

Effect of Nozzle Diameter on Mixing Time During Bottom-Gas Injection in Metallurgical Ladles

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The improvement of mixing conditions in metallurgical vessels is of fundamental importance to increase furnace productivity, steel cleanliness, removal of impurities, and so on. Water modeling has been used to investigate mixing phenomena; however, there is still a need to clarify the role played on mixing time by process variables such as the nozzle diameter to properly represent the real process conditions. In water modeling design, this parameter is usually ignored. The current investigation has found that changes in nozzle diameter affect mixing time; however, the extent of this effect is influenced by nozzle radial position and gas flow rate. The conditions to minimize mixing time with one nozzle and a top layer of 2 pct have also been identified.

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I. INTRODUCTION

WATER modeling has been employed for more than 40 years to investigate fluid flow in metallurgical vessels. This technique overcomes the limitation of opacity of liquid metals. In spite of satisfying geometrical, kinematic, and the main dynamic criteria on similitude, water modeling still has several drawbacks.

A. Type of Injection Device

Bottom gas stirring in industrial metallurgical ladles is carried out with porous plugs, and most water models employ nozzles. Bubble formation in nozzles and porous plugs in gas/water systems is different. Anagbo and Brimacombe^[1] reported the bubble size in a water model for a low gas flow rate in the range from 8 to 14 cm³/s per cm² of porous plug area, indicating a smaller bubble size with porous plugs in comparison with nozzles, 3 to 4 mm and 15 mm, respectively. Above this gas flow rate, incipient bubble coalescence starts to develop and the bubble diameter increases up to 35 to 50 mm. In addition to this, the bubble size in gas/water and gas/metal systems is also different. There is strong experimental evidence that bubbles in gas/metal systems are significantly larger than in identical gas/water systems.^[1-3] The bubbles in a gas/metal system are bigger because of the nonwetting conditions, and their final volume is dominated by the fluid properties: surface tension (σ) and density (ρ). The ratio σ/ρ is 73 for the air/water system and 251 for the air/steel system. Irons and

Guthrie^[2] reported that the nonwetting conditions in a gas/metal system lead to bubble formation at the outer nozzle diameter.^[2] Stapurewicz and Themelis^[4] investigated mixing time in a large water model using porous plugs and a nozzle with central gas injection. Three different diameters were employed arbitrarily in the experiments. They reported similar results in terms of mixing time as well as an improved mass transfer coefficient with porous plugs in comparison with nozzles; however, this effect decreased as the gas flow rate increased. Sahai and Guthrie^[5] postulated on theoretical grounds that any hydrodynamic analysis of flow recirculation is not affected by the bubbles formed by either nozzles or porous plugs. Mazumdar and Guthrie^[6] also stated in a review paper that the equilibrium distribution bubble size in the fully developed region of the plume is determined by the thermophysical properties of the system and not by the inlet operating variables (gas-injection device, orifice diameter, *etc.*). Bubbles reach an equilibrium bubble size in the plume region due to the decrease in hydrostatic pressure and thermal expansion. The plume region occupies a much larger volume of the reactor in comparison with the inlet region. If the injection device does not have a marked effect on the equilibrium distribution bubble size, then a negligible effect on mixing time is to be expected. The results from Stapurewicz and Themelis^[4] are strong evidence of this behavior; however, Cho *et al.*^[7] reported different results. They found that for the range from 1 to 5 L/min, porous plugs yield a shorter mixing time if the ladle aspect ratio is close to 1. When the aspect ratio is close to 0.8, mixing time was similar in both injection devices.

B. Wetting

In the real gas/metal system, the contact angle leads to non-wetting conditions in contrast to gas/water modeling. Wang *et al.*^[8] reported experimental values of contact angles. The contact angle between porous plugs

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and water was reported as 16.8 deg and that between porous plugs and hot metal as 145 deg. In water modeling, there are wetting conditions; meanwhile, under industrial conditions, there are nonwetting conditions. The nonwetting conditions increase the bubble size; therefore, the small bubble size observed with porous plugs in water models will be different with respect to the real process.

C. Bubble Thermal Expansion

Thermal expansion due to bubble heating is quite large taking into account that the temperature gradient is in the order of $1873/298 = 6.3$ times. In water modeling, bubble thermal expansion is not taken into account. Using the equilibrium bubble size in the plume region could solve this limitation; however, it is necessary to clearly identify the bubble size representing the industrial process.

D. Top Slag Layer

The top slag layer has not been included in the vast majority of investigations on water modeling for 30 years. In the last 5 years, this layer is being taken into account; however, a top layer that satisfies equivalent viscosity and density ratios to the real steel/slag system is still an unresolved issue. Mazumdar and Evans^[9] suggested that it is impossible to represent the steel-slag density in any aqueous system.

