Book Chapter

Changes of Multiphase Flow Patterns during Steel Tapping with Simultaneous Argon Bottom Stirring in the Ladle

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Abstract

Changes of the unsteady multiphase fluid flow patterns of liquid steel during tapping operations from the Electric Arc Furnace to Ladle, under simultaneous bath bottom stirring with argon, are simulated using interfacial-tracking computing techniques. The impinging jet or entry interacts with the rising argon bubbling plume suffering mutual bending effects and imparting non-symmetric flows of liquid steel during the whole ladle filling time. At low bath levels radial-recirculating flows are generated and at high bath levels, these flows are substituted by vertical long flows generated by the permanent interaction between the impinging jet and the argon plume. Turbulence intensity increases as the bath level rises. Low bath levels are suitable for pre-melting and preheating ferroalloy particles. High bath levels of steel in the ladle, close to total ladle filling, are the most suitable conditions for thermal and chemical homogenizations. Argon gas forms an intermittent blanket over the air-argon-liquid steel mix, separating it from the top air in the ladle, due to its higher density than air during the whole ladle filling time.

Keywords

Steel Tapping; Bottom Stirring; Simulation; Fluid Flow; Ladle

Nomenclature

C_μ : Constant in the Turbulence Model

H: radius of Curvature

I: Identity Matrix

k: Kinetic Energy

t: Time

u: Velocity

V: Volume

Greek Letters

α : Volume Fraction

ε : Dissipation Rate of Kinetic Energy

μ : Viscosity

ρ : Density

σ : Surface Tension

T: Strain Stress

X: Phase Indicator

Sub Indexes

q: Phase

m: Mixture

n: Normal

I: Interface

Introduction

Steel tapping is, without doubt, the most important operation of all the steelmaking processes. An optimum tapping should be performed with a compact steel jet exiting from the Eccentric Bottom Tapping (EBT) system, embedded in the Electric Arc Furnace, an optimum timing of fluxes and alloying additions, suitable sizes of ferroalloys and steel temperature, and small amounts of slag carry over into the ladle. A successful tapping yields maximum efficiency of deoxidants and alloying elements, low pickups of nitrogen and oxygen from the surrounding air and fast slag formation, making the ladle ready for its transport to the ladle furnace. Once in the ladle furnace, steel will be readily refined with simultaneous flotation of inclusions, through ladle bottom stirring with argon, to be absorbed eventually by the slag. Any misstep in this operation will have a charge in the process like longer refining times with larger energy consumptions,

higher consumptions of deoxidants and, possibly, dirtier steel. Fluid flow dynamics of steel during tapping operations has been studied from the point of view of ferroalloy particles regarding their trajectories and distribution in the bath. Guthrie *et al.* [1] employed a balance of forces on a particle entering in a liquid and evaluated the importance of drag, buoyancy, added mass and history forces acting on the particle once it is submerged in the liquid. Their physical and mathematical models included experiments of wooden particles with different densities into a tank of still water. Their results indicated that the history term in the balance of forces has a negligible influence on the particle dynamics, emphasizing the importance of drag, buoyancy and mass added forces. Maximum depth penetration of particles, for a given initial entry velocity, depend on the density ratio between the particle of ferroalloy and liquid steel, higher ratios lead to deeper penetrations. Tanaka *et al.* [2] performed also physical and mathematical modeling for additions of ferroalloys in a 250-ton steel ladle. They established, through dimensional analysis, modeling criteria for scaling up sizes of added particles and their entry velocities in a model to particles in the actual ladle linked by the square root of the model scale. These authors simulated the effects of steel motion on spherical particles trajectories assuming a one-way coupling mechanism between liquid and particles (liquid steel flow influences particle dynamics and no the other way). According with these authors buoyant additions, such as aluminum and Fe-Si, are hardly affected by the flow pattern of steel since the buoyancy force is so large that it makes them to float out rapidly and then the dynamic behavior of these particles does not change, even when added in a stagnant liquid. The reverse is true for denser particles, whose trajectories are strongly influenced by fluid flow dynamics. The penetration of either, dense or light additions is improved when they are injected close or in the plunging or entry steel jet. Maximum penetration depths and total immersion times were substantially smaller when particles with different geometries, like cubes and cylinders, are added to the bath. However, according to Guthrie *et al.* [1], when a ferroalloy particle enters in a bath of liquid steel, a solid steel shell very rapidly forms around it. This freezing shell would tend to mask sharp irregularities of the particle's shape maintaining valid the

