Mechanism of the Formation of Slag Particles by the Rotary Cylinder Atomization

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Slag is a potential resource of energy and materials because it contains a lot of elements and is at the high temperature of around 1500°C when exhausted.

In the previous study, we developed a rotary cylinder atomizing (RCLA) method that can efficiently use the rotation energy for atomizing the molten slag. The minimum diameter of the slag particle was from 10 to 50% of the nozzle diameter. The obtained slag particles were amorphous spheres with high aspect ratios. The higher rotation speed and smaller nozzle diameter could make smaller particles. In the present study, the mechanism of slag particle formation from spouting slag string through the nozzle was investigated using the high-speed camera and the theoretical approach was performed.

The relationship between the particle diameter \(d\) and nozzle diameter \(2a\) was derived as follows:

\[
2a = \frac{\pi^2 \rho L z^3}{5400 \gamma} d^3
\]

Where \(\rho\) is density, \(L\) is the distance from the center of rotation to the tip of the slag string, \(z\) is rotation speed and \(\gamma\) is surface tension of slag.

The flow rate of slag was evaluated using Hagen–Poiseuille’s equation and the relationship between the particle diameter and the slag string diameter was obtained using Weber’s equation. By comparison between the experimental and calculated results, we concluded that a string diameter of 0.2 mm for a 1.3 mm nozzle diameter was adequate in this experiment.

KEY WORDS: mechanism of slag atomizing; slag recycle; amorphous slag; rotary cylinder atomizing.

1. Introduction

The decrease of CO\(_2\) emission is a main subject for steel industry. Many approaches for the reuse and recycle of the waste energy and materials are conducted for developing and modifying the processes in many fields. Under such circumstances, slag is a potential resource of energy and materials because it contains a lot of elements and is at the high temperature of around 1500°C when exhausted. In addition, the effective use of the waste energy and the by-product as a high temperature slag would be quite fundamental approach for CO\(_2\) reduction.

Several dry quenching and atomizing processes not requiring water have been studied \(^1\)-\(^3\) including hydrogen production using the methane–water chemical reaction. The RCS (Rotary Cup Atomizer) method is a typical dry process for making slag particle \(^4\),\(^5\) however, it has some disadvantage on the mechanism of slag atomizing that the energy of rotation can be not used.

In the previous study \(^6\), we developed the two kinds of rotary cylinder atomizing (RCLA) method (two-nozzle cylinder and multi-nozzle cylinder) for utilizing the heat and slag itself.

In the present study, the mechanism of the slag particle formation by the RCLA method was investigated and the theoretical approach of the formation of slag particle from a slag string was performed.

2. Experimental

The details of the experimental setup were shown in the previous paper \(^6\). The rotation speed can be change from 600 to 3000 rpm. The observation system consisted of a high-speed camera, metal halide light and computer.

The slag is heated up in a graphite crucible. When the temperature becomes stable at the given experimental temperature and the rotation speed reaches its desired speed, the slag melt is dropped into the cylinder. The obtained slag particles are received by the container wall and pan set in the bottom of container, and collected at the end of experiment.
The crucible for slag melting is made of graphite and located just above the center of the rotary cylinder. The bottom of the crucible has a 6-mm hole, which is closed by a graphite stopper. The stopper is put on the tip of the alumina thermocouple protection tube (B type, 0.5 mm). Therefore, the stopper has a combined function for temperature measurements and slag casting.

In this study, two kinds of cylinders were used. The first is a two-nozzle rotary cylinder and the other is multi-nozzle rotary cylinder, they are compared in Fig. 1.

Figure 1(a) depicts a schematic of the two-nozzle rotary cylinder used for the BF slag atomizing. The nozzle has a screw on one end that can be changed for differently sized nozzle diameters. Because the graphite material has a relatively high thermal conductivity, the cylinder body is insulated by a porous mullite tube.

In this experiment, slag (15 g) with a volume of about 5.7 cm³ was heated to 1550°C. When the slag was completely melted and the temperature was stabilized, the stopper was pulled out for dropping the molten slag into the cylinder. The behaviors of the slag spouting and atomizing were simultaneously digitally recorded by a high-speed camera.