E. Criteria to Define the Minimum Size of a Water Model

In previous investigations, a range in geometric-scale factors from 0.05 to 1 have been employed. There is a concern that a too-small geometric scale cannot guarantee the criteria on dynamic similarity. To satisfy this criterion, the inertial, gravitational, and viscous forces between model and prototype should be similar. The Froude and Reynolds numbers represent these forces. Because of the large values in the Reynolds number, in the range^[10] from 3×10^4 to 1×10^6 , it is implied that viscous forces are negligible; therefore, the inertial and gravitational forces dominate bubble-driven flows. As the geometric-scale decreases, the magnitude of the Reynolds number also decreases by approximately one order of magnitude,^[11] indicating an increasing influence of viscous forces. Therefore, fluid flow could no longer be represented exclusively by the Froude number. However, the current experimental results indicate that the geometrical-scale factor is not a critical parameter in water modeling. For example, Oymo and Guthrie^[12] compared two scales (1:19 and 1:5) obtaining similar results.

F. Heat and Mass Transfer

Mixing phenomena involve thermal and chemical mixing. One author has described previously the lack of information on thermal mixing in water modeling and reported that bottom-gas injection could even affect thermal homogenization of liquid steel in a ladle.^[13] To

the authors' knowledge, one publication^[14] involves thermal mixing in water modeling. With regard to mass transfer, it is important to notice that the primary purpose of a ladle furnace is as a refining reactor. Consequently, the removal rate of impurities from liquid steel to the top slag layer is one of the most important process parameters. In contrast to mixing phenomena, mass transfer in gas-stirred ladles^[15-18] has received less attention. Kim and Fruehan^[15] reported the complexity to simultaneously improve mixing phenomena and mass transfer because the conditions that improve mass transfer are not necessarily the same that provide the shortest mixing time.

G. Criteria to Define the Nozzle Diameter in Water Models

Of particular interest for the current investigation is the criterion to define the nozzle diameter in water modeling. In the past, previous researchers always have arbitrarily chosen the diameter of the injection device. If the conditions in the inlet region are of secondary importance to flow recirculation, then the selection of an arbitrary size is irrelevant. However, based on the information previously discussed, this subject is not conclusive.

One important aspect from the previous information is the need to produce bubbles representative of the gas/metal system of interest. Oryall and Brimacombe^[19] at one time were concerned on the validity of water models to properly represent the real gas/metal systems.

It is well known that the bubble size in the inlet region is affected by the diameter of the nozzle. This behavior was experimentally confirmed by Andreini *et al.*,^[3] who applied an acoustical method to measure bubble size in gas/metal systems, reporting the following relationship:

$$d_b = d_n \frac{(Fr_o)^{0.224}}{(We_o)^{0.109}} \quad [1]$$

where d_b represents the bubble diameter, d_n is the nozzle diameter, Fr_o is the orifice Froude number, and We_o is the orifice Weber number.

The orifice Froude and Weber numbers are defined as follows:

$$Fr_o = \frac{v_o^2}{gd_n} \quad [2]$$

$$We_o = \frac{\rho_g v_o^2 d_n}{\sigma} \quad [3]$$

where v_o represents the gas velocity at orifice in cm/s, d_n is the orifice diameter in cm, g is the gravitational constant in cm/s^2 , ρ_g is the gas density in g/cm^3 , and σ is the liquid surface tension in dyne/cm.

Mori *et al.*^[20] reported an equation to predict the bubble size valid for low and high gas flow rates. In this equation, the bubble size also increases when the nozzle diameter increases:

$$d_b = \left\{ \left(\frac{6\sigma d_n}{\rho_l g} \right) + 0.0242(Q^2 d_n)^{0.867} \right\}^{\frac{1}{6}} \quad [4]$$

where d_b is the bubble diameter in cm, g is the gravitational constant in cm/s^2 , ρ_l is the liquid density in g/cm^3 , σ is the liquid surface tension in dyne/cm , and Q is the gas flow rate in cm^3/s .

In water modeling design, the nozzle diameter is never included. It is perhaps accepted that a nozzle of any size yields similar results. Investigations from the past show different results. Krishna-Murthy *et al.*^[21] reported physical modeling results on mixing time as a function of nozzle diameter for axisymmetric conditions and neglecting the top slag layer. They obtained minimum changes in mixing time when the gas flow rate was changed from medium (84 L/min) to high values (200 L/min); however, when the gas flow rate was low (37 L/min), an increase in nozzle diameter from 2.77 to 10 mm also increased mixing time from 40 to 60 seconds. This result was not discussed in their report. Kim and Fruehan^[15] provided experimental evidence of the benefits to increase the nozzle diameter to increase the mass transfer coefficient between the steel and slag with a water model. The mass transfer coefficient was similar for two nozzle diameters investigated (2 and 4.8 mm) at low gas flow rates. At high gas flow rates, the mass transfer coefficient was slightly higher for the case with a bigger nozzle diameter. The transition in regimes was reported for a stirring energy of approximately 5 Watts/ton, which correspond to conditions for slag emulsification. Li^[22] reported mathematical modeling results on mixing time as a function of nozzle diameter for axisymmetric conditions and neglected the top slag layer. He reported a small effect of nozzle diameter on mixing time for a nozzle diameter ranging from 1 to 6 mm. When the diameter was changed from 1 to 3 mm, the mixing time did not change, but it increased less than 3 seconds when the nozzle diameter increased from 3 to 6 mm.