approximation of a spherical shape. Rodriguez *et al.* [3] reported Computer Fluid Dynamic (CFD) simulations regarding trajectories of particles of ferroalloys such as Fe-Si, Fe-Nb, Al and Fe-Mn defining the optimum locations in the ladle and bath height to maximize their residence time in the melt. In another work, Mazumdar and Guthrie [4] applied their model to the CAS (Composition Adjustment by sealed Argon Bubbling Systems) process and found that the shape of particles have negligible effect on the overall nature of particles trajectories. Berg *et al.* [5] reported CFD simulations of fluid flow and alloy dissolution during steel tapping. Efforts in the direction to model physically tapping operations of steel have made use of plunging water jets, dragging air from the surroundings, and have been reported by Hammad [6] using PIV measurements and Iguchi *et al.* [7] who employed LDV measurements. The first authors found that two-phase flow dynamics are overly sensitive to ambient perturbations, such as free surface instability and external vibrations. On the other hand, LDV measurements were not possible in the developing region of the two-phase flow making difficult to model closely this complex flow. The characteristic of all these works is that none of them reported the interaction of the bottom argon injection, to provide additional pneumatic stirring to the bath for enhancing alloy dissolution rate and chemical and thermal homogenizations, together with the impinging or entry jet.

The objective of the present work is to study the changes of fluid flow dynamics during tapping and filling times of liquid steel in a ladle with simultaneous pneumatic stirring with bottom argon bubbling. The approach employed to reach this objective, due to the difficulties of direct observations or observations through physical models, is numerical simulation using CFD techniques. The results of this work will be used to simulate, in future works, heat transfer to the particles with their dynamics and melting rates under the conditions described here. The final goal is the optimization of steel tapping in the steelmaking shops.

The Mathematical Model

Model Assumptions

This model is elaborated under the following assumptions:

- The system is considered isothermal and then, there is no need to solve the equation for energy transport. The temperature of the system is 1620 °C.
- The previous assumption involves, implicitly, that the buoyancy forces are negligible compared with the inertial forces. To test the viability of this assumption, Berg *et. al.* [5] had previously simulated the flow patterns under isothermal and non-isothermal conditions without finding any signifying differences.
- The physical properties of argon and air were evaluated at the film temperature (average of room and liquid steel temperatures).
- Addition of ferroalloys and fluxes are not considered. Therefore, only the flow dynamics of gaseous and liquid phases are reported in these simulations.
- The solubility of air and argon in liquid steel is negligible.
- The impinging jet of steel has a compact structure. This assumption is reasonable if the EBT system is clean of debris. This is true specifically when the sleeve of the EBT is new.
- Strictly speaking, air and argon form a gaseous phase. However, since the densities are different, in this work, both are considered different phases by using jumping boundary conditions at the argon-air-liquid steel interphases. This trick will allow to follow the segregation of argon inside and outside the bath.

The physical properties for each gas and liquid steel employed in the model are reported in **Table 1** and the specific conditions of the tapping process are summarized in **Table 2**.

Table 1: Physical properties of the phase in the tapping operations.

Phase	Density (kg m ⁻³)	Viscosity (Pa-s)
Liquid Steel	7 100	0.006
Argon	0.458	5.7X10 ⁻⁵
Air	0.3289	4.36X10 ⁻⁵

Note. Properties estimated at an average temperature between steel temperature (1620 °C, 1893 K) and room temperature (25 °C, 298K).

Table 2: Tapping conditions of liquid steel from furnace to ladle.

