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Effect of Separation Angle and Nozzle Radial Position on Mixing Time in Ladles with Two Nozzles

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ABSTRACT

Chemical, thermal and mechanical homogenization of both slag and steel during the ladle furnace process depends on the design of the gas injection system in gas bottom stirred ladles. In the past, a large number of variables have been investigated, nevertheless due to the importance of the slag layer during the process, it has been incorporated in water modeling studies in more recent investigations. In large industrial size ladles is common to use two porous plugs. The configuration of the injection system with two porous plugs requires optimization of both nozzle radial position and nozzle separation angle. In this work the effect of nozzle radial position, nozzle separation angle, gas flow rate and slag thickness on mixing time has been investigated using a water model. The effect of tracer concentration on mixing time was also explored. It is shown that a separation angle of 60 degrees provides the best mixing efficiency.

Keywords: Water model; Mixing phenomena; Ladle furnace; Slag layer.

1. INTRODUCTION

Mixing phenomena due to bottom gas stirring in metallurgical ladles is a critical variable that defines the refining time. The full refining potential cannot be achieved if mixing in the ladle is poor. In order to investigate mixing phenomena from industrial metallurgical ladles, water modeling has been employed for the last 40 years.

Mixing efficiency increases by decreasing mixing time, however, the value of mixing time for the same volume of steel to be mixed in a ladle depends on many operational variables: Turkoglu and Farouk (1991) and Helle (1981) reported the effect of the ladle aspect ratio (height/diameter), Nakanishi *et al.* (1975) reported the effect of gas flow rate, Joo and Guthrie (1992) reported the effect of the number and position of injection elements, Mazumdar *et al.* (1988) included the effect of slag thickness and more recently, Terrazas and Conejo (2015) also included the effect of nozzle diameter. In addition to the large number of variables affecting mixing time, the volume and concentration of tracer as well as the monitoring point affect mixing time. To minimize its effect, it is usually employed a tracer with a concentration that reaches its saturation value and a monitoring point that corresponds to the last volume element to get mixed (dead zone). The location of the dead zones is not static and change depending on the set of operational variables. If the monitoring point is exactly in a dead zone in each experiment, then it is possible to report the true mixing time for the entire system, however this is not the case in typical water modeling experiments and therefore it is more appropriate to call it local mixing time. On the other hand, once the optimum injection conditions have been defined it is important to have in mind two limitations; first, mixing time is a concept applied to describe the stirring conditions in the bath. Kim and Fruehan (1987) proved that central gas injection is the optimum configuration to improve the stirring conditions in the slag phase but inefficient to mix the steel bath. Second, the conditions that yield the fastest mixing time usually increase the slag eye area and affect refractory wear. The gas flow rate is the variable with strongest effects on mixing time but it should be limited to decrease reoxidation due to an increase in exposure of the slag eye area to the atmosphere.

In spite of the limitations to fully represent mixing phenomena of the real steel-slag system at high temperatures, water modeling provides valuable information to describe fluid flow phenomena. In industrial size ladles, especially if the weight of steel is larger than 150-200 tonnes, it is common to have two porous plugs to improve mixing efficiency.

The nozzle position is defined in terms of two variables; distance from the center to the ladle wall (or porous plug radial position) and its separation angle. The optimum nozzle position has been investigated in the past, however the top slag layer has not been included in most of this work and in those cases where it has been included, the range of separation angles investigated has been narrow, furthermore, there is a big disagreement among previous researchers about the optimum values, suggesting the need for further research.

Joo and Guthrie (1992*)* developed a mathematical model and conducted the model validation with a one-third scale water model of a 100 tonne ladle. They reported the effect of 4 separation angles at four nozzle radial positions. Their results clearly indicated a shorter mixing time by increasing the separation angle from 45 to 180 degrees and a minimum value for a nozzle radial position at half radius (0.5R). This behavior was associated with a higher angular momentum when the injection elements were moved from the center to the wall. Zhu *et al*. (1995) developed a mathematical model and validated their results with a one-tenth-scale water model of a 350 tonnes ladle. They investigated configurations including 1-4 injection elements. The configuration employing two nozzles was for a fixed nozzle radial position at half radius. The separation angles included 90 and 180 degrees. They reported a shorter mixing time with a separation angle of 180 degrees in comparison with 90 degrees. Jauhiainen *et al*. (2001) developed a mathematical model to describe homogenization of alloy additions, including two porous plugs in four different locations. In terms of alloy homogenization, the central position was the best configuration, however, the authors claimed that slight changes in the point of injection resulted in drastic increments in mixing time; therefore, on the basis that a separation angle of 60 degrees was the second option, they recommended this angle. It is interesting to notice from their results that the separation angle of 180 degrees was the worst case in terms of alloy homogenization. Chiapparoli *et al*. (2003) analyzed two separation angles at one nozzle radial position. They reported better mixing conditions with a separation angle of 90 degrees. Chen *et al*. (2007) reported a full analysis of separation angles, nozzle radial positions, its symmetry and also included a top slag layer employing a one-fourth scale water model of a 150 tonnes ladle. Details of the thickness of the top slag layer in the experiments on mixing time were not reported. For symmetric injection elements, a nozzle radial position at 0.5R gave the shortest mixing time. At this nozzle radial position, the smaller angles, 15 to 45 degrees result in the shortest mixing times, however, at high gas flow rates the difference in mixing time between the smallest angle, 15 degrees, and the largest angle, 135 degrees, was less than 5 seconds. The optimum configuration was defined for a separation angle of 45 degrees and a nozzle radial position of 0.5R. The benefits of this configuration compared with the original design (90 degrees and asymmetric position at 0.67R and 0.79R) reported shorter mixing times in the water model and slightly better desulfurization rates in plant trials. Chattopadhyay *et al*. (2009) included symmetric and asymmetric nozzle positions and three separation angles. In general, the shortest mixing time was achieved with a separation angle of 135 degrees and the two nozzles placed asymmetrically, 0.75R and 0.25R, however, at high gas flow rates the symmetric position at 0.5R and a separation angle of 180ºC reported not only a shorter mixing time but also less erosion of the refractory. Geng *et al*. (2010) reported results from a mathematical model including five nozzle radial positions and four separation angles, from 90 to 180 degrees. Their results suggest that it is not possible to define an optimum single configuration because the shortest mixing time depends on both nozzle radial position and nozzle separation angle. It was reported that for a separation angle of 90 degrees, an increase in nozzle radial position increases mixing time and for a separation angle of 180 degrees it is observed an opposite effect. For intermediate angles, for example 120 degrees, there is a minimum value in mixing time. However, a more detailed analysis of their results indicates that for the whole experimental work, the shortest mixing time is achieved for a separation angle of 180 degrees and a nozzle radial position of 0.75R. Their results were fitted to the following equation with a standard deviation of approximately 15%.