Two types of investigations dealing with mixing phenomena in a different context to metallurgical ladles have also included the effect of nozzle diameter. One investigation dealt with the strong mixing conditions between steel and slag and the second one with jet mixers. In the context of iron bath smelting, Su *et al.*^[23] reported an optimum nozzle diameter of 10 mm to minimize mixing time. The nozzle diameters investigated in their water model ranged from 7.5 to 15 mm. The experiments were conducted at high gas flow rates, from 320 to 480 NL/min, under a jetting regime. With a small nozzle diameter, the kinetic energy is maximum; however, there is a large loss in energy due to severe spout formation and liquid ejection. On the other hand, with a large nozzle diameter the total stirring energy decreases. Patwardhan and Gaikwad^[24] reported physical modeling results on mixing time on jet mixed tanks. In jet mixers, stirring is conducted with water jets; the water is partially withdrawn with the help of a pump and returned through a nozzle at high velocity into the reactor. They reported a decrease in mixing time from 35 to 20 seconds when the nozzle diameter was increased from 5 to 20 mm.

The contribution of the kinetic energy to the total stirring energy has been neglected because most of this energy is consumed at the orifice and less than 6 pct is

transferred to the bath. However, Taniguchi *et al.*^[25] indicated that it should be taken into account when the temperature is high and the gas flow rate is also high.

The kinetic energy decreases as the nozzle diameter increases, as shown below:^[23]

$$\varepsilon_k = \frac{32\rho_g Q^3}{\pi^3 d_n^4 D^2 H} \quad [5]$$

where ρ_g is the density of the gas; d_n is the nozzle diameter; D and H are the diameter and height of the reactor, respectively; and Q is the gas flow rate.

One of the primary objectives of this work is to evaluate the effect of nozzle diameter on mixing time in a water model. The relationships on mixing time reported in the literature include gas flow rate, reactor dimensions, and more recently some of the physical properties of the top layer. None of them include the effect of nozzle diameter, based on the assumption that a change in nozzle diameter has a negligible effect on mixing time.

II. EXPERIMENTAL WORK

An industrial size metallurgical ladle of 120 tonnes was used as prototype to design the present water model. The dimensions of the water model with a scale factor 1:8 are reported in Table I. The whole experimental setup is shown in Figure 1. The volume of water corresponds to 34.33 L. The height/diameter (H/D) ratio in the model is 1.16. A ladle geometry with an H/D ratio between 1.0 and 1.3 has been reported to provide better mixing conditions.^[26,27] Air was employed as the stirring agent.

The experiments were carried out with one nozzle. The variables investigated are nozzle diameter (1.5 to 5 mm), nozzle radial position (0 to 0.85R), and gas flow rate (1.7 to 7.8 NL/min) with and without a top slag layer. The thickness of the top slag layer in the industrial practice usually ranges from 1 to 3 pct. In the water model, the oil thickness was fixed at 2 pct with respect to the height of water.

The gas flow rate in the water model was computed employing the dynamic similarity criteria based on equal modified Froude numbers in both the model and prototype ($Fr_m = Fr_p$), assuming a major role of the inertial and gravitational forces over viscous and surface tension forces.

The top layer is a critical issue in water modeling. The authors could not identify an oil with representative density and viscosity ratios of the industrial practice, a limitation in all water models up to this moment. The oil selected was a motor oil with a density of 890 g/m^3 and a kinematic viscosity of $215 \times 10^{-6} \text{ m}^2/\text{s}$. The oil/water density ratio is 0.89, which is much higher than in the real process, around 0.5 to 0.6. The kinematic viscosity of a metallurgical slag ranges from 60 to 120 times higher than that of liquid steel. The oil selected has a higher viscosity than that of water.

Measurements on mixing time were carried out recording the instantaneous change in electric conductivity, using an apparatus manufactured by Eutech

Table I. Prototype and Ladle Dimensions, and Experimental Variables

	Prototype	Water Model
Liquid height (H), mm	3130.8	391
Diameter (D), mm	2673.55	335
H/D ratio	1.16	1.16
Number of nozzles	1	1
Top slag (oil) thickness, mm	2 pct	0, 7.8
Gas flow rate (Q), NL/min	100 to 450	1.7, 5.1, 7.8
Nozzle diameter (d_n), mm	120	1.5, 3.0, 5.0
Nozzle radial position (r/R)	0.7	0, 0.33, 0.5, 0.67, 0.8, 0.85

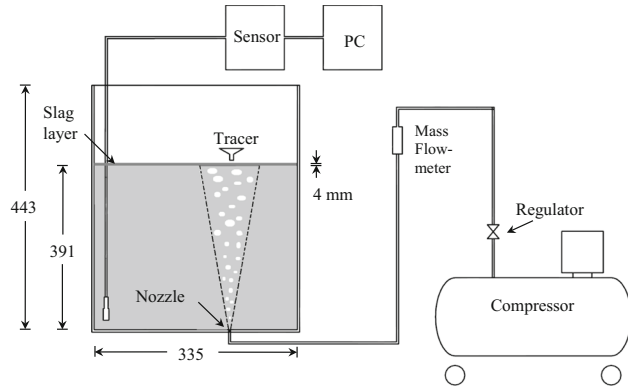


Fig. 1—Experimental setup.

Instruments, Mexican (model CON 110). The electrode was placed at the bottom of the vessel, 10 mm away from the wall and 10 mm away from the bottom. This position was chosen based on previous experience indicating the presence of a dead zone. The tracer employed was 3.5 mL of a saturated aqueous solution of potassium chloride. The tracer was always injected at the top of the spout. The concentration signal as a function of time was recorded in a computer. The criterion to define mixing time was the conventional value of 95 pct homogenization. Each experiment was repeated three to five times.