In the previous paper, the rotation speed was changed from 600 to 1600 rpm, and the nozzle diameter was changed from 1.0 to 2.0 mm. Among these conditions, the results for the two-nozzle cylinder with 1100 rpm at 1.3 mm of nozzle diameter and for the multi-nozzle cylinder with 300 rpm at 1.3 mm of nozzle diameter were analyzed.

Because the throughput of the two-nozzle cylinder was relatively low, a multi-nozzle cylinder was developed to increase the slag treatment. A schematic of the multi-nozzle cylinder is shown in Fig. 1(b). The multi-nozzle cylinder contained 63 (1.3-mm) holes on its side, with 3 vertical rows spaced at 8 mm and each containing 21 holes. The slag melting crucible is attached on top of the multi-nozzle cylinder to minimize the heat loss during atomization.

A high-speed camera equipped with metal halide light is used to monitor the slag atomization. The shutter speed is 1/8000 s, and the frame rate is 2000 fps (frame per second). The camera is set in the upper direction at 45° from the rotary cylinder.

3. Results and Discussion

3.1. Observation of Slag Atomizing Behavior by a High-speed Camera

Figure 2 shows a typical observation by the high-speed camera; in this case, the sample was BF slag, the nozzle diameter was 1.3 mm and the rotation speed was 1100 rpm. The nozzle position is emphasized by white lines and the direction of rotation is indicated by a gray arrow. The coil of the induction furnace and the white portion near the coil, which is the body of cylinder and made of an alumina tube for insulation, can be seen. The spouted slag is initially a string, but then the string separates into particles that Rayleigh’s theory can be applied. The spouting slag from the nozzle was stretched from both sides by the centrifugal force at the string tip and the rotation movement of the nozzle at the other end of string (when the string was connected to the nozzle). From this force balance, the slag string became thin and a necking occurred. Finally, the string separated into particles. The diameter of the slag string was not always the same as the nozzle diameter. This mechanism is illustrated in Fig. 3.

The centrifugal force is expressed by Eq. (1).

$$F_c = rac{mV^2}{L} \quad (1)$$

where $L$ represents the distance from the center of rotation to the tip of the slag, $m$ is the weight of slag, and $V$ is the velocity of rotation, as expressed by Eq. (2).

$$V (m/s) = \frac{2\pi ZL}{60} \quad (2)$$

where $Z$ (rpm) is the rotation speed. The velocity could be estimated exactly at the point of the nozzle. However, the point at the tip of the slag string is difficult to measure and has a variable length ($L$). In this study, a simplified assumption was adopted, as shown in Fig. 3.

The weight of particle $m$ (g) was calculated by Eq. (3).
\[ m = \frac{\pi}{6} d^3 \cdot \rho_s \] ...............(3)

where, \( d \) is the diameter of the particle obtained in the present experiment, and \( \rho_s \) is the density of the slag at the experimental temperature and was assumed to 2.62 g/cm³.

The surface tension acting opposite to \( F_s \) is expressed as in Eq. (4).

\[ F_s = 2 \pi a \cdot \gamma \] ..................................(4)

where \( \gamma \) is the slag surface tension, which was assumed to be 0.55 N/m, and \( a \) is the radius of the slag string. In this study, the diameter of the slag string (\( 2a \)) was estimated using the obtained particle size, assuming the balance between \( F_s \) and \( F_T \) was preserved.

\[ 2a = \frac{\pi^2 \rho LZ^2}{5 \cdot 400 \gamma} d^3 \] ..................(5)

On the other hand, Rayleigh’s equation \(^1\) for a non-viscous liquid is expressed in Eq. (6).

\[ 2a = \frac{d}{1.89} \] ..................(6)

The results calculated using Eq. (5) at 1 100 rpm, 1 600 rpm and 3 000 rpm are shown in Fig. 4. When the particle diameter was 0.1 cm (1.0 mm), the diameter of slag string was almost the same at 1 100 rpm, twice its size at 1 600 rpm and 0.8 cm at 3 000 rpm. If the particle diameter was decreased to half of its size (0.05 cm), which was near the minimum size of the obtained particle diameters, the string diameter became around 0.02 cm. The string size is quite thin in comparison to the nozzle diameter. When Rayleigh’s equation (Eq. (6)) for a non-viscous liquid was used, a relatively large string size yielded a small particle size less than 0.07 cm in diameter and vice versa.