Item	Description	Observations
Electric Arc Furnace	AC EAF with a capacity of 100 tons, hot heel of 12-15 tons	Burners, oxygen lances and EBT system
Ladle	Capacity of 80 tons, straight geometry, dolomite lining	Eccentric argon plug, pneumatic stirring
EBT	Sleeve diameter is 114 mm, flow rate of argon is 400 l/min	Straight sleeve pointing toward the center of the ladle
EBT-Ladle bottom	The distance between the tip of the EBT sleeve and the ladle bottom is 3.50 m	The length of the EBT is 0.90 m, embedded in the bottom of the EAF
Steel throughput	Averaged as 16 tons/min	The steel throughput depends on the wear condition of the sleeve

Dynamics of the Multiphase Flow

In the study of dynamics of multiphase flows is very important to track the interfaces in the 3D domain and their evolution with time. Hence, to simulate the dynamics of the multiphase flow during steel tapping the Volume of Fluid (VOF) model, which is one of the most effective for this purpose, is employed in the present work. In this model, the volume fraction of one of the fluids is defined by the volume averaged [8], [9] of the phase indicator χ^q according to,

$$\langle \chi^q \rangle = \alpha_q = \lim_{V \rightarrow \infty} \frac{1}{V} \iiint \chi^q(x, y, z, t) dV \quad (1)$$

The phase indicator must fulfill the following constraints:

$$\chi^q(x, y, z, t) = \begin{cases} 1 & \text{if } (x, y, z) \text{ is in the } q\text{th phase} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

At any interface the gradient of this indicator is defined by,

$$\nabla \chi^q = n^q \delta_s(x - x^{int}, t) \quad (3)$$

Where n^q is the unit external vector pointing toward the bulk of phase q , δ_s is Dirac's delta function, and $x = (x, y, z)$ and $x^{int} = (x^{int}, y^{int}, z^{int})$ referring to the coordinates in the interphase. The model employs only one set of momentum transfer equations according to,

$$\begin{aligned} \nabla \cdot u_m &= 0 \quad (4) \\ \frac{\partial u_m}{\partial t} + u_m \cdot \nabla u_m &= -\frac{1}{\rho_m} \nabla p_m + \nu_m \nabla^2 u_m + g + F_\sigma \quad (5) \end{aligned}$$

Equations (4) and (5) are solved simultaneously for the respective partial differential equations for the balances of the turbulent kinetic energy, k , and its dissipation rate, ε , embedded in the model of turbulence k - ε [10, 11]. The last term of Equation (5) is the surface tension force at the interface implemented in this model as a jump boundary condition. This momentum jump condition, using the continuous surface stress model (CSM) [13], is expressed as:

$$F_\sigma = \nabla \cdot \left[\sigma \left(|\nabla \alpha| I - \frac{\nabla \alpha \times \nabla \alpha}{|\nabla \alpha|} \right) \right] \quad (6)$$

The velocity u_m is the representative velocity for all phases involved in the system or what may be called the velocity of the mixture of phases. The velocity field, u_m , is employed to solve the advection equation for the transport of the volume fractions of each phase as is explained below.

The evolution of the volume fraction function with time and space is determined by a scalar advection equation for the $1 - \sum_q^{n-q} \alpha_q$ phases (as the sum of all volume fractions should be equal to one):

$$\frac{\partial \alpha_q}{\partial t} + (u_m \cdot \nabla) \alpha_q = 0 \quad (7)$$

The volume fraction, α_q , represents the fractional volume of the cell occupied by the fluid q. A unit value of α_q represents a cell full of q, while a zero value indicates that the cell contains no fluid q. Cells with α_q between 1 and 0 must contain an interface where the jump boundary conditions must be applied. Implicitly, equation (7) assumes a null mass transfer between the gas and liquid phase in the present case. The physical properties of the fluids are weight pondered by the respective volume fractions,

$$\rho_m = \sum_{q=1}^n \alpha_q \rho_q \quad (8a) \quad \mu_m = \sum_{q=1}^n \alpha_q \mu_q \quad (8b)$$

The implicit discretized expression for solving the advection equation (7) is given as:

$$\frac{\alpha_q^{n+1} \rho_q^{n+1} - \alpha_q^n \rho_q^n}{\Delta t} V + \sum_f [\rho_q^{n+1} u_m^{n+1} \alpha_{q,f}^{n+1}] = 0 \quad (9)$$

Therefore, the velocity field calculated through the k-ε, u_m , is dependent on the volume fractions of each phase through the mixed physical properties of the multiphase system as given by Equations (8a) and (8b). Hence, the velocity field and the volume fractions of the phases are, then, interdependent.