III. RESULTS AND DISCUSSION

Stirring energy was computed applying the relationship reported by Sano and Mori.^[28]

$$\dot{\epsilon} = 6.18QT \ln \left(1 + \frac{\rho_l g H_0}{1.013 \times 10^5 P} \right) \quad [6]$$

where $\dot{\epsilon}$ represents the stirring energy in Watts, T is the temperature of water in K, Q is the gas flow rate in Nm^3/min , ρ_l is the density of water, g is the gravity constant in m/s^2 , H is the height of water in the ladle, and P is the atmospheric pressure in atm.

The gas flow rate in the range from 1.7 to 7.8 NL/min is equivalent to 3.3 to 15.2 Watts/ton in the current water model.

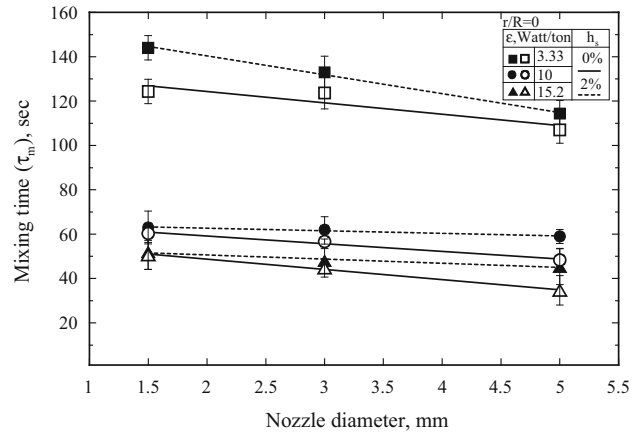


Fig. 2—Effect of nozzle diameter on mixing time for a central position at different gas flow rates, with and without a top layer.

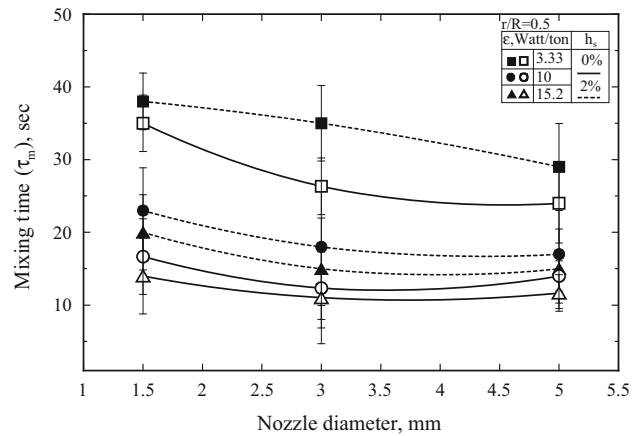


Fig. 3—Effect of nozzle diameter on mixing time, for a radial position $r/R = 0.5$ at different gas flow rates, with and without a top layer.

A. Nozzle Diameter

The effect of nozzle diameter on mixing time as a function of nozzle radial position, slag thickness, and gas flow rate is shown in Figures 2 through 6. These results clearly indicate that fluid flow becomes extremely complex in the presence of multiple variables.

To simplify the following discussion, a criterion of low and high stirring conditions is defined taking into consideration that the range of gas flow rates employed in this investigation was from 1.7 to 7.8 NL/min. The corresponding values of stirring energy for the three gas flow rates were 3.3, 10, and 15.2 Watts/tonne. In the context of mass transfer studies in a water model, Kim and Fruehan^[15] reported low stirring conditions below 5 Watts/tonne. In our case, based on the experimental results above 10 Watts/tonne, this value is chosen as a reference to define low and high stirring conditions.

The results from previous research^[21] analyzing the effect of nozzle diameter on mixing time have been obtained on the basis of changes in stirring conditions but fixing the nozzle radial position in the center. In the following analysis, it will be shown that the rate of

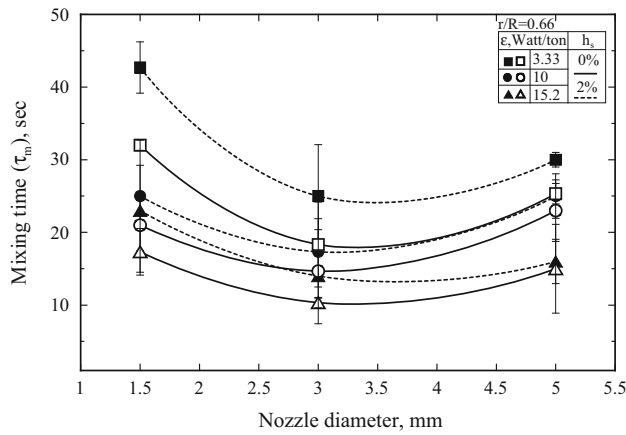


Fig. 4—Effect of nozzle diameter on mixing time, for a radial position $r/R = 0.66$ at different gas flow rates, with and without a top layer.

