated through the cylindrical and the plate walls calculated according to Darcy’s law.

![Diagram](image)

**Fig. 5.** Relation between flow rate of permeated gas and pressure difference \(\Delta P\).

When a compressive gas permeated through a porous cylindrical tube with inner and outer radii \(R_1\) and \(R_2\), the flow rate of the gas permeated through a porous tube can be given by Darcy’s law. When the pressures are \(P_{\text{in}}\) and \(P_{\text{out}}\) at inner and outer surfaces and the length of cylindrical tube and the thickness of bottom of the hole in a test piece are \(h\) and \(L\), the permeated gas volume, \(Q_G\), is given as

\[
Q_G = \frac{k \eta G (P_{\text{in}}^2 - P_{\text{out}}^2)}{\eta_G P_{\text{in}} \ln(R_{\text{out}}/R_{\text{in}})} + \frac{k \pi R_1^2 (P_{\text{out}} - P_{\text{in}})}{\eta_G L}\quad \quad (2)
\]

Here, \(\eta_G\) is the viscosity of gas at high temperatures and was estimated using an estimation equation in the literature. \(^5\)

Substituting numerical values of the dipping test condition into Eq. (2), we calculated the permeability, \(\kappa\). The permeability is in an order of \(10^{-11}\) to \(10^{-14}\) m\(^2\) as shown in Fig. 7 as a function of porosity of the test piece. The \(\kappa\) is increased with increasing porosity. The \(\kappa\) of refractory castables is reported in the ranges of \(1 \times 10^{-17}\) to \(1 \times 10^{-15}\) m\(^2\). \(^6\)

The permeability determined in this experiment is fairly larger than that reported in the literature. The reason for larger permeability is not made clear in this study.

The reason for smaller flow rate of permeated gas for the test piece-A than that for the test piece-Z seems to be attributable to a difference in porosity. For a refractory coated with an anti-oxidation reagent the permeability is decreased about one-thirds in comparison with a refractory without anti-oxidation reagent. Because the anti-oxidation reagent is changed to a viscous liquidus state at 1853 K, the liq-

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\(^5\) Fig. 5. Relation between flow rate of permeated gas and pressure difference \(\Delta P\).

\(^6\) Fig. 6. Flow rate of gas permeated through (a) a cylindrical wall and (b) a plate calculated from Darcy’s law.

\(^7\) Fig. 7. Relation between permeability calculated from observation of the flow rate of permeated gas and porosity of refractory.
uidus reagent will penetrate into the refractory. Hence the apparent porosity seems to be lowered.

We will check the validity of the observed permeability using Kzeny–Carmann’s equation\(^7\) given as

\[
\frac{u}{H_11005} = \frac{Q_G}{A_S} \cdot \frac{G}{\eta_0 \cdot L} \quad \quad (3)
\]

where, \(u\) is the flow rate of permeated gas, given by \(u=Q_G/A_S\).

By comparing Eq. (3) with the second term in right side of Eq. (2), the permeability, \(\kappa\), is given as

\[
\kappa = \frac{e^3}{(1 - e)^2} \frac{D_p^2}{180} \quad \quad (4)
\]

In order to evaluate the \(\kappa\) from Eq.(4), we necessarily know the porosity, \(e\) of refractory and the shapes of materials of which the refractory is composed. When we assume that the shape of materials is sphere and the diameter are 10 \(\mu\)m or 25 \(\mu\)m, which is smaller among particle diameters, we can predict the permeability by the two curves in Fig. 7, respectively. The predicted permeability comparatively agrees with the determined one from measurement of the flow rate of permeated gas.

3.3. Change of Chemical Composition of Molten Steel before and after Dipping Test

Change of chemical composition of molten steel is shown in Fig. 8 before and after the dipping test under a dipping time of 60 min, Ar+20%O\(_2\) gas and a pressure in the chamber of 4.7\(\times\)10\(^4\) Pa. In the case of test piece-A, although the concentration changes, \(\Delta[C]\) and \(\Delta[Si]\), of carbon and silicon are increased, the concentration change, \(\Delta[Al]\), of aluminum is decreased. In contrast, for the test piece-Z, \(\Delta[C]\) is increased, but \(\Delta[Si]\) is approximately zero, that is, the concentration of Si, ([Si]), is remained constant, and \(\Delta[Al]\) is similarly decreased. The reason for remaining [Si] constant is that the amount of SiO\(_2\) contained in test piece-Z is negligible as shown in Table 1.