$$\tau_m = 9.448\times10^{-5}\,\frac{\left(\frac{r}{R}+2.60\theta\right)^{10.19}}{\left(\frac{r}{R}\right)^{2.13}\theta^{8.15}Q^{0.26}} \tag{1}$$

Where: τ_m represents mixing time in seconds, r/R is the nozzle radial position, θ is the nozzle separation angle in degrees and Q is the gas flow rate in Nl/min.

Liu *et al.* (2011) reported a mathematical model for an industrial size ladle including one nozzle radial position (0.687 R) and two separation angles, 90 and 180 degrees, for one and two porous plugs. They reported that mixing time for a separation angle of 180 degrees was shorter in comparison with 90 degrees, except at high gas flow rates, where mixing time is slightly shorter for a separation angle of 90 degrees. A more recent work, carried out by Lou and Zhu (2014) reported a mathematical model including six nozzle radial positions and four separation angles from 45 to 180 degrees. The optimum conditions were not only related to mixing time but also included the conditions to improve the removal of non-metallic inclusions (NMI). The shortest mixing time was reported for a separation angle of 90 degrees and the largest rate of removal of NMI was reported for a separation angle of 180 degrees. The authors finally suggest a separation angle of 135 degrees and a radial position of 0.6R, because the rate of removal of NMI and mixing time are both improved.

A summary of the effect of separation angles and nozzle radial positions on mixing time is indicated in Table 1. It is clearly shown that in most of previous investigations the top slag layer has been neglected in spite of its big role on mixing phenomena, as proved by Amaro *et al*. (2014), Patil *et al*. (2010) and Mazumdar and Guthrie (2010).

Table 1 Summary of previous research indicating optimum conditions on separation angle and nozzle radial position, to decrease mixing time with two porous plugs

Ref	Year	N	M	P	S	r/R (N =2)	Θ, degrees (N=2)	Optimum (N=2)
Joo	1992	1-2	■	■		0, ⅓, ½, ⅔	45, 90, 135, 180	½ R, 180°
Zhu	1995	1-4	■	■		½	90, 180	180°
Jauhiainen	2001	2	■			0, ½, ⅔	0, 60, 180	½ R, 60°
Chiapparoli	2003	1-2		■	■	½	90, 180	90°
Chen	2007	2		■	■	½, ⅔, ¾.	15, 30, 45, 60, 90, 120, 135	½ R, 45°
Chattopadhy	2009	1-2		■		¼, ½, ¾.	90, 135, 180	(3/4R, 1/4R) 135°
Geng	2010	2	■			¼, ⅓, ½, ¾, 4/5	90, 120, 150, 180	¾ R, 180°
Liu	2011	1-2	■		■	2.75/4	90, 180	90º
Lou	2014	2	■			⅓, $\frac{2}{5}$, ½, $\frac{3}{5}$, $\frac{3.5}{5}$, $\frac{4}{5}$	45, 90, 135	½ R, 90°

N is the number of nozzles, M indicates mathematical model, P indicates physical model, S is slag

It is the main objective of this work to investigate the effect of separation angle and nozzle radial position on mixing efficiency with two injection elements in bottom stirred metallurgical ladles, including the top slag layer.