3.2. Estimation of Slag Flow Rate from the Nozzle

The slag now from the nozzle decreased with diminishing amounts of slag remaining in the cylinder and lower temperatures. The Hagen–Poiseuille law was applied to estimate the slag flow rate.

Figure 5 shows a schematic of the cylinder and nozzle. \( L (m) \) is the length from the rotating cylinder to the inlet position of the nozzle. The nozzle radius is \( \text{‘} r(m) \) and the length is \( \text{‘} L(m) \). The radius of the cylinder is \( \text{‘} R(m) \), and \( \text{‘} L_s(m) \) is the length of the slag remaining in the cylinder, which changes with time. The pressure applied by the centrifugal force at the nozzle inlet and outlet is \( \text{‘} P_s (N/m^2) \) and \( \text{‘} P_t (N/m^2) \), respectively.

The velocity of the nozzle \( V(m/s) \) at position \( L \) is expressed by Eq. (7).

\[ V(m/s) = \frac{2\pi ZL}{60} \] ..................(7)

where \( Z \) is the rotation speed (rpm).

The initial weight of the slag was \( m_0 \) (kg) and can be expressed by Eq. (8).

\[ m_0 (kg) = \rho \pi R^2 L_s \] ..................(8)

The weight of slag decreased with time (s),

\[ m_t (kg) = \rho \pi R^2 L_s - Q \cdot t \cdot \rho \] ..........(9)

where \( Q (m^3/s) \) is the slag flow rate and \( \rho (kg/m^3) \) is the slag density and was assumed to be 2.620 kg/m³. In the next session, the precise equation was used, as shown in Appendix I(1). However, constant density was used here for simplification.

The centrifugal force \( F_L (N) \) at position \( L \) is

\[ F_L = \frac{m_0 V^2}{L} \] ..................(10)

Form Eqs. (7), (9) and (10), the time-dependent centrifugal force is expressed by Eq. (11).

\[ F_L = \frac{\pi^2 Z^2 L^2 (\rho \pi R^2 L_s - Q \rho)}{900} \] ............................(11)

The pressure \( P_L \) at position \( L \) is expressed by the addition of the atmospheric pressure \( P_o \).

\[ P_L = \frac{F_L}{\pi R^2} + P_o \] ............................(12)

Using Eqs. (11) and (12), the pressure for the slag spouting can be expressed by Eq. (13).

\[ P_L = \frac{\pi^2 Z^2 L^2 (\rho \pi R^2 L_s - Q \rho / \pi R^2)}{900} + P_o \] ............................(13)

The flow rate of the slag from the nozzle \( Q (m^3/s) \) can be expressed by the Hagen–Poiseuille law.

\[ Q = \frac{(P_s - P_t)}{8 \mu l} \pi r^4 \] .................(14)

where \( \mu (N\cdot s\cdot m^{-2}) \) is the slag viscosity and can be calculated using the empirical equation Eq. (17) for simplification. A more accurate equation was used in the next session for estimation of the flow rate, as described in Appendix I(3).

The pressure at the nozzle outlet, \( P_t (N/m^2) \), can be assumed to be equal to \( P_o (N/m^2) \). The derivation of Eq. (13)
provides the variation of the slag flow rate with time.

\[
Q = \frac{\pi^{-4}}{8\mu l} \left( \frac{\pi^2 L^4 (\rho L_S - \frac{Q^2}{\pi R^2})}{900} \right)
\]

\[
= \frac{\pi^3 r^4 Z^2 L^2 (\rho L_S - \frac{Q^2}{\pi R^2})}{7200\mu l}
\] ............(15)

Finally, the flow rate can be expressed by Eq. (16).

\[
Q = \frac{\pi^3 r^4 Z^2 L^2 \rho L_S}{7200\mu l + \pi^2 r^4 Z^2 L^2 \rho}
\] ............(16)

where the values for the calculations were assumed to be:

- \(L=0.076\ m\), \(R=0.004\ m\)
- \(Z=600, 1100\) and \(1600\) rpm, \(l=0.01\ m\)
- \(\rho=2.620\ \text{kg/m}^3\), \(L_s=0.01425\ m\)

In addition, the temperature dependence of viscosity, \(\mu\) (N·s·m²), was calculated by Eq. (17).

\[
\mu = 0.46 \times 10^{-6} \exp \left( \frac{2.03 \times 10^4}{T} \right)
\] ............(17)

The total slag spouting from the nozzle, \(Q_T\), can be expressed as the summation of the two nozzles integrated with time.

\[
Q_T = 2\rho \sum Q \cdot \Delta t
\] ............(18)

Using Eq. (16) and Eq. (18), the slag now rate (\(Q\)(cm³/s)) and the total slag flow rate (\(Q_T\)) were estimated with the following conditions: Nozzle diameter: 1.0 mmφ, 1.3 mmφ, and 2.0 mmφ, Rotation speed: 600 rpm, 1100 rpm and 1600 rpm, Temperature: 1400°C, 1500°C and 1600°C. The calculated results are shown in Figs. 6, 7 and 8.

Figure 6 shows the calculated results of the slag flow rate and the total weight of slag with a 0.1 mmφ nozzle diameter and 600 rpm rotation speed. With a decreasing rotation speed, the initial flow rates ranged from 0.2 to 1.0 cm³/s. The time for the decreased flow rate was about 0.1 s. The initial slag weight was 15 g and the time to reach the initial slag weight was 300 s at 1400°C, 150 s at 1500°C and 80 s at 1600°C. Although the slag was melted at 1450°C, the actual temperature during atomization was around 1400°C or less. The amount of slag spouting from the nozzle was very small, because the temperature decreased before all of the slag spouted. Therefore, some of the slag solidified in the cylinder.

Figure 7 shows the results using a speed of 1100 rpm and a nozzle diameter of 1.3 mmφ. The initial flow rates were from 1.7 to 7.3 cm³/s, as the temperature increased from 1400 to 1600°C. After 0.01 s, the flow rate started to decrease. The time to reach a slag weight of 15 g was 40 s at 1400°C, 22 s at 1500°C and 12 s at 1600°C. Using the slag string movement shown in Fig. 2 and the frames before and after 0.0005 s, the length of the slag before separating was measured. The length of the string elongated within 0.0005 s was 15 mm, from which the flow rate \(Q_{exp}\) (cm³/s) was estimated as 39.8 (cm³/s) when the diameter of the slag string (\(d_s\)) was assumed to be 1.3 mm. The flow rate of 39.8 (cm³/s) is plotted in Fig. 7 at \(t=0\), which is a relatively large value even for a temperature of 1600°C. However, as mentioned above (Fig. 4), the minimum diameter of the ob-

Fig. 6. Flow rate of slag estimated from the Hagen–Poiseuille equation (nozzle diameter=1.0 mm, rotation speed=600 rpm).

Fig. 7. Flow rate of slag estimated from the Hagen–Poiseuille equation (nozzle diameter=1.3 mm, rotation speed=1100 rpm).

Fig. 8. Flow rate of slag estimated from the Hagen–Poiseuille equation (nozzle diameter=2.0 mm, rotation speed=1600 rpm).
tained slag particle was around 0.6 mm\(\phi\), from which the diameter of slag string could be estimated as 0.2 mm\(\phi\) in Fig. 4. Using this value (0.2 mm\(\phi\)), \(Q_{\text{exp}}\) (cm\(^3\)/s) was calculated to be 0.94 (cm\(^3\)/s), which is also plotted in Fig. 7. The results indicated that the assumption of the thin slag string around 0.2 mm\(\phi\) is in excellent agreement with the calculated results at temperatures less than 1400°C. The value of 0.2 mm\(\phi\) was also used later with Weber’s equation.

In Fig. 8, slag flow rates with a nozzle diameter 2.0 mm\(\phi\) and speed of 1600 rpm are shown. At three temperatures, the slag flow rates were quite high and a total slag weight of 15 g was quickly attained in 1 s.