The drawback of the VOF model is just to solve the system of equations (9) for the advection of the volume fractions preserving the conservation of mass. The difficulties arise because the conventional differencing schemes for the convection term, which guarantee the volume fraction field obeying the physical bounds on zero and unity, smear the step profile of the interface over several mesh cells due to numerical

diffusion. This is particularly a severe problem when using an upwind scheme. To overcome this condition, the second upwind discretization scheme [12, 13] was applied to Equation (9). In addition of using the 2nd upwind discretization, a piecewise linear interface construction method was applied to reconstruct the interfaces as proposed by Youngs [14]. The geometric features of the ladle are shown in **Figure 1**. An inlet velocity boundary condition was applied for the argon gas. The computation mesh consisted of 3 344 679, hexahedral cells with maximum aspect ratio of 12.99 and maximum ortho-skewness of 0.631 and a minimum orthogonal quality of 0.153. The method of gradient [13] was used for the interpolation of the flow variables between the centers of the computational cells and their respective faces. **Figure 2** shows the computational mesh employed for the solution of the system of partial differential equations.

Figure 1: Geometry of the ladle furnace (m). a) Top view, b) Frontal view.

Figure 2: Computational mesh employed to solve the equations of the mathematical model.

Method of Solution

The segregated method was employed to solve each equation of continuity, momentum and the respective equations of the turbulent kinetic energy and its dissipation rate of the $k-\epsilon$ model of turbulence under unsteady state conditions. At solid surfaces of the EBT sleeve, bottom, and walls of the ladle, the logarithmic wall function [15] was used to link the flow field, out of the boundary layer, with the velocities close to the wall inside this layer. The no-slip boundary condition was applied to all solid surfaces in the physical system. Inside of the EBT sleeve, a turbulent velocity profile is assumed through the $1/7^{\text{th}}$ law for turbulent flows in pipes [16]. A pressure boundary condition is applied on the bath surface during all ladle filling time. The PISO [17] algorithm was applied, in the segregated scheme, for linking the pressure-velocity coupling. The numerical convergence was attained when the sum of the residuals for the flow variables was less than 10^{-4} .

Results and Discussion

Velocity Fields in Vertical Planes

To describe the flow patterns of liquid steel during the tapping operation, different vertical planes were chosen as is indicated in **Figure 3a** located in sectors north (N) where the argon plug is

located, south sector (S) in the lower side of this figure, and west (W) and east (E) sectors, left and right sides of **Figure 3b**, respectively. **Figures 4a-4d** show the velocity fields in the plane of symmetry, C, at different steel levels or tonnages of 16, 30, 50 and 80 tons in the ladle.

Figure 3: a) Vertical planes examined in the mathematical model in the North, East, West and South sectors. b) Planes in the East and West sectors. Numbers in the planes indicate their distances from the plane of symmetry of Center plane.

Due to the high momentum rate transferred from the liquid phase to the surrounding air, a boundary layer between air and the falling steel jet is developed, which drags air all its way until the bath surface introducing air in the bulk of the liquid. These volumes of dragged air are partially entrained in the melt increasing, eventually, the pickups of oxygen and nitrogen. The interface between the bath of steel and air is delineated by the region where the jet splashes. The impinging jet impacts the bath surface with smaller momentum rates as the bath level increases and its penetration in the bath is shallower. At low bath tonnages, the column of argon bubbles has small effects on the velocity patterns in this plane and increasing the liquid volume leads to a close interaction between the jet and the plume. This interaction induces a biasing or bending effect of the impinging jet by the rising motion of the argon-liquid steel (two-phase) plume. At medium and high tonnages of liquid (50 and 80 tons) the rising plume pushes upwards the entering jet forming non-symmetric vertical-recirculating flows. Besides, regions of low velocities are generated in the corners between the wall and the

bottom of the ladle. Figures 5a-5d show the velocity fields during the filling step from 16 to 30 tons, the time difference between each image is 10 seconds. The flow is characterized by small rotating flows in the ladle corners due to the small bath height and the entry jet impacts with high velocity the ladle bottom. The splashing pattern changes from time to time depending on the local turbulent conditions.