2. EXPERIMENTAL WORK

2.1 Experimental Set Up

A water model with a geometrical scale 1:8 was built, based on a ladle of 120 tonnes of liquid steel. Oymo and Guthrie (1984) compared small and large scales and found no differences, suggesting that there are no limitations to the geometric scale. Geometric similarity is obeyed when all the dimensions of the water model are scaled based on the dimensions of the prototype, as shown in Table 2. The water model has a working volume of 34.46 liters. Acrylic with a thickness of 6 mm was employed in the construction of the water model. The stirring gas was air using an air compressor with a capacity of 40 liters. This air is passed through a filter to remove humidity. The air pressure was adjusted to 90 PSI. The gas flow rate was controlled with two mass flow meters manufactured by Cole Palmer with a nominal range from 0-50 Nl/min. Air was injected through the ladle bottom using nozzles with a diameter of 3 mm.

Table 2 Dimensions of water model and prototype

	Model (mm) Scale: 1:8	Prototype (mm)
Internal diameter (D)	335	2673.55
Height of liquid (H)	391	3130.8
Thickness of slag layer (h_s)	0, 7.8, 15.6	62
Nozzle diameter, d_n	3	120
H/D ratio (-)	1.168	1.168

Mixing time was analyzed with the addition of potassium chloride as tracer and measuring the electric conductivity with an equipment manufactured by Eutech Instruments, model CON110. This equipment has three scales. The measuring range employed was from 0 to 2000 $\mu S/cm$. The sensor was placed 10 mm away from the wall and 10 mm from the bottom, in a region observed as a dead zone, based on preliminary experimental work. A single addition of 3.5 ml of KCl was made on top of one of the spouts. This amount of tracer provided a clear signal of the electric conductivity. The final set of experiments were made with an aqueous solution saturated with KCl, prepared with 35 g KCl/100 ml of water taking into account that the water temperature in the current experimental work was maintained at 21±1.3ºC.

Tap water at room temperature was employed. The electric conductivity of the tap water was in the range from 550 to 600 $\mu S/cm$. After a set of five continuous experiments the water was changed because it reached the upper limit in the measuring range employed. At lower gas flow rates, 0.5-1.7 Nl/min, the experiments were repeated 5-8 times and at higher gas flow rates, 4-6 Nl/min, were repeated 8-10 times to overcome the interference of slag emulsification. The criterion of 95 pct homogenization was used to define mixing time.

The top slag layer was motor oil with a density of 890 kg/m^3 and a kinematic viscosity of 215×10^{-6} m^2/s. The oil/water density ratio corresponds to 0.89. The typical slag thickness in industrial operation is in the range from 2-3%. A thickness from 0-4% was employed in the experiments. This percentage is defined as the height of the top oil layer with respect to the height of the water column.

The experimental set up is shown in Fig. 1. This figure represents the case with a separation angle of 180 degrees.

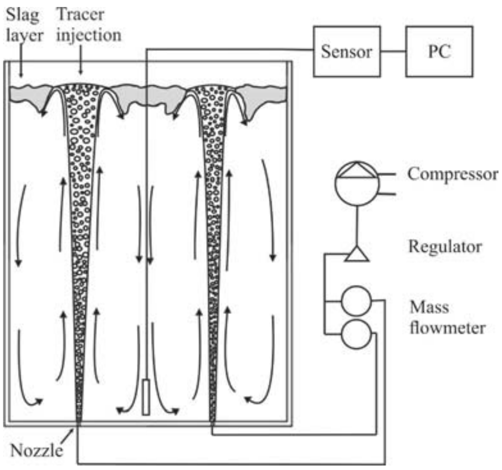

Fig. 1. Experimental set up.

The dimensions of the water model and the configuration of the injectors are indicated in Fig. 2.

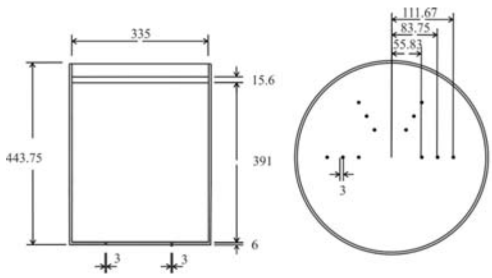

Fig. 2. Dimensions of water model (mm).

2.2 Experimental Conditions

The experiments were designed to measure mixing time with two injections elements as a function of nozzle separation angle, radial position, slag thickness and gas flow rate. Three separation angles, 60, 120 and 180 degrees were investigated, each one at three nozzle radial positions, 0.3R, 0.5R and 0.67R with three values of slag thickness, 0, 2 and 4% and four gas flow rates of 0.5, 1.7, 4 and 6 Nl/min. The gas flow rates in the water model were defined applying a criteria on dynamic similarity based on the modified Froude number. The details of these calculations are described elsewhere by Amaro *et al.* (2014). The energy supplied by the stirring gas in the current experimental work was in the range from 0.9-11.5 Watts/ton. The set of variables investigated is summarized in Table 3. The ladle aspect ratio and nozzle diameter remain constant during the experimental work.

Table 3 Design of experiments

	Value
Separation angle, θ, degrees	60, 120, 180
Nozzle radial position, r/R	⅓, ½, ⅔
Slag thickness, h_s, %	0, 2, 4
Gas flow rate, Q, l/min	0.5, 1.7, 4, 6
Number of nozzles	2

Figure 3 is a schematic representation of the three separation angles investigated, 60, 120 and 180 degrees. The configurations involve only symmetrical nozzle radial positions.