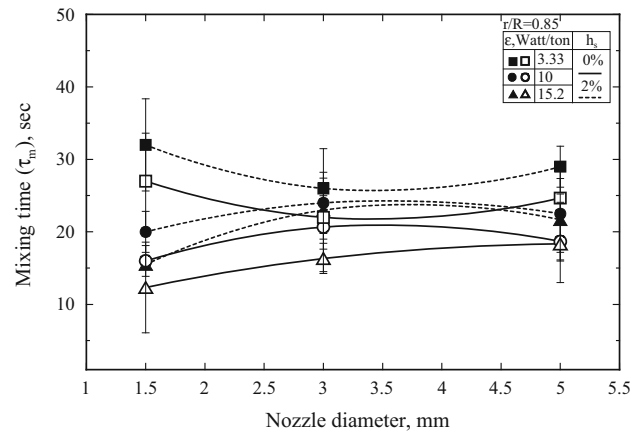


Fig. 6—Effect of nozzle diameter on mixing time, for a radial position $r/R = 0.85$ at different gas flow rates, with and without a top layer.

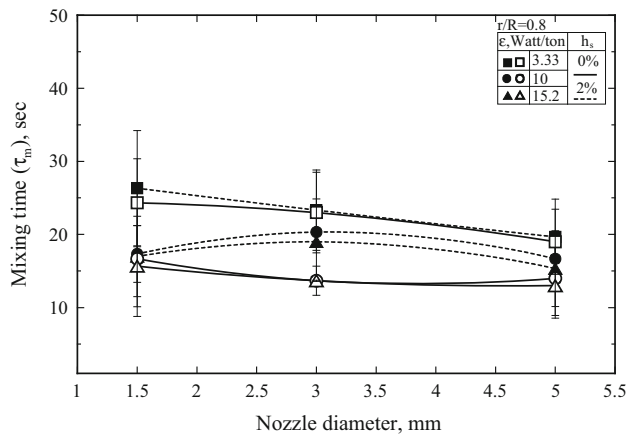


Fig. 5—Effect of nozzle diameter on mixing time, for a radial position $r/R = 0.8$ at different gas flow rates, with and without a top layer.

change of mixing time as a function of nozzle diameter can be significant depending on the nozzle radial position and stirring conditions.

B. Axisymmetric Radial Position (0R)

Figure 2 shows the results for an axisymmetric nozzle radial position. It is observed that an increase in nozzle diameter decreases mixing time; however, this effect is small because by increasing the nozzle diameter by a factor of 3.3, mixing time only decreases 10 to 15 pct. In this radial position, the slope is constant at different stirring conditions. The gas flow rate has a stronger effect on mixing time. Mixing time decreases on average 60 pct, from 120 to 50 seconds by increasing stirring energy from 3 to 15 Watts/tonne.

In all cases, the top layer increases mixing time. The increment ranges from 5 to 15 seconds. This effect is caused by the energy consumed in the motion of the top layer in detriment of the motion of the underlying phase. The increment in mixing time is not uniform for all

nozzle diameters. The increment depends not only on nozzle position but also on gas flow rate. The increment in mixing time due to the top layer is of the same order of magnitude when the nozzle diameter is increased, suggesting that the negative effect of the slag layer on mixing time could be compensated with an increase in nozzle diameter.

C. Nozzle Radial Position at 0.33R and 0.5R

The mixing times as a function of nozzle diameter for nozzle radial positions at 0.33 and 0.5R are similar. Figure 3 shows the results for a nozzle radial position of 0.5R. The effect of nozzle diameter on mixing time at high stirring energies is relatively small, considering that the difference in mixing time between opposite diameters is less than 3 seconds. At low stirring energies, the mixing time is also small, on the order of 4 to 5 seconds. Mixing time increases at the same order of magnitude due to the presence of the top slag layer. A mixing time of 3 to 5 seconds is considered small taking into consideration the scale for mixing time in the current set of experiments, which ranges from 10 to 140 seconds. The largest decrease in mixing time takes part in about 100 seconds.

The shortest value on mixing time is found for a nozzle radial position of 0.5R, practically independent of nozzle diameter, with values from 10 to 12 seconds.

D. Nozzle Radial Position at 0.66R

When the nozzle radial position is changed from the central part to the middle of the ladle, an increase in nozzle diameter decreases mixing time. This phenomenon can be explained based on physical observations, in terms of higher velocity fields caused by larger bubbles. If the nozzle radial position is moved closer to the walls, at 0.66R, then it is found that as the nozzle diameter increases from 1.5 to 3 mm, the mixing time decreases. But if the nozzle diameter is further increased to 5 mm, then the mixing time increases, as shown in Figure 4. A

minimum in mixing time is obtained with a nozzle diameter of 3 mm. The variations in mixing time, either to decrease or increase are not large, in the order of 3 to 7 seconds. An increase in mixing time could be attributed to the Coanda effect.^[29] The stirring energy consumed by the walls increases the mixing time.

E. Nozzle Radial Position at 0.8R and 0.85R

Both radial positions are in close proximity to the walls. There is some randomness in the results due to a stronger interaction between bubbles and the wall. For a nozzle radial position of 0.8R and without a top layer, an increase in nozzle diameter decreases mixing time, as shown in Figure 5. At high stirring energies, there is no difference in mixing time for 10 and 15.2 Watts/tonne. In the presence of the top layer, the mixing time slightly increases when the nozzle diameter is increased from 1.5 to 3 mm.