3.3. Slag Atomizing Behavior in Multi-nozzle Cylinder

Observations by a high-speed camera were performed on the slag atomization behavior in the multi-nozzle rotary cylinder, as shown in Fig. 9. The rotation direction of the cylinder is shown by an arrow on the left side. A 1.3 mm\(\phi\) nozzle diameter and 3000 rpm rotation speed were used.

Figures 9(a), 9(b) and 9(c) are images taken at every 0.0005 s. These pictures revealed two kinds of particle movements. One is the same movement as in the two-nozzle cylinder as described above. When focusing on the nozzle (notation: \(N_{\text{A}(1)}\) at \(t=0\) s), the slag was string-shaped (Fig. 9(a)). The slag string moved to \(N_{\text{A}(2)}\) at \(t=0.0005\) s (Fig. 9(b)) and to \(N_{\text{A}(3)}\) at \(t=0.001\) s (Fig. 9(c)) indicating that the tip of the string gradually separated into particles.

The other movement was in an upward direction from the left to right, which is characteristic for the multi-nozzle cylinder. The slag particles undergoing this movement were relatively large and the slag became spherical on the front of the nozzle, before being directly ejected in the direction of the arrows.

As shown in Fig. 1(b), the multi-nozzle cylinder has a total of 63 nozzles, which from three lines of 21 nozzles each. Because the total slag weight was 15 g (about 5.7 cm\(^3\), 2.62 g/cm\(^3\)) and the volume of the cylinder was about 47 cm\(^3\), the slag in the cylinder only occupied 12% of the cylinder space. Therefore, the slag in the cylinder did not touch the inlet of all nozzles, so the slag spouting pressure was not uniform. When the slag volume was large enough (Fig. 10(a)), similar results as those from the two-nozzle experiment were expected.

While the slag volume behind the nozzle was small (Fig. 10(b)), the sprouting pressure was small and the slag could be spherical at the nozzle tip.

3.4. Theoretical Approach with Rayleigh’s and Weber’s Law

Rayleigh’s equation\(^1\) (Eq. (6)) describes atomization in a non-viscous liquid. On the other hand, Weber’s equation\(^1,7,8\) (Eq. (19)) was derived for viscous liquids as follows:

\[
\frac{d}{2a} = 1.88 \left(1 + \frac{3\mu}{\sqrt{2\sigma \rho \gamma}}\right)
\]  

(19)

where ‘\(d\)’ is the diameter of the particle and ‘\(a\)’ is the radius of the slag string. \(\rho\) (kg/m\(^3\)), \(\gamma\) (N/m) and \(\mu\) (Ns/m\(^2\)) are the density, surface tension and viscosity of the liquid, respectively. In this study, parameters, such as density,\(^9,13\) surface tension\(^9,12\) and viscosity,\(^9-11\) were formulated as a function of temperature, as shown in Appendix I.

The calculated results for the particle diameter (‘\(d\)’) are shown in Fig. 11. The diameters of slag string (‘2\(a\)’) were assumed to be 1.3 mm\(\phi\) (solid line) and 0.2 mm\(\phi\) (broken line). The former is the same as the nozzle diameter and the latter was as estimated as above (Fig. 4). The temperature of the slag was 1450°C before being thrown into the cylinder. However, the actual temperature during atomization was expected to be less than 1450°C. The ranges of the obtained particle sizes at 600 rpm, 1100 rpm and 1600 rpm are plotted in Fig. 11. A 0.2-mm in diameter of the slag string agrees well with experimental results. The results shown in Fig. 11 reveal that the diameter of the slag string must be less than 0.2 mm at higher rotation speeds (1100 rpm and 1600 rpm).

4. Conclusions

The slag atomizing mechanism was studied through the results of high-speed camera and the theoretical approach was performed on the basis of Rayleigh’s law and Weber’s law.
The obtained results are as follows:

1. The slag was a string-shaped when it was spouted from the nozzle. The relationship between particle and particle diameter (d) and nozzle diameter (2a) was derived as follows:

\[
2a = \frac{\pi^2 \rho L Z^2}{5400 \gamma} \frac{1}{d^3}
\]

2. The slag flow rate was evaluated using Hagen–Poiseuille’s equation. We concluded that a slag string about 0.2 mm in diameter, which was smaller than the nozzle diameter of 1.3 mm, was adequate for explaining the flow rate of slag.