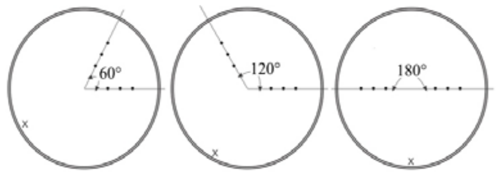

Fig. 3. Separation angles included in the experimental work.

Mark (×) indicates sensor position

3. RESULTS AND ANALYSIS

3.1 Effect of Tracer Concentration on Mixing Time

One of the most common methods to analyze mixing time is the addition of a tracer and measure the electric conductivity. KCl and NaCl salts are the most common tracers to measure electric conductivity. The tracer is prepared as an aqueous solution, saturated with either KCl or NaCl. One problem is that the saturation point depends on the temperature of the water and the temperature of the water can change during the experimental work. This observation was the motivation to initially explore the effect of the saturation concentration of KCl. The saturation concentration of KCl as a function of temperature has been reported by Pinho and Macedo (2005) and Zhang *et al*. (1998) as 34.6 and 38 g/100 ml H_2O, for 19 and 29ºC, respectively. On this basis, the range explored was from 20 to 40 g/100 ml H_2O.

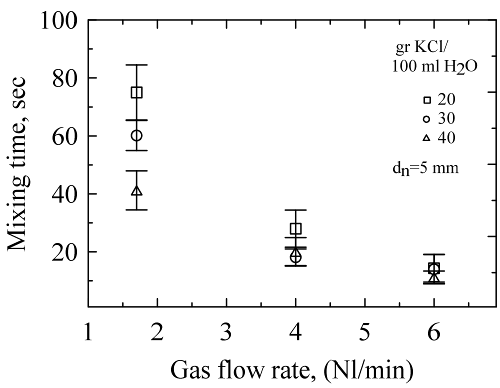

Fig. 4. Effect of gas flow rate and tracer amount on mixing time.

Figure 4 reports the effect of the tracer saturation concentration and gas flow rate on mixing time. It is evident that the tracer saturation concentration does have a direct effect on mixing time, especially at lower gas flow rates. At high gas flow rates, its effect can be neglected. Chen *et al.* (2012, 2013) reported that both, an increase in saturation concentration and tracer amount, decrease mixing time. This effect was attributed to higher buoyancy forces by the tracer.

The density of the saturated solution is higher than that of water, 1162.3 and 998.21 kg/m^3, respectively. They also suggested a dimensionless value of 0.2×10^{-3} as the minimum tracer amount (defined as Dta) to obtain a clear concentration signal. The Dta value in our current work was 3.5/34460 = 0.1×10^{-3} close to the suggested value. Our value was defined based on trials changing the tracer amount.

An important consequence of the previous results is that direct comparison of mixing times between different investigations in water modeling is complicated because there are too many variables involved in the definition of mixing time. Chen *et al.* (2013, 2012) reported that the concentration amount employed in a large number of investigations was in the range from 0.0076×10^{-3} to 19.6×10^{-3}. The huge difference in the amount of tracer employed in different experiments is expected to report large differences in mixing time.

3.2 Effect of Separation Angle, Nozzle Radial Position and Top Slag Layer on Mixing Time

Separation angle and nozzle radial position: Based on the literature review summarized in Table 1 for two injection elements, the values of separation angle more frequently reported as optimum values are 90 and 180 degrees. It has been argued that smaller angles lead to plume coalescence and then their individual effect is decreased. In addition to this, Chen *et al.* (2007) also reported that the optimum separation angle is connected with the nozzle radial position. In most of this previous research the effect of the top slag layer has been ignored. The top slag layer has a significant role on mixing time because a fraction of the potential mixing energy is consumed to open the spout, thus decreasing the energy to stir the molten metal.

Figure 5 describes the effect of the nozzle separation angle and nozzle radial position on mixing time for a constant gas flow rate of 0.5 Nl/min and three different slag thicknesses. These cases correspond to the weakest stirring conditions in the whole experimental conditions from this work. In general, an increase in nozzle separation angle, from 60 to 180 degrees, increases mixing time. The extent of this change depends on the nozzle radial position, nozzle separation angle and slag thickness. At this gas flow rate, with a nozzle radial position at 0.3R a change in separation angle has a small effect on mixing time except when the slag thickness is 2 pct. With this thickness, an increase in nozzle separation angle decreases mixing time by 30 pct. By contrast, when the nozzle radial position is 0.67R, changes in both nozzle separation angle and slag thickness have a large effect on mixing time, for example, for a slag thickness of 4 pct., an increase in nozzle separation angle from 60 to 180 degrees increases mixing time by 300 pct. To emphasize the exceptions to the general trend, those cases where mixing time decreases with an increase in separation angle are indicated by a dotted line. An overall comparison at 0.5 Nl/min indicates that mixing time is the shortest for a nozzle separation angle of 60 degrees, a nozzle radial position of 0.67R and without a top slag layer.

The longest mixing time was obtained for a nozzle radial position of 0.67R and a nozzle separation angle of 180 degrees.