A nozzle radial position of 0.85R produces irregular fluid flow patterns probably due to maximum interaction between bubbles and refractory walls. This would explain the complex behavior in mixing time as a function of nozzle diameter, as shown in Figure 6. At high stirring energies, mixing time slightly increases by increasing nozzle diameter, on the other hand, at low stirring there is a minimum value for a nozzle diameter of 3 mm.

The increase in mixing time for a nozzle radial position closer to the walls was attributed to the Coanda effect. This behavior can explain the results at 0.66R and 0.85R. However, for a nozzle radial position of 0.8R, which is also pretty close to the walls, there should be operating additional mechanisms that contribute to decrease mixing time. On a closer examination, it can be observed that the shortest mixing time at 0.8R is only 1.3 seconds higher in comparison with that for 0.66R but in comparison with a nozzle radial position of 0.85R, mixing time for 0.8R is always lower. One possible explanation to this behavior is that this position yields a higher value of angular momentum. Joo and Guthrie^[30] reported the shortest mixing time as a function of nozzle radial position based on the angular momentum values derived from a numerical model.

The positions 0.8R and 0.85R were chosen on purely academic basis because even if mixing time were the shortest in these conditions, the friction caused by the bubbles with the refractory wall would increase exogenous inclusions and severe erosion of the refractory walls. It is to be noted that the magnitude of mixing time is still smaller in comparison with positions in the center and one-third radius. Therefore, in spite of stirring energy losses to the walls, mixing is improved by displacing the nozzle from the center.

F. Nozzle Radial Position

In the previous figures, the main focus was on the effect of nozzle diameter on mixing time. The results were reported at different nozzle radial positions. The effect of nozzle radial position on mixing time is much larger than that due to changes in nozzle diameter, as

shown in Figure 7. It is shown that a change in position from the center to 0.33R does not affect mixing time; however, the mixing time drastically decreases when the nozzle radial position is moved closer to the walls, at half radius. The decrease in mixing time is approximately 80 to 100 seconds. The order of magnitude of this change is usually observed when the stirring energy is drastically increased, for example, from 1 to 10 Watts/ton. It can also be observed that mixing time does not experience major changes when the nozzle radial position is moved closer to the walls. Geng *et al.*^[31] also reported negligible changes in mixing time by moving the radial position from the center to 0.5R, employing two nozzles and for separation angles of 90 deg and 120 deg.

This trend was expected because of stirring energy losses due to bubble/walls interaction; however, when the position was moved to 0.8R, a small decrease in mixing time was observed. This behavior was unexpected; the energy losses due to the interaction between bubble and refractory walls would increase the mixing time. A new set of experiments at 0.85R was implemented in the analysis observing a small increase in mixing time. In a general way, the behavior reported with positions closer to the refractory walls is the result of the complex and random interaction between bubbles and refractory walls. As mentioned, a position too close to the walls accelerates the erosion rate of the refractory walls. It has been reported^[32] that the erosion rate was increased by 11.1 pct, from 0.108 to 0.120 mm/h when a porous plug was moved closer to the walls, from 0.4R to 0.6R.

G. Stirring Energy

This section is included to compare in more detail the effects of stirring energy, nozzle radial position, and nozzle diameter on mixing phenomena. The results indicate a large effect of stirring energy on mixing time if the nozzle radial position is located between the center and 0.5R, as shown in Figure 8. For these conditions, at low gas flow rates, the mixing time is in the range of 110 to 140 seconds, decreasing to 10 to 40 seconds at higher gas flow rates. However, if the nozzle radial position is closer to the walls, as shown in Figure 9, the results on mixing time are weakly affected by an increase in stirring energy because the fluctuations in mixing time are less than 15 seconds, with and without the top slag layer and for the whole range of nozzle diameters investigated. There is an important practical implication from this behavior, which suggests to decrease the gas flow rate if the nozzle radial position is close to the walls in order to minimize the consumption of stirring gas. By comparison, it can be observed that the effect of nozzle diameter on mixing time on a quantitative basis is not as significant as the effects of stirring energy and nozzle radial position. The largest decrease on mixing time due to stirring energy or nozzle radial position is in the order of 100 seconds. Meanwhile, for an increase in nozzle diameter, the mixing time is 15 seconds. Despite the relative importance of nozzle diameter to decrease mixing time, its main role can be played under

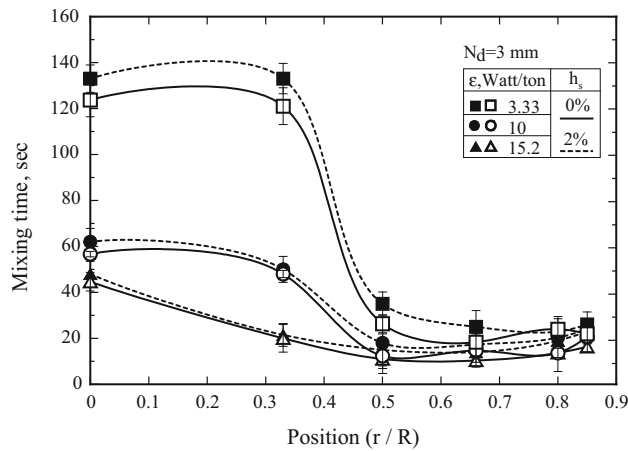


Fig. 7—Effect of nozzle radial position on mixing time, for a constant nozzle diameter of 3 mm at different gas flow rates, with and without a top layer.