Figure 4: Velocity profiles in the symmetry-impinging planes (Center plane) at different bath levels in the ladle with simultaneous argon bottom stirring.

Figure 5: Unsteady fields of velocity in the Center plane during ladle filling from 16 to 30 tons. Each figure shows a time step of 10 seconds.

Figures 6a-6d show the corresponding velocity fields in the symmetric plane, during ladle filling between 50 and 80 tons, the time difference between each figures is 10 seconds. At these tonnages, the entry jet impacts the ladle bottom with considerable smaller velocities than those where the jet impacts the bath surface. It is also evident that the jet oscillates continuously, suffering stretching and straightening effects, as seen in figures 6a and 6c inside the metal, at other times, it is bent upwards by the influence of the rising argon plume as seen in Figures 6b and 6d.

Figure 6: Unsteady fields of velocity in the Center plane during ladle filling from 50 to 80 tons. Each figure shows a time step of 10 seconds.

The velocity fields of liquid steel at a tonnage of 30 tons in planes E1, E3 and E5 are shown in Figures 7a, 7b and 7c respectively and the velocity fields in planes W1, W3 and W5 in Figures 7d, 7e and 7f, respectively. The jet impacts the ladle bottom and the liquid stream flowing toward the ladle wall meets, on its way, with the rising argon plume plume, producing the deviation of the entry jet toward the west sector as can be seen by comparing Figures 7a and 7d. Figures 7b and 7e, show the velocity fields of high turbulence and the flow yields higher velocity magnitudes in the right bottom side of these figures produced by the rising plume. In planes further away from the symmetric plane, Figures 7c and 7f, yield smaller velocities, although, in the west sector (Figure 7f) the turbulence is larger

due to the effects of the proxy argon plume. The velocity fields of liquid steel at a tonnage of 80 tons in planes E1, E3 and E5 are shown in Figures 8a, 8b and 8c respectively and the velocity fields in planes W1, W3 and W5 in Figures 8d, 8e and 8f, respectively. At high bath levels, Figures 8a and 8d, the plume rises oscillating between planes E1 and W1 inducing long recirculating flows of relatively high velocities. Meanwhile, the entry jet losses momentum and its tail is clearly upraised by the argon plume. The velocity field in Figure 8e (plane W3) shows, in the upper part, a clear view of the rising plume print and the entry jet completely bent inducing a large recirculating flow along the bath height. This effect is less apparent in Figure 7b (plane E3) where the velocities are smaller, although, the recirculating flow prevails.

Figure 7: Velocity fields in planes East and West sectors at a bath level of 30 tons. a) E1, b) E3 and c) E5 correspond to the East sector, respectively. d) W1, e) W3 and f) W5 correspond to the West sector, respectively.

Figure 8: Velocity fields in planes East and West sectors at a bath level of 80 tons. a) E1, b) E3 and c) E5 correspond to the East sector, respectively. d) W1, e) W3 and f) W5, correspond to the West sector, respectively.

The proximity of the impinging jet of steel to planes W1 and E1 together with the combined effect of the argon plume provides highly turbulent flows and it are, probably, the best positions for fast melting, dissolution and dispersion processes of the ferroalloys particles. When the ferroalloys are added at lower bath levels, like those reported in Figure 7, the turbulence is considerably smaller and at this stage heating process and steel shell formation on the surface of these particles can be expected with poor or even without mixing and homogenization. As the bath level increases during the ladle filling, the steel shell (surrounding the ferroalloy particle) melts away and the ferroalloy particle, inside the shell, can be already melted as well. If that is not the case, further heat transfer from the melt will continue until melting this addition. However, it is a fact that the trajectories and residence times of particles of ferroalloys are considerably dependent of their ratio of densities with respect of the density of liquid steel, the bath height, the

position in the ladle where they are added, on the local level of turbulence and the magnitudes of local velocities in the flow [2, 3], [5]. As the intuitiveness would indicate, high levels of turbulence are helpful to melt, dissolve and homogenize the alloying elements in liquid steel. Hence a flow variable useful to quantify the turbulence level in the bath, at macroscopic levels, is the turbulent or eddy viscosity of the liquid through the fields of the turbulent kinetic energy and its dissipation rate calculated by the present mathematical [10] as,