A nozzle separation angle of 60 degrees and a nozzle radial position closer to the center can produce coalescence of both plumes, consequently it is possible to anticipate an increase in mixing time. This phenomenon could explain why mixing time is the longest for a nozzle radial position of 0.3R.

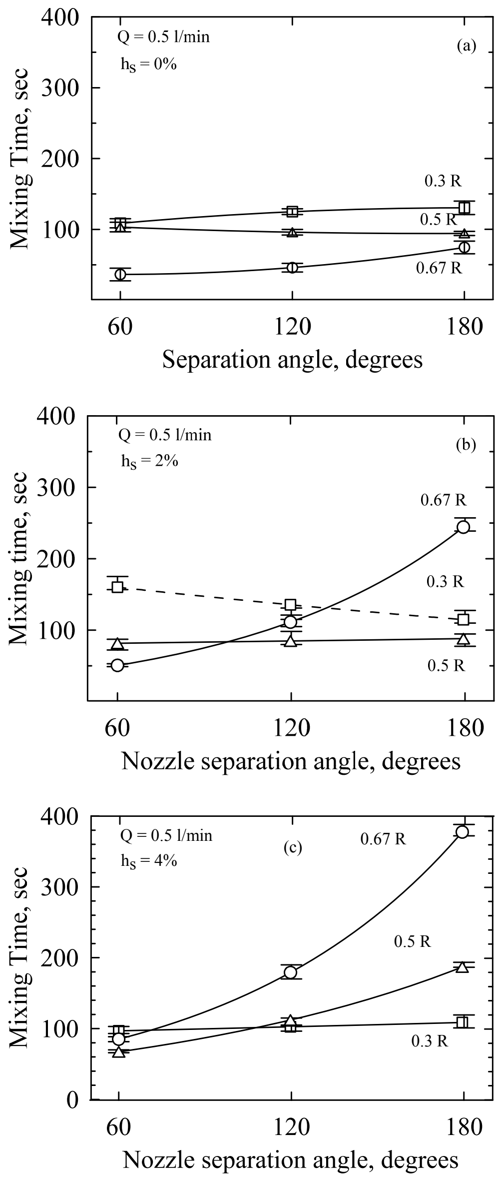

Fig. 5. Effect of nozzle separation angle on mixing time at different nozzle radial positions, for a gas flow rate of 0.5 Nl/min and different slag thicknesses; (a) 0%, (b) 2% (c) 4%.

The complex behavior of fluid flow phenomena in metallurgical ladles when multiple variables are involved can be partially explained by a complex interaction between plumes. The recirculation loops have different type of interactions (momentum exchange) depending on the combination of nozzle separation angle, nozzle radial position, gas flow rate, slag thickness, etc. For example, Liu *et al.*

(2011) reported that for a separation angle of 180 degrees and a nozzle radial position of 0.687R, there are two distinct recirculation loops; however, as the separation angle decreases to 90 degrees, the plumes interact to produce a combined and bigger recirculation loop. They also suggested that better mixing conditions are related with a higher turbulent viscosity distribution. In addition to the multiple interactions between recirculation loops, the location of its central part changes position. Cho *et al.* (2006) reported the center of the recirculation loop in the center of the ladle if a top slag layer was not present and a displacement of this center to the side wall below the top slag layer when there was a top slag layer. Its final position is also affected by the slag viscosity and slag thickness.

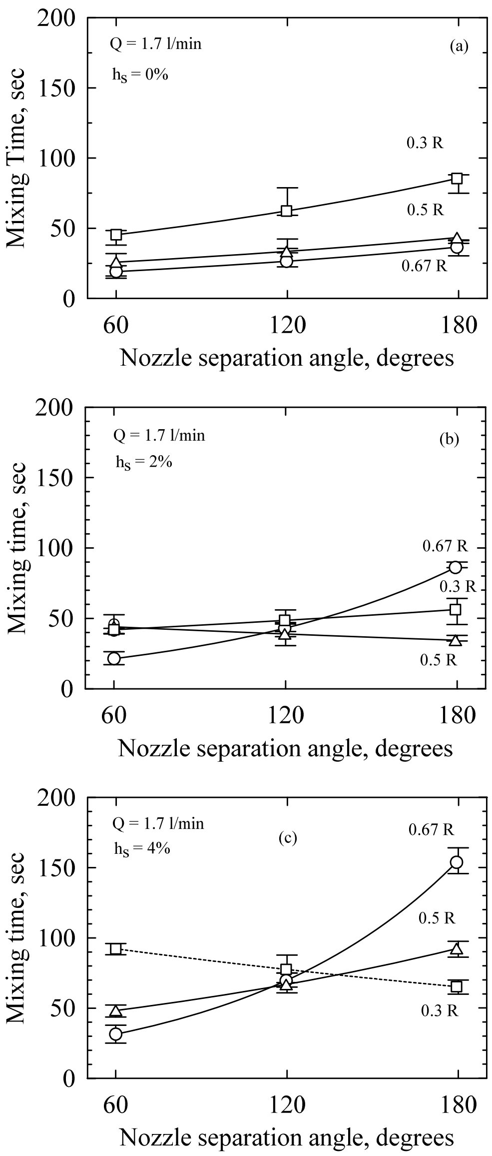

Fig. 6. Effect of nozzle separation angle on mixing time at different nozzle radial positions, for a gas flow rate of 1.7 Nl/min and different slag thicknesses; (a) 0%, (b) 2% (c) 4%.