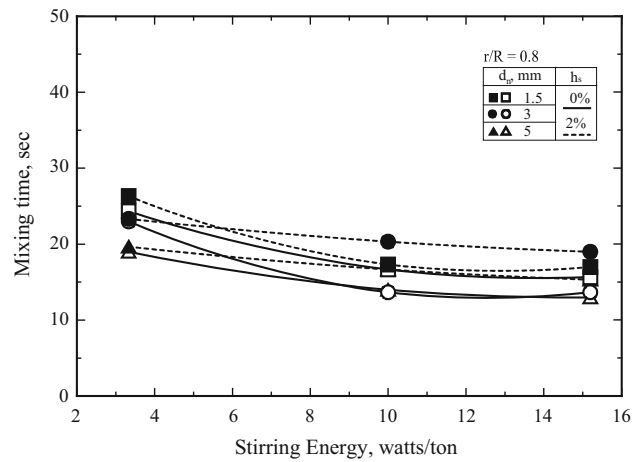


Fig. 9—Effect of stirring energy on mixing time for a constant nozzle radial position (0.8R) at different nozzle diameters, with and without a top layer.

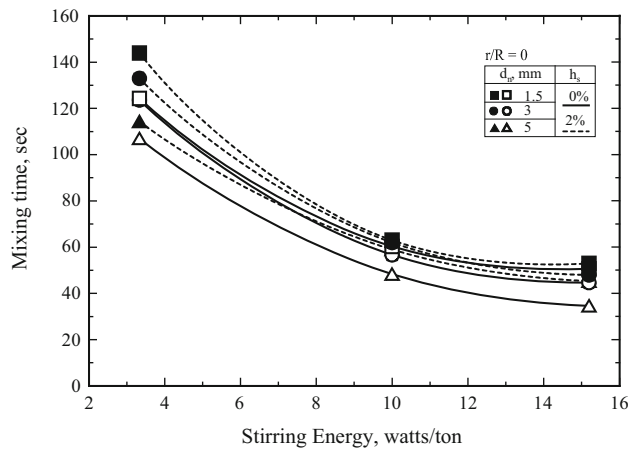


Fig. 8—Effect of stirring energy on mixing time for a constant nozzle radial position (0R) at different nozzle diameters, with and without a top layer.

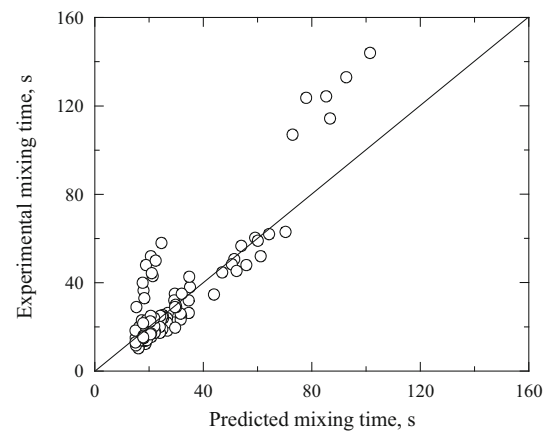


Fig. 10—Relationship between experimental and predicted results on mixing times, employing Eq. [7].

conditions of nozzle radial positions closer to the walls. Under these conditions, the effect of the gas flow rate substantially decreases and a higher nozzle diameter can be used to enhance mixing phenomena.

H. Relationship Between Experimental Data and Predicted Values on Mixing Time

The relationship of mixing time between experimental data and predicted values for the current experimental work is defined by Eq. [6]. This equation has a coefficient of determination of 72 pct. The exponent of one third on stirring energy is in line with previous investigations. [33,34] The exponent on nozzle diameter indicates this variable is second in importance, after stirring energy. The exponent on nozzle radial position (r/R) is pretty small, suggesting a minor importance, contrary to what it has been discussed previously. The reason for this lies on the fact that mixing time is insensitive to

nozzle radial positions at both low and high r/R values, but at intermediate values, it was found to have a drastic effect. Figure 10 describes the relationship between experimental and predicted data.

$$\tau_m = 54.26(\varepsilon)^{-0.327}(d_n)^{-0.131}\left(\frac{r}{R}\right)^{-0.0027}(h_s)^{+0.004} \quad [7]$$

IV. CONCLUSIONS

A water model investigation has been carried out to analyze the influence of nozzle diameter (1.5 to 5 mm) on mixing time nozzle at different nozzle radial positions (0 to 0.85R), gas flow rates (1.7 to 7.8 NL/min), with and without a top layer.

1. In general, an increase in nozzle diameter decreases mixing time; however, this effect is not significant, especially at high stirring energies. The extent of the

effect of nozzle diameter on mixing time depends not only on nozzle diameter but also on the nozzle radial position and gas flow rate. For nozzle radial positions between 0 and 0.5R and low gas flow rates, an increase in nozzle diameter has a stronger influence on mixing time. The improved mixing conditions as nozzle diameter increases are attributed to the formation of larger bubbles.