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (10)$$

Figures 9a-9d show the turbulent viscosity contours in the symmetric plane and planes, N1, N2 (this plane corresponds to the position where the argon plug is located) and N3 respectively at a bath level of 30 tons. Figures 10a-10c show the turbulent viscosity contours for planes S1, S2 and S3 at the same tonnage. The viscosity pattern in plane of symmetry, yields high levels of turbulence in the liquid jet and its surroundings; planes N1 and S1 have, apparently similar levels of turbulence. Observing the turbulence viscosity fields in planes N2 and S2; it is seen that the turbulence level is slightly higher in plane S2 which is just the counterpart of plane N2 where the argon plug is located. This later plane does not report the highest levels of turbulence due to the deviation of the plume. This effect, as mentioned before, is due to the interaction of the rising plume with the entry jet resulting in a momentum transfer from the north sector to the south sector by convected liquid streams. Similarly, the turbulence level in the plane S3 is slightly higher than in the plane N3. The overall turbulence at this bath level of 30 tons has essentially viscosity magnitudes between 30 and 60 Pa-s, which corresponds to relatively short length eddies resulting from a short bath level. When the bath level increases up to 80 tons, a considerable fraction of the volume of liquid in the ladle reaches the highest levels of turbulent viscosity of 80 Pa-s. Indeed, Figures 11 and 12 show the turbulent viscosity contours in the symmetric plane, and in planes N1, N2 and N3 in the first figure and in the planes S1, S2 and S3 in the second one for a steel tonnage of 80 tons. The levels of turbulence, interpreted through

the turbulent viscosity, are similar in the pairs of planes N1/S1. However, comparing the pairs of planes N2/S2 and N3/S3 their results make evident that the volumes of liquid with the highest level of turbulence are in the South sector. Indeed, the asymmetric flows observed between sectors N and S come from the interaction between the impinging or entry jet with the argon plume. In a broad view, comparing Figures 11-12 with Figures 9-10, it is again corroborated that in the large bath levels the turbulence is larger and these are the conditions appropriated for thermal and chemical homogenization of the bath and rapid ferroalloy melting.

Figure 9: Fields of turbulent viscosity (Pa-s) in planes of the North sector at a bath level of 30 tons.

Figure 10: Fields of turbulent viscosity (Pa-s) in planes of the South sector at a bath level of 30 tons.

Figure 11: Fields of Turbulent viscosity (Pa-s) in planes of the North sector at a bath level of 80 tons.

Figure 12: Fields of Turbulent viscosity (Pa-s) in planes of the South sector at a bath level of 80 tons.

Velocity Fields in Horizontal Planes

Other important information of the flow patterns during steel tapping corresponds to the horizontal planes of the ladle including regions close to the ladle bottom. Figures 13a-13d, show the velocity fields in a plane located at a level of 0.20 m from ladle bottom at the bath levels or tonnages of 16, 30, 50 and 80 tons, respectively. At low bath levels, the flow patterns consist of recirculating flows around the impinging or entry jet together with radial and vortexing flows with medium and small magnitudes of velocities in regions approaching to ladle wall. At high bath levels, the impinging jet together with the argon plume induce rotating and peripheral flows.

Figure 13: Velocity fields in a horizontal plane located 0.20 m from the ladle bottom at different bath levels: a) 16 tons, b) 30 tons, c) 50 tons and d) 80 tons.

Figures 14a-14d show the velocity fields in a plane located 0.1 m below the bath surface at bath levels of 16, 30, 50 and 80 tons, respectively. At the lowest bath level there are large and small radial flows around the proximities of the impinging jet and the argon plume, respectively. At a level of 30 tons, the impinging jet maintains a radial flow around its entry region while the bending effect of the argon plug induces a rotating-peripheral flow. At higher bath levels such as 50 and 80 tons, the argon plume forms radial flows influencing mostly the flow pattern. There are also vortexing flows in regions which are close to the ladle wall.

