Effect of Both Radial Position and Number of Porous Plugs on Chemical and Thermal Mixing in an Industrial Ladle Involving Two Phase Flow

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Gas injection in metallurgical vessels is an important tool to improve chemical and thermal mixing. Chemical mixing has been extensively studied in the past 40 years, however, thermal mixing is still poorly understood. This work reports a mathematical model developed to describe the effect of the number and position of porous plugs on thermal and chemical mixing under industrial conditions.

A relevant contribution of this work is the evidence indicating a suppressing effect of bottom gas injection on thermal homogenization with off-center gas injection; furthermore, it also suggests that mixing time is optimized with only one nozzle instead of two or three.

KEY WORDS: thermal mixing; chemical mixing; mixing time; gas stirring.

1. Introduction

It is desired to increase both thermal and chemical mixing in a metallurgical reactor, in this way both thermal gradients and mixing time will decrease. In the past, few investigations have been carried out analyzing simultaneously both types of mixing phenomena.

Studies on thermal stratification have been reported in the literature. In most of these previous studies it has been assumed an initial uniform temperature in the entire liquid with an axisymmetric gas injection. These studies represent the holding period before continuous casting.

Ilegbusi and Szekely1) reported results from a mathematical model, indicating that gentle induction stirring created velocities 3 times larger than natural convection, enough to minimize thermal gradients. The characteristic velocity calculated for natural convection was in the order of 5 cm/s in contrast to 30–100 cm/s for argon/induction stirred ladles. Heat losses from the top surface were neglected assuming a thick slag layer.

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Chakraborty and Sahai2) reported results from a mathematical model indicating the effect of slag thickness on thermal stratification in a 250 ton ladle, considering uniform heat losses from liquid steel to the refractory walls and two different conditions on heat losses from the top surface; in one case zero heat losses were considered due to the presence of a thick slag layer and a second case assuming a heat loss rate of 100 kW/m², corresponding to a thin layer of slag. Contrary to intuitive thinking, it was found larger thermal stratification in the case with a thick slag due to a smaller extent of mixing. In spite of the larger thermal stratification in the case of the thick slag layer, temperature decrement in liquid steel was smaller after 45 minutes (5–10°C) in contrast with a decrease of 45°C with the thin layer of slag. The larger extent of mixing with a thin layer of slag resulted from higher velocities, 0.05 m/s, in comparison with 0.01 m/s with a thick layer of slag. The larger extent of mixing is beneficial in terms of flotation of non-metallic inclusions. The authors suggest the control of slag thickness in order to balance heat losses and adequate mixing.

Neifer et al.3) reported results from a mathematical model for an industrial ladle of 250 tonnes which included a slag thickness of 50 mm. They reported the effect of a ladle cover on thermal stratification in the presence of central gas injection. Thermal stratification decreased from 60°C without the ladle cover to 1–2°C with the ladle cover.

Grip et al.4,5) made experimental measurements on thermal stratification in 7 and 107 tonnes ladles, the results were used to validate their mathematical model. Heat losses from the steel to the refractory for the industrial ladle were initially taken from plant experience as 9.6 kW/m². This value was changed to 22.4 kW/m² in the computations. In the 7 ton ladle heat losses are bigger, estimated as 110 kW/m². Heat losses from the top surface in both industrial and pilot plant ladle were estimated as 9.03 and 0 kW/m², respectively. The initial uniform temperature was set at 1940 K. The agreement between predicted and measured temperatures was good using the experimental data from the pilot plant ladle, however, the experimental measurements in the industrial ladle were complicated. It was experimentally observed a homog-
enization time of 3 minutes with gas stirring, in agreement with previous results from Castillejos et al.\textsuperscript{9} Castillejos et al.\textsuperscript{9} considered a temperature difference of 40°C between the top and the bottom of the ladle with central gas injection.

Xia and Ahokainen\textsuperscript{7} reported results on thermal stratification from a mathematical model for an industrial ladle. They did not make any assumptions on heat losses from the steel to the refractory walls ($q_{w}$), instead they were calculated by the conservation energy equations. Heat losses from the top surface were estimated as 10 kW/m². They found out that $q_{w}$ is not constant but changes rapidly with time, at the beginning is higher due to the larger temperature gradient between the steel and the refractory wall and after 900 seconds heat losses became dominated by heat conduction within the walls which yields a constant value in heat losses. Pan and Bjorkman\textsuperscript{9} reported experimental measurements on thermal stratification from a water model due to natural convection. They reported that heat losses are not uniform along the refractory sidewall. Applying the similarity criteria they reported empirical equations to describe heat losses. Based on their results they confirmed that the stratification rate linearly increases with the bulk cooling rate.