When the oxygen in permeated gas is assumed to react with aluminum dissolved in molten steel and alumina is formed, the concentration change, \(\Delta[Al]_{\text{cal}}\), of aluminum can be predicted from the total amount of permeated gas as

\[
\Delta[Al]_{\text{cal}} = \frac{4}{3} \frac{Q_G \cdot f_{Al} \cdot f_{O_2}}{R \cdot T_G} \cdot \frac{m_{Al}}{\rho_S} \quad \quad (5)
\]

The prediction is compared with the concentration change, \(\Delta[Al]_{\text{cal}}\) of aluminum determined from chemical analysis as shown in Fig. 9. The line in Fig. 9 indicates the predicted concentration change from Eq. (5). All predicted data are larger than the observation, and a datum for the pure oxygen gas test, which is shown in a filled round mark, is especially larger.

When we observed the molten steel surface from a window of the chamber during dipping test we could see always gas release from the surface of molten steel. Figure 10(a) shows a state of surface of molten steel when the gas flow is stopped, while Fig. 10(b) shows the same surface of molten steel when the pure oxygen gas was flown at 100 ml/min. We can see a difference of state of molten steel between Figs. 10(a) and 10(b). The gas is clearly released from the molten steel surface. In this experiment, it is implied that the amount of oxygen in the diffusing gas was not fully consumed for oxidation of aluminum.

3.4. Prediction of Oxidation of Molten Steel by Air Permeated through a Submerged Entry Nozzle

We will predict an amount of oxidation of molten steel by air permeated through a SEN during continuous casting.

In order to predict the flow rate of the air permeated through the SEN, we need to know a pressure drop in the molten steel when molten steel flows into a SEN just after a sliding nozzle.

3.4.1. Pressure Loss of Molten Steel Flow Passing through the Submerged Entry Nozzle

(1) Analytical Method

When molten steel is transferred from a tundish to a
mold through a sliding nozzle gate and a SEN, molten steel flow is enlarged in a SEN just below the sliding nozzle as shown in Fig. 11. Since the depth of molten steel bath is remained constant, the velocity of molten steel flow is constant at the exit of the sliding nozzle. The flow rate control system with a sliding nozzle gate has a pressure-loss, $\Delta P_f$, associated with a sudden enlargement. Now, planes (1) and (2) in Fig. 11 are located at the exit of sliding nozzle and in a SEN just below the sliding nozzle gate. Since the head, $h$, is small, we assume it is neglected. For simplicity, molten steel flow is assumed an ideal fluid. For steady state condition, Bernoulli’s equation is given as

$$\rho \cdot Q = \rho \cdot A_1 v_1 = \rho \cdot A_2 v_2 \quad \text{(9)}$$

Combining conservation of momentum equation [Eq. (8)] and continuity equation [Eq. (9)] with Eq. (7), we get Eq. (10).

$$\frac{\Delta P_f}{\rho g} = \left(1 - \frac{A_1}{A_2}\right) \frac{v_1^2}{2g} \quad \text{(10)}$$

When a molten steel flow is suddenly enlarged, the pressure drop generated can be calculated from Eq. (10).

For an actual caster an opening area ratio, $A_1/A_2$, of sliding nozzle ranges from 0.2 to 0.7. We predict the pressure drop, $\Delta P_f$, using the following values: the velocity of molten steel at plane (1), $v_1/\sqrt{\rho g h}$, the bath depth in tundish, $h_1 = 1.3$ m, the opening area ratio, $A_1/A_2 = 0.2–0.7$ and the density of molten steel, $\rho = 7000\text{ kg/m}^3$. The pressure drop, $\Delta P_f$, is attained about 57 000 Pa and 8 000 Pa, respectively, corresponding to the opening area ratios $A_1/A_2$ of 0.2 and 0.7. The pressure in molten steel at the plane (2) is predicted to be $0.57 \times 10^5 \text{ Pa (0.44 atm)}$ and $0.93 \times 10^5 \text{ Pa (0.92 atm)}$ for an opening area ratio, $A_1/A_2$, of 0.2 and 0.7, and lower than the atmospheric pressure ($1.0133 \times 10^5 \text{ Pa}$).