Figure. 6 describes the effect of the nozzle separation angle and nozzle radial position on mixing time for a constant gas flow rate of 1.7 Nl/min and three different slag thicknesses. In general, an increase in nozzle separation angle, from 60 to 180 degrees, increases mixing time. This behavior is clearly observed for a nozzle radial position of 0.67R, independently of slag thickness.

In the whole set of experiments from this work, mixing time increases when the nozzle separation angle increases and there is not a top slag layer, however the presence of a top slag layer creates a complex flow structure, for example with a slag thickness of 2% and for two nozzle radial positions, 0.3R and 0.5R, mixing time is insensitive to changes in nozzle separation angle but if the slag thickness is 4% and the nozzle radial position is 0.3R, an increase in nozzle separation angle from 60 to 180 degrees produces a decrease in mixing time. These results are an indication that the top slag layer has a major influence on every aspect of the flow structure, such as velocity fields, size of recirculation loops, etc.

For a gas flow rate of 1. 7 Nl/min, the overall shortest mixing time is reported for a nozzle separation angle of 60 degrees, a nozzle radial position of 0.67R and without a top slag layer. In general, the longest mixing time corresponds for a nozzle separation angle of 180 degrees. A possible mechanism that explains this behavior is the dynamic interaction between recirculation loops. For a separation angle of 180 degrees and a nozzle separation angle of 0.67R there is the formation of four recirculation loops that collide in the center of the ladle, as shown by Joo and Guthrie (1992). Collision of recirculation loops involves shear flow and a decrease in momentum. In the case of a separation angle of 60 degrees the collision also happens but the original plumes interact to form one single recirculation loop, especially for a nozzle radial position of 0.67R. In these conditions and given the improved mixing conditions, the collisions among streamlines have a smaller effect on the velocity fields.

Figure 7 describes the effect of the nozzle separation angle and nozzle radial position on mixing time for a constant gas flow rate of 4 Nl/min and three different slag thicknesses. It is observed that in general, an increase in separation angle from 60 to 180 degrees leads to an increase in mixing time. In the cases that follow this trend, the nozzle radial position at 0.67R generally yields a shorter mixing time. In the absence of the top slag layer, mixing time decreases if the nozzle radial position moves from the center to the walls, independently of the nozzle separation angle, however, with a top slag layer and a nozzle radial position of 0.3R, mixing time remains almost constant with changes in separation angle from 60 to 180 degrees. If the slag thickness is increased to 4% and the separation angles increase from 60 to 180 degrees there is a significant increment in mixing time, more than 100%, for the nozzle radial positions of 0.5R and 0.67R. It can be observed that the overall shortest mixing time is again reported for a nozzle separation angle of 60 degrees, a nozzle radial position of 0.67R and without a top slag layer.

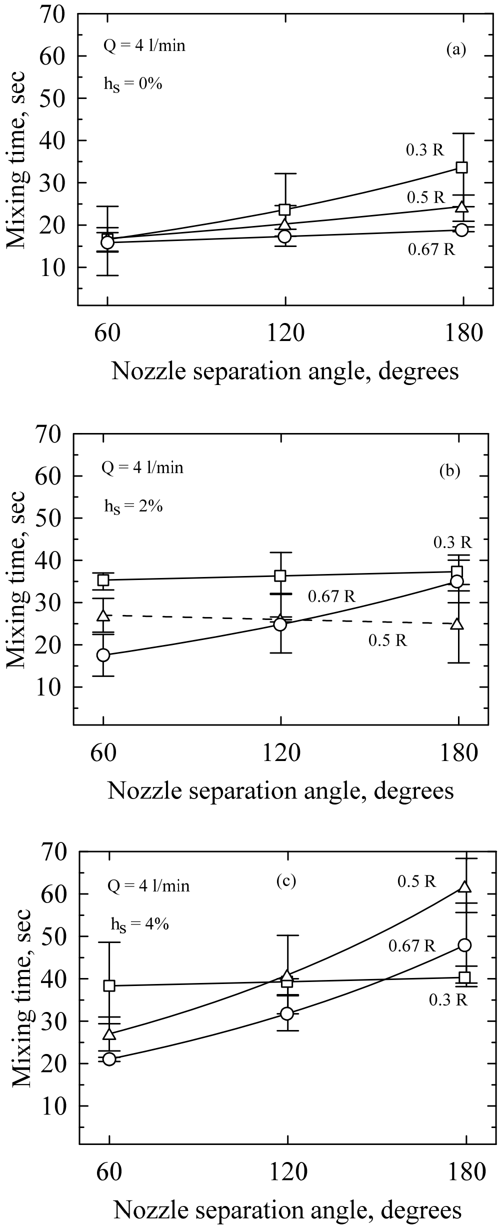

Fig. 7. Effect of nozzle separation angle on mixing time at different nozzle radial positions, for a gas flow rate of 4 Nl/min and different slag thicknesses; (a) 0%, (b) 2% (c) 4%.