Ganguly and Chakraborty\textsuperscript{9} analyzed thermal stratification in terms of the homogenization time for a system initially homogeneous, with heat losses from the side walls of the ladle and with central gas injection. They reported that even at small gas flow rates, gas injection promotes thermal homogenization.

It has been pointed out that previous research on thermal stratification has focused on the holding period between the end of the ladle furnace process and the start of teeming at the continuous casting machine, this situation justify to start with a relatively homogeneous temperature in the liquid steel, however, there is a complete different situation on thermal stratification during the ladle furnace process. In this case, the localized heating by the electrodes produces a large thermal stratification. This case has not been investigated in detail in the past. Rogler et al.\textsuperscript{10} reported the influence of gas flow rate on thermal stratification in a water model. A hot stream of hot water was added on the top surface, equivalent to a heating rate of 1°C/min. The authors reported faster homogenization rates with two nozzles.

Jauhianen et al.\textsuperscript{11} reported a mathematical model cast in the CFD code PHOENICS, analyzing the effect of position of 2 nozzles, on the theoretical mixing of Mn into steel in a 110 tons industrial gas stirred ladle, keeping the gas flow rate constant. They evaluated the separation angle and distance away from the center. The four nozzle configurations involve 2 nozzles separated 60° at 0.5R and 2/3R, 2 nozzles separated 180° at 0.5R, and the 2 nozzles in the center (this case is in fact a single plug injection in the center of the bottom ladle). They did not present computed mixing times but rather the evolution of the minimum concentration in the ladle and the standard deviation from the mean concentration, to infer the best mixing conditions with both batch and continuous alloy injection. Actually, they found that centric injection stirring with a single plug gave the best mixing conditions. They also modeled the Asea – SKF process to simulate the rate of hydrogen removal with both gas and induction stirring.\textsuperscript{12}

The objective of this work was to develop a mathematical model to investigate the influence of the number of porous plugs and its radial position on mixing phenomena both thermal and chemical, considering the localized source of heating from three electrodes in an industrial ladle.

2. Mathematical Model

2.1. Governing Equations

A simultaneous two phase (Gas-Liquid), three dimensional CFD mathematical model was developed which simulates heat and momentum transfer in an industrial steel ladle due to bottom gas injection. The two phase system, gas bubbles-liquid steel, is analyzed using the Eulerian frame of reference. The calculations were performed in the transient solution mode. This approach requires the formulation of conservation equations for both phases (G-L). The gas stirred ladle furnace represents a turbulent and recirculatory two-phase flow problem. In this flow, the two phases are in relative motion to each other, exchanging momentum, energy, and mass.

The assumptions in this model are: (i) Both phases, gas and liquid, are Newtonian fluids, (ii) bubble size is constant, i.e. coalescence and bubble breakup phenomena are neglected, (iii) cylindrical vessel, which allows a representation in cylindrical coordinates.

In general form, the governing equations of continuity, momentum and thermal energy can be expressed as follows:

Equation of continuity for the phase $i$, Eq. (1)

$$\frac{\partial (\rho R_{i})}{\partial t} + \nabla \cdot (\rho \mathbf{v}_{i} R_{i}) - \nabla \cdot (\Gamma_{i} \nabla R_{i}) = \dot{n}_{j,i} \quad ...... (1)$$

The first term of Eq. (1) represents the accumulation of phase $i$ at a fixed point, the second term represents the transport of phase $i$ due to convection, the third term is the transport of phase $i$ due to turbulent dispersion. The term on the right side of the equation represents the net velocity of mass entering into the phase $i$ from phase $j$, which in this case is zero. In this equation $R_{i}$ represents the volume fraction of phase $i$, $\rho$ is the density of phase $i$, $\mathbf{v}_{i}$ the velocity vector of phase $i$ and $\Gamma_{i}$ the turbulent dispersion coefficient of phase $i$.