2. The gas flow rate is considered the variable with a stronger influence on mixing time. The current results show that the nozzle radial position can have the same influence. It has been found that for a large decrease in mixing time when the nozzle radial position is changed from the center of the ladle to half radius and with further positions closer to the walls, the mixing time remains almost constant.
3. The effect of gas flow rate on mixing time when the nozzle radial position is located close to the walls, between 0.5R and 0.85R, is not significant. Therefore, in these conditions the current results suggest to operate with lower stirring energies in order to minimize steel reoxidation and enhance savings in stirring gas.

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REFERENCES

1. P.E. Anagbo and J.K. Brimacombe: *Metall. Trans. B*, 1990, vol. 21B, pp. 637–48.
2. G. Irons and R. Guthrie: *Metall. Trans. B*, 1978, vol. 9B, pp. 101–10.
3. R.J. Andreini, J.S. Foster, and R.W. Callen: *Metall. Trans. B*, 1977, vol. 8B, pp. 625–31.
4. T. Stapurewicz and N.J. Themelis: *Can. Metall. Q.*, 1987, vol. 26, pp. 123–28.
5. Y. Sahai and R.L. Guthrie: *Metall. Trans. B*, 1982, vol. 13B, pp. 193–202.
6. D. Mazumdar and R.L. Guthrie: *ISIJ Int.*, 1995, vol. 35, pp. 1–20.
7. S. Cho, C. Kim, J. Han, B. You, and D. Kim: *Mater. Sci. Forum*, 2006, vols. 510–511, pp. 494–97.
8. Z. Wang, K. Mukai, and D. Izu: *ISIJ Int.*, 1999, vol. 39, pp. 154–63.
9. D. Mazumdar and J. Evans: *Modeling of Steelmaking Processes*, CRC Press, Boca Raton, FL, 2010, pp. 116–20.
10. D. Verhelst: M.Sc. Thesis, McGill University, Montréal, Québec, Canada, 1991, p. 19.
11. D. Mazumdar, H.B. Kim, and R.I.L. Guthrie: *IM&SM*, 2000, vol. 27, pp. 302–09.
12. D. Oymo and R.I.L. Guthrie: *4th Process Technol. Conf. Proc., I&SS*, Chicago, IL, 1984, pp. 42–52.
13. F. Maldonado-Parra, M.A. Ramirez-Argáez, and A.N. Conejo: *ISIJ Int.*, 2011, vol. 51, pp. 110–18.
14. J. Rogler, L. Heaslip, D. Xu, and M. Mehrvar: *AIST Trans.*, 2004, p. 93.
15. S.-H. Kim and R.J. Fruehan: *Metall. Trans. B*, 1987, vol. 18B, pp. 381–90.
16. S.K. Ajmani and A. Chatterjee: *IM&SM*, 2005, vol. 32, pp. 515–21.
17. A.K. Singh and D. Mazumdar: *Metall. Trans.*, 1997, vol. 28B, pp. 95–102.
18. K. Ogawa and T. Onoue: *ISIJ Int.*, 1989, vol. 29, pp. 148–53.
19. G.N. Oryall and J.K. Brimacombe: *Metall. Trans. B*, 1976, vol. 7B, pp. 391–403.
20. K. Mori, M. Sano, and T. Sato: *Trans. ISIJ*, 1979, vol. 19, pp. 553–58.
21. G.G. Krishna-Murthy, S.P. Mehrotra, and A. Ghosh: *Metall. Trans. B*, 1988, vol. 19B, pp. 839–50.
22. L. Li: Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1996, p. 66.
23. C.-J. Su, J.-M. Chou, and S.-H. Liu: *Mater. Trans.*, 2010, vol. 51, pp. 1602–08.
24. A.W. Patwardhan and S.G. Gaikwad: *Trans. IChemE*, 2003, vol. 81, pp. 211–20.
25. S. Taniguchi, M. Ohmi, S. Ishiura, and S. Yamauchi: *Trans. ISIJ*, 1983, vol. 23, pp. 565–70.
26. H. Turkoglu and B. Farouk: *ISIJ Int.*, 1991, vol. 31, pp. 1371–80.
27. L.W. Helle: *J. South Afr. Inst. Min. Met.*, 1981, pp. 329–37.
28. M. Sano and K. Mori: *Trans. ISIJ*, 1983, vol. 23, pp. 169–75.
29. M. Iguchi and K. Sasaki: *ISIJ Int.*, 1999, vol. 39, pp. 213–18.
30. S. Joo and R.I.L. Guthrie: *Metall. Trans. B*, 1992, vol. 23B, pp. 765–78.
31. D.-Q. Geng, H. Lei, and J.-C. He: *Int. J. Min. Met. Mater.*, 2010, vol. 17, pp. 709–14.
32. A. Huang, H. Gu, M. Zhang, N. Wang, and T. Wang: *Metall. Mater. Trans. B*, 2013, vol. 44B, pp. 744–49.
33. S. Asai, T. Okamoto, J.-C. He, and I. Muchi: *Trans. ISIJ*, 1983, vol. 23, pp. 43–50.
34. D. Mazumdar and R.I.L. Guthrie: *Metall. Trans. B*, 1986, vol. 17B, pp. 725–733.