Velocity Fields and Distribution of Phases in 3D Views

Overviews of the, velocity field, argon-air-liquid interfaces in a 3D view for a bath level of 16 tons, are shown in Figures 15a, 15b and 15c, respectively. The difference of density between argon (which is denser than air) and air leads to the formation of a blanket layer on the bath surface separating the top air in the

ladle from the air-liquid steel mixture and argon is partially dragged and entrained inside the bath, together with air, by the entry liquid jet. In these figures it is seen that the streams of liquid steel formed after the impact of the impinging jet on the ladle bottom biases and bends the rising argon plume.

Figure 14: Velocity fields in a horizontal plane located 0.10 m from the bath surface at different bath levels: a) 16 tons, b) 30 tons, c) 50 tons and d) 80 tons.

Figure 15: Flow interfaces. a) 3D view of the velocity field b) Dynamics of Interfaces air-argon, c) 3D view of the velocity with interface air-argon. Bath level of 30 tons.

Figures 16a, 16b and 16c are the corresponding overviews at the level of 80 tons for interface argon-air, velocity of interfaces and a 3D view of the velocity field, respectively. The argon, from the plume, ascends through the bath height and once reaching the bath surface, a thick blanket of this gas is accumulated on the opposite side of the ladle from where the plug is located. A small portion of the argon accumulated on the bath surface is entrained together with the atmospheric air by the impinging jet, dragging both gases inside the bath. The interaction between the

impinging jet and the argon plume results in a permanent bending of the entry jet with a biased plume; this effect results in the generation of high turbulence particularly in the South sector of the ladle, different from the North sector where the argon plug is located. The level of turbulence related with the height of the bath and the specific position for the addition of ferroalloys have effects with the speed of melting and mixing kinetics of the alloy elements.

Figure 16: Flow interfaces. a) 3D view of the velocity field b) Dynamics of Interfaces air-argon, c) 3D view of the velocity with interface air-argon. Bath level of 80 tons.

Finally, a word regarding the validity of these simulations is suitable at this point to reinforce the findings presented here. The plume velocity simulated, in a water-model of the same ladle, through the VOF model and the multiphase Population Balance Model (PBM) supported by the Eulerian-Eulerian two-phase model were compared in a previous publication [18]. It was found that the PBM model predicted upper and lower bounds of velocity for the gas and liquid phases, respectively, for some given operating conditions. Meanwhile, the VOF model simulations of velocity, of the same flow, fall in between those two bounds corresponding to the sudden passage of gas bubbles and liquid streams at some given fixed point in the gas plume. Both models were validated with experimental measurements of velocities of the bath surface finding excellent agreements with both approaches of simulation. Therefore, the flow patterns described here, although representing averaged fields, describe acceptably well the actual levels of turbulence in an actual steel tapping operations.

Conclusions

The velocity fields of liquid steel during tapping operations considering the simultaneous effects of the imping jet and the argon plume from the ladle bottom were simulated using the multiphase Volume of Fluid model and from the results the following conclusions are drawn:

- At low liquid steel levels in the ladle the flow turbulence is smaller than at high steel levels. A tall bath allows larger recirculations of the flow enhancing the transport of kinetic energy, enhancing the turbulence of the system.
- The eccentric position of the argon plug in the ladle bottom and the impinging jet interact in such a way that the melt streams formed after impacting the ladle bottom bend the argon plume inducing asymmetric flows throughout all the liquid volume at any bath level.
- The bending effect of the imping jet and the resultant deviation of the argon plume remain during the full time of the ladle filling operation. Besides the unsteadiness of

the velocity fields of this complex flow is a clear indication of the existing potential for particle melting and thermal and chemical mixing during steel tapping.

- The argon bubbles travel all the plume height in the plume and when it reaches the bath surface, this gas is accumulated in the opposite side to where the plug is located forming a thick blanket of this gas covering a mixture of steel, air and argon separating it from the top air in the ladle. This effect decreases a further direct contact between the top air in the ladle and the steel-air-argon mixture during the ladle filling operation.
- The generation of high levels of turbulence during the tapping operations give origin to steep gradients of velocity in the liquid metal, which would have consequences on the levels of heat transfer from the liquid to ferroalloys particles. Therefore, the bath level, the position of additions in the ladle, steel superheat and other factors are critical for fast melting of particles, thermal and chemical bath homogenizations of the bath. Steel tapping is not a trivial operation and it is actually, the most important step to refine liquid steel.

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