General momentum conservation equation , Eq. (2):

$$\frac{\partial (\rho_{i} R_{i} \mathbf{v}_{i})}{\partial t} + \nabla \cdot (\rho_{i} \mathbf{v}_{i} R_{i} \mathbf{v}_{i}) - \nabla \cdot (\Gamma_{i} \nabla \mathbf{v}_{i}) = S_{v,i} + S_{IP}^{v,i} \quad ...... (2)$$

On the left side of Eq. (2) the terms are related with accumulation, momentum transport due to convection, momentum transport due to diffusion and momentum transport due to turbulent dispersion, respectively. The two terms on the right side represent momentum source terms, within the phase $i$ and that for the interphase, respectively. In Eq. (2) $\mathbf{v}_{i}$ represents the velocity component of phase $i$ in the directions $r$, $\theta$, $z$. $\Gamma_{i}$ is the diffusion coefficient within the phase $i$. The momentum source term for the interphase, neglecting the net rate of mass transfer among the two phases ($\dot{n}_{i,j}=0$), is given by the following expression:

$$S_{IP}^{IP} = f_{i,j} \left( \mathbf{v}_{i} R_{i} - \mathbf{v}_{j} R_{j} \right) \quad ...... (3)$$

In Eq. (3) $S_{IP}^{IP}$ represent the momentum source term at
the interphase for the velocity of phase $i$ in the directions $r$, $\theta$, $z$. $f_{i,j}$ is the friction coefficient that depends on the drag coefficient at the gas-liquid interphase. $v_{r,i,j}^{i}$ is the velocity in the directions $r$, $\theta$, $z$ for the phase $i$. $v_{z,i,j}^{i}$ is the velocity within the phase $i$ in the directions $r$, $\theta$, $z$. The source term within the phase $i$, depends on the pressure gradients in the directions $r$, $\theta$, $z$.

General energy conservation equation, Eq. (4),

$$
\frac{\partial}{\partial t} \left( \rho_i H_i \right) + \nabla \cdot \left( \rho_i v_i H_i \right) - \nabla \cdot \left( \Gamma_{\text{th}} R_i \nabla H_i \right) = S_{Hi} + S''_{Hi} \quad \ldots (4)
$$

$H_i$ represents enthalpy or thermal energy of phase $i$, $S_{Hi}$ is the source term for heat transfer within the phase $i$ and $S''_{Hi}$ is the interphase source term for heat transfer.

The source terms in the equation for energy conservation are given by the following expressions:

$$
S_{Hi} = \Phi_i + \frac{\partial p_i}{\partial z} + \nabla \cdot \mathbf{V}_i \quad \ldots (5)
$$

$$
S''_{Hi} = h_{i,j} A_j \left( T_j - T_i \right) \quad \ldots (6)
$$

In Eqs. (5) and (6), $\Phi_i$ is the viscous dissipation function for the phase $i$. $P_i$ is the dynamic pressure of phase $i$, $h_{i,j}$ is the heat transfer coefficient at the interphase $i-j$ given as $h_{i,j} = k_{i,Nu}$, $k_i$ is the thermal conductivity of phase $i$, $Nu_i$ is the local Nusselt number for the phase $i$. $D_p$ is the bubble diameter, $A_j$ is the surface area of all bubbles, given as $A_j = \frac{6R_i V_{cell}}{D_p}$ being $V_{cell}$ the volume of each cell in the domain, and finally $T_j$ and $T_i$ are temperatures of phases $j$ and $i$, respectively.

The diffusion coefficient for the phase $i$, $\Gamma_{i}$, is defined in terms of laminar and turbulent viscosities ($\mu_i$, $\mu_{turb}$) as well as the laminar and turbulent Prandtl numbers, as follows:

$$
\Gamma_{i} = \mu_i \Pr_i \left( R_i \right) + \mu_{turb} \Pr_{turb} \left( R_i \right) \quad \ldots (7)
$$

The diffusion coefficient within the phase $i$, for momentum and energy transport, ($\Gamma_{i}$, $\Gamma_{\text{th}}$), are also defined in a similar way.