(2) Numerical Calculation Method

A computer simulation was conducted in three dimensions of pressure distribution in molten steel flow pouring into a mold through a tundish nozzle and a SEN as shown in Fig. 12. Navier–Stokes equation was solved for steady state condition by a finite-volume approach with a computer simulation of fluid dynamics, Fluent code. The number of small body cells is about 65 000 to 70 000. A standard $k-\varepsilon$ model is used as a turbulent model. Temperature is constant in a whole calculation area.

The boundary conditions are also shown in Fig. 12. The static pressure is given $4 \times 10^4 \text{ Pa}$ at the inlet of tundish nozzle and zero at the outlet of calculation area, i.e., at the exit of a mold. A sliding nozzle gate adjusts the flow rate of molten steel. The opening area ratio in a sliding nozzle gate to a SEN is given 0.2, 0.4 and 0.6, and the resultant flow rate is attained 3.6, 5.1 and 6.3 t/min, respectively. In the calculation, the density is 7 000 kg/m$^3$, and the viscosity of molten steel is $7 \times 10^3 \text{ Pa} \cdot \text{s}$.
Area in the SEN where the total pressure in molten steel flow is lower than the atmospheric pressure, and the pressure contours are shown in Fig. 13 for an opening area ratio of sliding nozzle gate, 0.2, 0.4 and 0.6. The negative pressure is revealed at the area except for the exit of the molten steel jet and below the sliding nozzle gate. The total pressure is steeply reduced. The area where the total pressure is decreased extends to wider area with decreasing opening.

Fig. 13. Calculated negative pressure area in nozzle with numerical calculation [opening area ratio in sliding nozzle gate: (a) 0.2, (b) 0.4, and (c) 0.6].

Fig. 15. Calculated contours of velocity in submerged entry nozzle with numerical calculation [opening area ratio in sliding nozzle gate: (a) 0.2, (b) 0.4, and (c) 0.6].
The minimum pressure in the molten steel flow is exhibited on the inner surface of the SEN just below the sliding nozzle gate. The minimum pressure is plotted in Fig. 14 against the opening area ratio of the sliding nozzle gate. This pressure is decreased with decreasing opening area ratio. At an opening area ratio of 0.2, the minimum pressure is attained about \(-0.3 \times 10^5\) Pa (about 0.7 atm).

Figure 15 shows the calculated contours of velocity of molten steel flow for an opening area ratio of 0.2, 0.4 and 0.6. The molten steel jet from the sliding nozzle gate extends downward along one-side wall in the SEN. The length of the molten steel jet becomes longer with decreasing opening area ratio. A circular flow is revealed on the opposite side to the jet in SEN just below the sliding nozzle gate.

3.4.2. Oxidation of Molten Steel by the Air Permeated through the Submerged Entry Nozzle

The flow rate, \(u\), of the air permeated through the SEN is calculated by the first term in Eq. (2). The analytical approach gives the pressure drop nearly \(0.44 \times 10^5\) Pa in the SEN just below the sliding nozzle, and the numerical calculation gives about \(0.3 \times 10^5\) Pa at a flow rate of \(3.6\) m/min. Thus when the pressure difference, \(\Delta P\), between outer and inner surfaces of SEN below the sliding nozzle gate is assumed \(0.4 \times 10^5\) Pa, the flow rate of the permeated air will be calculated. The length, \(h\), of negative pressure area is assumed equal to around 5 to 8 times of a fluid flow jet diameter, \(D\), i.e., \(h = 8 \times D\). The numerical values used for prediction of the flow rate of permeated gas are as follows: \(P_{in} = 0.6 \times 10^5\) Pa, \(P_{out} = 1.0133 \times 10^5\) Pa, \(R_{in}/R_{out} = 0.64\), \(\kappa = 1.2 \times 10^{-14}\) m², and the viscosity is given by an estimation equation in the literature.

When the permeated air is all consumed to oxidize molten steel, the concentration change of aluminum formed by oxidation of molten steel caused by the permeated air is estimated 0.35 ppm as shown in Fig. 16. The amount of oxygen equivalent to the decrease of aluminum is fairly small, 0.53 ppm in this case, in comparison with the total amount of oxygen remaining in molten steel, about 15–20 ppm.