Finally, Fig. 8 describes the effect of the nozzle separation angle and nozzle radial position on mixing time for a constant gas flow rate of 6 Nl/min and three different slag thicknesses. In general, as the separation angle increases, there is an increase in mixing time. The increment in mixing time depends on the nozzle radial position and slag thickness. The highest value on mixing time is obtained with a separation angle of 180 degrees, nozzle radial position of 0.5R and a slag thickness of 4%. It can be observed that the overall shortest mixing time, approximately 10 seconds, is reported for a nozzle separation angle of 60 degrees and a nozzle radial position of 0.67R.

Top slag layer: In all the experimental results from this work, when there isn´t a top slag layer mixing time always increases as the separation angle increases from 60 to 180 degrees and also always decreases when the nozzle radial position increases from 0.3R to 0.67R. This behavior changes in the presence of a top slag layer. Most of the previous investigations involving mixing phenomena indicate that mixing time increases due to the presence of the top slag layer. (Kim and Fruehan, 1987; Joo and Guthrie, 1992; Zhu *et al.*, 1995; Jauhiainen *et al.*, 2001; Chiapparoli *et al.*, 2003; Chen *et al.*, 2007; Chattopadhyay *et al.*, 2009; Geng, *et al.*, 2010; Liu *et al.*, 2011; Lou and Zhu, 2014; Patil *et al.*, 2010; Haida *et al.*, 1983; Ying *et al.*, 1983; Yamashita *et al.*, 2003; Mazumdar and Kumar, 2004). The explanation is due to energy consumed to stir the slag and formation of the spout.

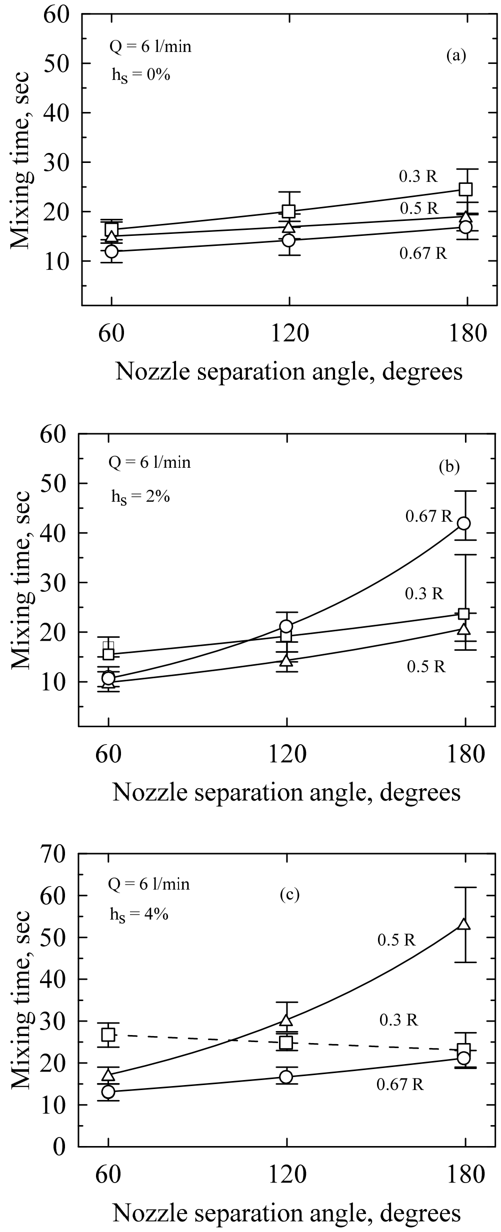

Fig. 8. Effect of nozzle separation angle on mixing time at different nozzle radial positions, for a gas flow rate of 6 Nl/min and different slag thicknesses; (a) 0%, (b) 2% (c) 4%.

In most part of the current experimental work, the top slag layer increased mixing time when its thickness increased, keeping constant the nozzle radial position, gas flow rate and separation angle, however in some case the effect was the opposite. Except for a gas flow rate of 4 Nl/min, in the other gas flow rates employed in the experimental work it was observed cases where mixing time decreased by increasing the top layer thickness. This behavior was observed in a broad range of experimental conditions, but more frequently for the lower gas flow rate of 0.5 Nl/min and when the thickness increased from 0 to 2%. There is only one previous investigation that reports a decrease in mixing time as the top layer thickness is increased, by Conejo *et al*. (2013). In that work hexane was employed to represent the top slag layer.

Based only on the information obtained from water modeling is complicated to define a possible mechanism that could explain a decrease in mixing time as the top layer thickness increases. However, in order to explore a solution it is important to clarify the exact role of the top layer in current water modeling experiments. In the current way to design a water model the criteria on geometric, kinematic and dynamic similarity are applied. In a water model, both water and the top oil layer should have the physical properties to represent the real slag-steel system. Because of a similar kinematic viscosity, water is a valid substance to represent liquid steel. On the other hand, the top slag layer employed in any water modeling doesn´t obey any similarity with a real steelmaking slag. The viscosity of steelmaking slags is 40-100 times higher but only half the density of liquid steel. All commercial oils with density ratios closer to the real steel/slag system have also similar viscosities and those cases where the viscosity is higher than water the density between oil and water is similar. Lin and Guthrie (1994) proved that emulsification is enhanced in the presence of two liquids with similar densities. The oil employed in the experiments conducted in this work has a density ratio of 0.89 suggesting the risk of emulsification. Once the oil droplets of different size are incorporated in the underlying liquid they can contribute with additional eddies and modify the flow structure. It is possible that in those cases where there is a decrease in mixing time with an increase in top layer thickness can be due to incorporation of small oil droplets that enhance the velocity fields of water. At this time the authors cannot provide an accurate explanation but in spite of this it is important to make emphasis on the need to define the proper oil to describe the real system and to be aware that different oils can produce different mixing times using similar injection conditions.