In addition to the previous equations, the following expression should also be fulfilled at each node:

$$
R_i + R_j = 1 \quad \ldots (8)
$$

The Turbulence model $k-\varepsilon$ is applied only to the liquid phase to compute the turbulent kinetic energy ($k$), the turbulent kinetic energy dissipation ($\varepsilon$) and the turbulent viscosity of the liquid ($\mu_{turb}$).

2.2. Initial and Boundary Conditions

The set of governing equations described above included the following initial and boundary conditions.

The initial condition for the ladle coming after tapping from the steelmaking furnace was calculated taking into consideration that the volume of the domain is occupied by molten steel at a specified initial temperature. Then, after 500 seconds the liquid experienced natural convection which produced initial thermal stratification.

Symmetry along the $\theta$-planes (symmetry planes depend on the plug configurations), i.e. zero flux boundary of all transported quantities:

$$
\dot{v}_{r,i}^j = \dot{v}_{\theta,i}^j = 0 \quad \ldots (9)
$$

$$
\frac{\partial \dot{V}_{r,i}^j}{\partial \theta} = \frac{\partial \dot{V}_{\theta,i}^j}{\partial \theta} = \frac{\partial \dot{V}_{z,i}^j}{\partial \theta} = \frac{\partial \dot{V}_{r,i}^j}{\partial \theta} = \frac{\partial \dot{V}_{\theta,i}^j}{\partial \theta} = \frac{\partial \dot{V}_{z,i}^j}{\partial \theta} = 0 \quad \ldots (10)
$$

Non-slipping conditions at the impermeable walls (bottom, Eq. (12) and cylindrical, Eq. (13)).

$$
\dot{v}_{r,i} = \dot{v}_{\theta,i} = \dot{v}_{z,i} = 0 \quad \ldots (11)
$$

$$
\frac{\partial \dot{R}_{i}}{\partial z} = 0 \quad \ldots (12)
$$

$$
\frac{\partial \dot{R}_{i}}{\partial r} = 0 \quad \ldots (13)
$$

The model considers the presence of heat losses from the side walls and the top surface of the domain and also, at the top surface, heat input from the electric arcs. Heat losses from the walls, defined at a constant value, are based on the work conducted by Alberny and Leclercq, cited in the work reported by Castillejos et al.\(^{6}\)

$$
q_{i}^t = -1.25 \times 10^4 \text{ W/m}^2 \quad \ldots (14)
$$

Heat losses from the top surface, $q_s$, are computed using the Stefan-Boltzmann equation, Eq. (15) where $\sigma$ is the Stefan-Boltzmann constant and $\varepsilon_i$ the emissivity, taken as 0.8

$$
q_s = -\sigma \varepsilon_i T^4 \quad \ldots (15)
$$

The heat input from the electric arcs is constant. Its value corresponds to the normal tap voltage in operation, 1R, equivalent to 25 MW, Eq. (16).

$$
q_{i} = 25 \text{ MW} \quad \ldots (16)
$$

Finally, the model considers a gas flow rate entering at a constant value of velocity, temperature, $k$ and $\varepsilon$ at every opened porous plug (inlet) and zero shear stress from the gas atmosphere at the top free surface, where gas is allowed to leave the system.

For the mixing time analysis it was considered the injection of a tracer on the top of one of the spouts. The standard criteria of 95% mixing was employed to measure mixing time.

The computational code PHOENICS version 3.4 was employed to solve the system of equations. This code uses the finite volume method which integrates the conservation equations in every cell. The two phase flow problem was solved under the Eulerian-Eulerian frame of reference by using the built-in PHOENICS Inter-Phase Slip Algorithm (IPSA), in which a complete set of conservation equations is solved for each phase and coupled through interphase drag terms. It is important to mention one advantage of this code in defining a constant bubble size, which in this case was fixed at 5 mm.
3. Results and Analysis

The industrial ladle employed in the simulations has a capacity of 220 ton of liquid steel, with the following dimensions; height 3.57 m and diameter 3.58 m. The diameter of the porous plug is 0.013 m.

The simulated experimental conditions are indicated in Table 1. The properties of the gas and liquid phases are indicated in Table 2.

It was observed a temperature increase during gas injection, due to the external supply of electrical energy, in the order of 4–5°C/min, independently of gas flow rate, which corresponds with observed results in the industrial practice.