3. Using Weber’s equation, the relationship between the particle diameter and slag string diameter was obtained. By comparison between the experimental and calculated results, we determined that a string diameter of 0.2 mm is adequate.

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Appendix I

(1) Density of BF Slag as a Function of Temperature

Equation (A1) was presented by Koshida. The reference data for two kinds of slag\(^9\) are plotted in Fig. A1 for comparison with the calculated results of Eq. (A1). The slag compositions in the reference are (a) CaO 45.3%, SiO\(_2\) 37.1%, Al\(_2\)O\(_3\) 17.6%, C/S = 1.22 and (b) CaO 43.6%, SiO\(_2\) 38.2%, Al\(_2\)O\(_3\) 18.2%, C/S = 1.14.\(^9\)

\[
1/\rho = 0.355 + (1.913 \times 10^{-5}) \cdot T(\degree C) \quad \text{.........(A1)}
\]

T: Temperature (\degree C) \((1380 \leq T \leq 1500^\circ \text{C})\), \(\rho\): density (g/cm\(^3\)).

(2) Surface Tension of BF Slag

The empirical equation, Eq. (A2) was obtained using data in literature\(^9,12\) (Table A1). The calculation results were compared in Fig. A2.

\[
\gamma (\text{N/m}) = (767.5 - 0.15809 \cdot T(\degree C)) \times 10^{-3} \quad \text{.........(A2)}
\]

T: Temperature (\degree C), \(\gamma\): Surface tension (N/m).

Table A1. Chemical compositions of slags used for the calculation of surface tensions.

|        | CaO  | SiO\(_2\) | Al\(_2\)O\(_3\) | MgO  | C/S |
|--------|------|-----------|----------------|------|-----|
| Present study | 42.99| 33.52     | 13.77          | 6.28 | 1.29 |
| Ref.00 | 38.7 | 35.3      | 15.0           | 10.6 | 1.13 |
| Ref.00 | 42.3 | 38.4      | 13.4           | 6.8  | 1.1  |
| Ref.00 | 43.5 | 37.1      | 15.2           | 4.9  | 1.17 |

Fig. A1. Temperature dependence of the density of blast furnace slag.\(^9,12\)

Fig. A2. Temperature dependence of the surface tension of blast furnace slag.\(^9,12\)
(3) Viscosity of BF Slag

The viscosity of the BF slag was estimated by Sugiyama’s equation (Eq. (A3)).\(^{10}\) The calculated results are compared with the results from Iida’s equation\(^{11}\) and data reported in the literature\(^9,10\) in Fig. A3. The slag compositions are compared in Table A2.

\[
\log_{10} \eta = 1.71(W_{\text{CaO}}/W_{\text{SiO}_2})^2 - 4.74(W_{\text{CaO}}/W_{\text{SiO}_2}) \\
+ 0.93(W_{\text{MgO}})^2 - 1.89(W_{\text{MgO}}) + 7.99(W_{\text{Al}_2\text{O}_3})^2 \\
- 1.03(W_{\text{Al}_2\text{O}_3}) + 4.27 \times 10^6/(T/°C)^2 \\
+ 2.68 \times 10^3/(T/°C) + 0.26
\]

\((A3)\)

\(\eta: \) viscosity (Pa \cdot s), \(W_i: \) mass fraction of component \(i\).

Fig. A3. Temperature dependence of the viscosity of blast furnace slag.\(^9,11\)

Table A2. Chemical compositions of slags used for the calculation of viscosity.

|                | CaO  | SiO₂  | Al₂O₃ | MgO | CS  |
|----------------|------|-------|-------|-----|-----|
| Present study  | 42.99| 35.52 | 13.77 | 6.28| 1.28|
| Nr17 \(^{10}\) | 35.0 | 35.0  | 15.0  | 15.0| 1.0 |
| Nr19 \(^{10}\) | 35.0 | 35.0  | 20.0  | 10.0| 1.0 |