In summary, the effect of the nozzle separation angle with dual nozzles and the presence of a top slag layer indicates that 60 degrees is in general the optimum value when the nozzle radial position is analyzed in the range from 0.33R to 0.67R. In Table 1 several separation angles have been reported as optimum values, 45, 60, 90, 135 and 180 degrees. A direct comparison with previous results is not possible because most of the previous work has been done without the presence of the top slag layer. We have found that the slag phase has a large effect on fluid flow phenomena and mixing time.

It is also important to analyze the role that mixing time has been playing in the past. In the past the top slag layer has been usually ignored. The value of mixing time describes mixing in the bulk of liquid steel. The optimum injection conditions therefore describe how to improve mixing in the bath but not necessarily those conditions involve improved mixing in the top slag layer. Future research should take this into consideration and find adequate experimental conditions to measure mixing conditions in both phases.

3.3 Effect of Gas Flow Rate on Mixing Time

The relationship between gas flow rate and mixing time has been explored extensively in the past. In order to summarize the current experimental work, some of the results from this investigation are illustrated in Fig. 9. The case shown, for a nozzle radial position of 0.67R, three separation angles and a slag layer of 2% indicates a decrease in mixing time as the gas flow rate increases. It is observed a shorter mixing time for a separation angle of 60 degrees. The case is employed to illustrate the general trend observed with the experimental results.

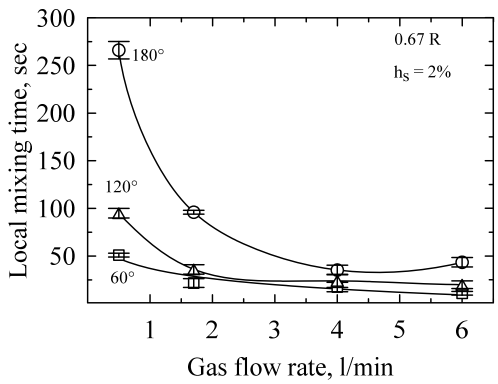

Fig. 9. Effect of gas flow rate and different nozzle separation angles, on mixing time a nozzle radial position of 0.67R and a slag layer of 2%.

3.4 Mixing Time Comparison with one and Two Nozzles

Previous experimental work by Terrazas and Conejo (2015) has reported mixing time phenomena with one nozzle. In that condition the nozzle radial position is one of the critical variables to decrease mixing time. Using one nozzle, it was found that for a nozzle radial position larger than 0.5R it is possible to decrease mixing time. Based on the experimental results from the current work, it has been found the shortest mixing time occurs for a separation angle of 60 degrees and a nozzle radial position of 0.67R. Fig. 10 compares the minimum values on mixing time with one and two nozzles. It is observed that two nozzles always provide better mixing efficiency in comparison with one nozzle. Similar results were obtained in the presence of a top slag layer.

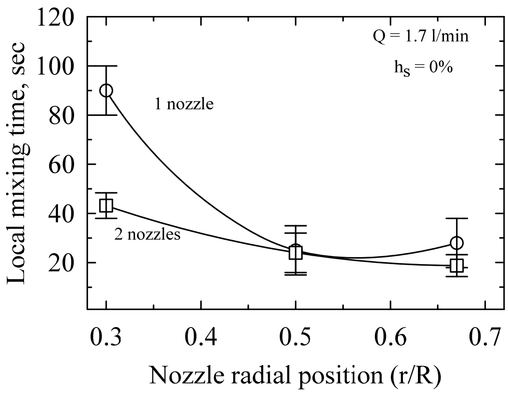

Fig. 10. Comparison between optimum conditions to decrease mixing time with one and two nozzles.

4. Conclusion

An experimental research work using a 1:8 scale water model with two nozzles and a top slag layer has been carried out to analyze the effect of nozzle separation angle, from 60 to 180 degrees, and nozzle radial position from 0.3 to 0.67R, on mixing time.

1. In general, the shortest mixing time has been reached with a configuration including a nozzle separation angle of 60 degrees and a nozzle radial position of 0.67R, with the maximum gas flow rate and without a top slag layer. With this configuration, the nozzle radial position avoids the formation of one single plume and the separation angle promotes a combined recirculation loop.
2. A comparison of mixing time with one and two nozzles suggests that it is possible to reach similar values if the nozzle radial position is higher than 0.5R.
3. The tracer concentration has also been found to have an effect on mixing time, however, this effect is important only at low gas flow rates. At high gas flow rates differences in tracer concentration have no effect on mixing time.

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