The initial temperature of the steel bath was 1 875 °K (1 602 °C), then for 500 seconds the liquid experienced natural convection which produced thermal stratification. This condition was used to simulate initial conditions for the ladle coming after tapping from the steelmaking furnace. At this time, argon was injected for 6 minutes and simultaneously heating with three electrodes was turned on.

The localized source of heating on the top surface of the liquid steel produces extremely large temperature gradients when the temperatures from top and bottom are compared. The criteria employed to evaluate thermal mixing was in terms of the temperature differences in three planes of the vessel; top, middle and bottom.

\[ \Delta T_z = T_{z_{\text{max}}} - T_{z_{\text{min}}} \]  

(17)

Chemical mixing is evaluated with mixing time using the criterion of 95% of chemical uniformity. It is important to note that the model is able to check the mixing criteria in every cell in the computational domain instead of using two or three measurement points as is experimentally done. Since the mathematical model considers the entire system, computed mixing times may be greater than measured mixing times. This fact it may be due to the presence of dead zones where mixing is slow and the criteria establishes that mixing is reached when 100% of the cells are in the range of +/- 95% of the equilibrium composition.

3.1. Model Validation

Gripi et al.\textsuperscript{5)} reported experimental measurements for thermal stratification in a 7 ton. pilot plant. This information was used to validate the mathematical model developed in the current work. The comparison between the experimental results and those from the mathematical model are reported in Fig. 1. It is readily apparent the good correlation among those results and thus the validation of the mathematical model is confirmed.

3.2. Effect of Gas Flow Rate

The effect of gas flow rate was analyzed fixing standard conditions for the number and location of porous plugs. In this case such conditions correspond to one porous plug located at half radius. The gas flow rate was increased from 5–38 Nm\textsuperscript{3}/hr using one nozzle located at half radius. The maximum gas flow rate for one porous plug was chosen based on the industrial practice.

Thermal mixing: The effect of gas flow rate on thermal mixing is relatively small, as can be seen in Figs. 2 and 3. Figure 2 shows the temperature difference on the top surface (ΔT\textsubscript{top}). The top surface shows the largest temperature difference; in the order of 350–400 °C. Such a large value is obtained due to the presence of three electrodes heating the top surface.

An increase in gas flow rate slightly decreases ΔT\textsubscript{top}, how-
ever this effect is less than 2%. Steady state in the temperature difference is achieved after 300 seconds. This condition is first achieved with the largest gas flow rate. Figure 3 shows the temperature difference in the middle of the ladle ($\Delta T_{\text{mid}}$). It is observed that $\Delta T_{\text{mid}}$ is much smaller than $\Delta T_{\text{top}}$ and also that the temperature difference remains almost constant, in the range from 5–10 °C up to 150 seconds. At this moment the temperature difference steadily increases, reaching 35 °C in 6 minutes. The time when the temperature difference decreases on the top surface is the same when it starts to increase in the middle region of the ladle. This behaviour indicates that it takes about 150 seconds to transfer heat from the top to the middle region of the ladle.

In regard with the temperature difference in the ladle bottom, it was observed a maximum temperature difference of 10 °C after 360 seconds of argon injection.

Chemical mixing: Mixing time was computed as a function of gas flow rate. Figure 4 shows the very well known relationship between mixing time and gas flow rate. The salient feature of this result is the magnitude of mixing time. At low gas flow rates, 5 Nm$^3$/hr, mixing time is quite large in the order of 41 minutes. This time decreases by almost 50% to 22 minutes at a higher gas flow rate of 38 Nm$^3$/hr. Mixing time in water models is in the order of 50–100 seconds, depending on gas flow rate and nozzle configuration. Only few investigations have reported mixing time for industrial size ladles. Abel et al. compared water modelling results and industrial size ladles, reporting mixing times one order of magnitude higher for industrial size ladles. In the experimental work of Schurmann et al. reported by Mietz et al. a mixing time of approximately 12 minutes is reported for an industrial ladle of 120 tonnes. Szekely et al. reported experimental measurements of mixing time using radioactive tracers in pilot and industrial scale ladles, ranging from 7 to 60 tonnes, using very low gas flow rates in the order of 3 Nm$^3$/hr. They reported a value of 7–8 minutes, independently of the ladle size. In contrast to these values, Warzecha et al. and Aoki et al. have reported mixing times in the range from 1.5–3 minutes for ladles of 110–140 tonnes, using gas flow rates in the order of 10 Nm$^3$/hr.