The alumina formed by the permeated air is deposited on the inner surface of the SEN will be converted to a build-up thickness when the volume space rate of the deposited alumina is assumed 0.5. Resultantly, the build-up thickness of alumina is predicted about 0.35 mm per hour. The value is very small in comparison with the total thickness, 10–20 mm, of alumina build-up after a casting time over 200 min in an actual caster.

Accordingly, the alumina formed by the air permeated through the SEN is not a cause of SEN clogging.

4. Conclusions

Refractory tubes are employed for molten steel transferring from a ladle to a tundish, and a tundish to a mold, to prevent molten steel from oxidizing. When the cross-sectional area is suddenly contracted and subsequently enlarged in the molten steel flow channel, the pressure in the fluid flow is generated lower than the atmospheric pressure. Thereby the air is sucked into the inside of the refractory tube and oxidizes the molten steel.

The flow rate of the gas permeated through the refractory tube was measured with a dipping test of the cylinder type test piece for submerged entry nozzle, and the permeability of the refractory was estimated from measurement of flow rate of permeated gas. The permeabilities of Al₂O₃–SiO₂–graphite type and ZrO₂–CaO–graphite type refractories for submerged entry nozzle are approximately \(1.2 \times 10^{-14}\) m² and \(2.6 \times 10^{-14}\) m², respectively, at a temperature of molten steel, 1853 K.

Also the refractory coated with an anti-oxidation reagent can reduce the permeated air to about one-thirds in comparison with the refractory without anti-oxidation reagent. The concentration change of aluminum by the air permeated through the refractory is predicted to be less than 0.35 ppm per hour during molten steel transferring from a tundish to a mold. Thus alumina formed by the permeated air does not attribute to alumina build-up in the submerged entry nozzle.

Nomenclature

- \(A_s\) : Surface area (m²) of gas permeated through a refractory
- \(A_1\) and \(A_2\) : Cross-sectional area (m²) at planes (1) and (2)
- \(D_2\) : Equivalent diameter (m) of jet at the sliding nozzle gate
- \(D_p\) : Diameter (m) of particles of which refractory is composed
- \(L\) : Thickness (m) of the bottom of the hole in the test piece or of porous plate
- \(f_{O_2}\) : Volume fraction (\%) of oxygen gas
\( g \): Gravity acceleration (m/s\(^2\))

\( h \): Length (m) where the air is permeated into an inside of the SEN

\( \Delta h \): Head (m) of molten steel

\( m_{\text{Al}} \): Atomic weight (g) of aluminum

\( m_{\text{G}} \): Molecular weight (g) of gas

\( P_1 \) and \( P_2 \): Pressure (Pa) in molten steel flow at planes (1) and (2)

\( P_{\text{in}} \) and \( P_{\text{out}} \): Pressure (Pa) in the inside and outside of refractory tube

\( \Delta P \): Pressure difference (Pa) between inside and outside of the SEN

\( \Delta P_f \): Pressure drop (Pa) of molten steel caused by enlargement of fluid flow

\( Q_{G} \): Permeated gas volume (m\(^3\)/s) through refractory

\( Q_{\text{in}}, Q_{\text{out}} \): Gas flow rate (m\(^3\)/s) at inlet and outlet sides

\( Q \): Volumetric flow rate (m\(^3\)/s) of molten steel at planes (1) and (2)

\( T_G \): Gas temperature (K)

\( t_{\text{dip}} \): Dipping time (s)

\( u \): Flow rate (m/s) of gas permeated through a refractory

\( v_1 \) and \( v_2 \): Velocity (m/s) of fluid flow above and below the sliding nozzle gate

\( W_{\text{Fe}} \): Weight (kg) of steel melt in the experiment

\( \eta_G \): Viscosity (Pa·s) of gas,

\[ \eta_G = 2.6693 \times 10^{-5} \sqrt{m_G T_G / \sigma^2 \Omega} \]

\( \varepsilon \): Porosity (—)

\( \rho \): Density (kg/m\(^3\)) of molten steel

\( \kappa \): Permeability (m\(^2\)) of the refractory

\( \sigma \): Characteristic diameter (m) of the molecule, i.e., a collision diameter

\( \Omega \): Parameter for estimation of gas viscosity

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