The large differences reported for mixing times in industrial size ladles can be attributed to different porous plugs configurations (i.e., number and location) as well as gas flow rate, however our current numerical predictions suggest that mixing times in industrial size ladles is at least one order of magnitude higher in comparison with water models. As it was previously stated the fact that mixing criteria is checked at every cell in the computation domain it may be the cause of larger computed mixing times than measured mixing times which are obtained by measuring the solute concentration in a single point in the ladle.

3.3. Effect of Radial Position

The effect of radial position ($r/R$) on thermal and chemical mixing was investigated using one and two porous plugs at a fixed gas flow rate of 35 Nm$^3$/hr. This gas flow rate is close to the upper limit with one porous plug. It should be noted that one advantage with two porous plugs is that the total gas flow rate can be increased twice, however, in order to have the radial position as the only variable, the total gas flow rate was fixed at the maximum value achieved with one porous plug. The radial positions investigated included the values of 0, 0.33, 0.5, 0.67, 0.75 and 0.9.

3.3.1. One Porous Plug:

Thermal mixing: The radial position has a large influence on thermal mixing on the top surface. Figure 5 shows that centric gas injection yields the smallest temperature difference on the top surface. This position gives a temperature gradient in the order of 200°C. Moving this position away...
from the center increases the temperature difference up to 450°C. Figure 6 shows the temperature difference in the middle region of the ladle, its magnitude is much smaller in comparison with the top surface. It is observed that $\Delta T_{\text{mid}}$ is smaller when gas is injected away from the center. Gas injection at a radial position of 0.67, gives in 6 minutes, a temperature gradient of 20°C, in contrast to 50°C when the gas is injected in the center, as shown in the figure. The improvement in thermal mixing in the middle region when the porous plug is located away from the centre, is attributed to a minimization of the dead zones. In Figs. 5 and 6 it is observed that at diametrically opposing radial positions the temperature gradients are not the same, this behaviour is due to the relative position of electrodes with respect to the position of the porous plugs. The region closer to the electrode will always exhibit a larger temperature gradient.

The largest thermal differences are found on the top surface, ten times higher than those for the middle section of the ladle. In principle, it appears that central gas injection is the optimum radial position to improve thermal mixing. This observation can be identified more clearly evaluating the global thermal behaviour in the whole ladle, as shown in Fig. 7. It is observed that temperature is more homogeneous in the whole system when gas is injected in the center. When the porous plug is moved away from the center, the overall temperature gradient in the ladle is increased. Centric gas injection promotes uniformity at the top surface due to the symmetric flow pattern developed.

The current results agree with similar results reported by Kim and Fruehan (19) who concluded that gas injection in the center improves mixing of the top layer which in turn improves impurity removal.

Chemical mixing: Mixing time is minimized moving the porous plug away from the center, as shown in Fig. 8. Mixing time is minimized with radial positions from 0.67 to 0.75, however if the plug is too close to the wall mixing time increases again. Mixing time decreases from 32 minutes for central gas injection to almost 22 minutes at $r/R = 0.67$.

Several investigations have been reported on the effect of radial position on mixing time with one porous plug, (19–21) however they have been limited to radial positions $r/R \leq 0.5$ reaching the conclusion that a radial position at half radius yields the shortest mixing time. Joo and Guthrie (19) included the radial position at 0.67, reaching the same conclusion. Due to the Coanda effect, which describes the interaction
between the gas bubbles with the sidewalls, it is expected that a radial position close to the wall will affect the mixing time.

Based on the previous results it can be concluded that the optimum radial position for the porous plugs to improve thermal and chemical mixing is different. The current predictions with one porous plug suggest an eccentric location to minimize mixing time, however the eccentric location yields poor thermal mixing. A possible solution to this situation could be the installation of a central porous plug in addition with eccentric positions.

Figure 9 summarizes fluid flow and isotherms resulting from the different radial positions of one porous plug. Due to symmetry it is shown only one half of the ladle. The top surface shows localized high temperatures in the arc attached zones.

3.3.2. Two Porous Plugs:

The radial position of two porous plugs was analyzed keeping their separation angle at 180°. The total gas flow rate was 35 Nm³/hr.

Thermal mixing: Figure 10 describes fluid flow and isotherms resulting with two porous plugs at three different radial positions. It can be observed how the hot liquid remains within the two plugs, which indicates that the gas plumes act as a barrier to heat transfer by convection.

Chemical mixing: Mixing time with two porous plugs is also shown in Fig. 8. With two porous plugs the total gas flow rate is decreased by half in each plug in order to compare changes in radial position at the same total gas flow rate. It is clearly observed that by increasing from one to two porous plugs that mixing time increases. It is also observed that the minimum in mixing time with respect to radial position is similar to the case with only one porous plug, i.e., at r/R = 0.67–0.75. This result suggests using only one porous plug instead of two and a radial position off-center, closer to the walls.

3.4. Effect of the Number of Porous Plugs

The influence of the number of porous plugs on thermal and chemical mixing was investigated using one, two and three porous plugs located at half radius with a total gas flow rate of 35 Nm³/hr.

Thermal mixing: Figures 11 and 12 show the velocity and temperature fields produced by bottom gas injection with one, two and three porous plugs. There are three major features from these figures:

- The gas column acts as a barrier to heat transfer inhibiting heat exchange between hot and cold liquid steel, therefore, the liquid between the gas column and the
walls remains colder.
- Thermal mixing occurs only within the liquid between the gas plumes.
- Increasing the number of porous plugs improves thermal mixing for the liquid between the gas plumes.

Comparing the results on thermal stratification with 1–3 porous plugs, in Figs. 7 and 12, it is observed that with one porous plug, central injection is better because of smaller temperature gradients in the entire ladle. If the porous plug is moved away from the center, thermal mixing is affected negatively. When two and three porous plugs are installed at half radius it is observed that better thermal mixing is achieved by increasing the number of porous plugs, however similar thermal gradients are comparable only with one porous plug-centrally located and three porous plugs at half radius. Based in these results it can be concluded that is more convenient-centrally located in order to improve thermal mixing.

Chemical mixing: Figure 13 shows the effect of increasing the number of porous plugs on mixing time. During simulation, when the number of porous plugs is increased, the total gas flow rate is kept constant (35 Nm³/hr). In all cases the porous plugs were located at the same radial position (r/R=0.5). For more than one plug the relative positions were as follows: two 2 nozzles separated 180° and three nozzles forming angles of 120°.

Mixing time with one porous plug for the industrial ladle is approximately 23 minutes, with two and three porous plugs increases to 25 and 28 minutes, respectively. The results appear to indicate that increasing the number of porous plugs is detrimental to the mixing time. One reason which explains why this happens is the decrease in gas flow rate as the number of porous plugs is increased. It was explained before that this is due to the requirement of a constant gas flow rate. The potential benefit with two porous plugs is the larger gas flow rate that can be supplied, in such case a shorter mixing time would be expected. The optimum number of porous plugs and its position is a subject highly debatable in the literature, however, there are previous investigations which also report that one porous plug is more recommended to decrease mixing time.20,22)

Our results agree well with Jauhianen et al.’s results11) since they found that using a single plug (they were supposed to use two plugs located at the center but since they
used a single cell for each plug, it is actually a single plug) located at the center it is better than using two plugs.

Our conclusion of a better chemically mixed bath with only one plug does not suggest operate with ladles having a single plug installed on them. Actually, industrial ladles with a single plug are very unusual since the plug may be plugged and in order to guarantee availability of gas to stir the melt, the ladle must have two or more plugs available.

4. Conclusion

The effect of both radial position and number of porous plugs on chemical and thermal mixing in an industrial ladle involving two phase flow has been numerically investigated. The initial conditions assume a large thermal gradient due to localized heating by the electrodes. Several configurations involving one to three porous plugs have been included in this analysis with different radial positions and gas flow rates. The following enumerated conclusions can be withdrawn from this work:

- The number of porous plugs and its radial position has a large influence on thermal and chemical mixing.
- Thermal mixing is improved with one porous plug located in the center of the ladle. The gas plumes act as thermal barriers when two and three porous plugs are included.
- Chemical mixing is improved with one porous plug located at a radial position of 0.67. This position yields the shortest mixing time, approximately 22 minutes for the industrial ladle.

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