Mathematical Modelling of the Effects of Transient Phenomena on Steel Cleanness during Tundish Transfer Practices

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Transient phenomena during tundish transfer practices have shown to be detrimental for the significance of clean steel production. These have become a distress for steelmakers; for this reason, there is opportunity for innovation in molten steel transfer devices, such as the dissipative ladle shroud. In the present modelling study the performance of this devise is fully analysed in order to quantify its efficiency in the reduction of the emulsification phenomenon and the slag aperture areas using a mathematical model to simulate a real steel-slag-air multiphase system during the ladle change-over practice. The most relevant results show that the convectional ladle shroud delivers a very turbulent steel flow generating strong mixing patterns, entrapping massive amount of air and slag into the tundish bath promoting a continuous emulsification and a permanent aperture of the slag layer. These phenomena are significantly reduced by using the dissipative ladle shroud technology since this innovative design reduces the emulsification phenomenon in more than a 50% and could decrease the steel re-oxidation by the reduction of the slag layer aperture in about 80%, all in comparison to the conventional ladle shroud; these will represent a diminishment in the amount of declassified steel to a less demanding application.

KEY WORDS: slag aperture; slag emulsification; ladle change-over; multiphase modelling; tundish.

1. Introduction

For the permanent requirement of producing clean steel, multiphase modelling has become a very important technology for process engineers, this tool is very useful to diagnose and control the refining operations in the ladle and the transfer operations from the ladle to the tundish and finally to the continuous casting mould. Most of the previous research studies on steel cleanness during tundish operations has been carried out during steady state periods, with the main purpose of developing an optimum tundish internal design implementing different flow control devices,1–3) and argon bubbling curtains.4,5) Nevertheless, during the unsteady state periods, at the start of a cast or a ladle change over, noticeable differences arise in the inclusion size and its morphology, also the amount of dissolved oxygen increases. These transient periods in tundish transfer operations have shown to be detrimental for the significance of clean steel production since some adverse phenomena are developed, like slag emulsification, slag layer aperture and dragged air into the steel bath.

When the tapping of a new ladle starts, the slide gate is fully open to regain the operational tundish bath level; this generates a strong increment of the entry jet velocity dragging slag and air into the molten steel bath forming a complex multiphase steel-slag-air mixture. These phenomena are a distress for steelmakers, despite of the importance of this operation, there are few studies on the subject.6,7) The understanding of the nature of turbulent flows during the transient period, which induce the slag aperture and entrapment, is of paramount importance to improve ladle change-over practices. In recent years, an innovative development on ladle shrouds have been proposed,8,9) involving a change from a simply ceramic pipe (Conventional Ladle Shrouds, CLS) to a duct consisting on internal chambers along its length with contractions and expansions, it was named as Dissipative Ladle Shroud (DLS). This last has been tested by physical modelling during steady state conditions for a four-strand tundish, showing good results with the advantage that pieces of furniture inside the tundish may be removed.9) Bearing in mind this, the present study considers a real steel-slag-air multiphase system to simulate the transient phenomena occurring during ladle change-over, employing the CLS and two DLS comparing their performance and quantifying its efficiency for the reduction of the emulsification and the areas of aperture of the slag.

2. Multiphase Modelling Technology

Multiphase modelling is mature technology to solve industrial problems, for the purpose to reduce the amount...
of slag emulsification and the areas of slag aperture during transient periods, a multiphase mathematical model was developed based on previous experiences, considering the Navier-Stokes equations; the time-dependent transport equations for mass and momentum are expressed as follow:

Mass Balance equation,

\[ \frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}_i) = 0 \]  

(1)

Momentum equation for turbulent flow conditions,

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho \mathbf{u}_i)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \mathbf{u}_i}{\partial x_j} \right) + \rho g_i + F_i \]  

(2)

Where subscript \( i, j \) represent the components in \( x \) direction, \( \mu = \mu_{\text{eff}} = \mu_{\text{vis}} + \mu_{\text{turb}} \) and \( \mu_{\text{vis}} = \rho C_{\mu \text{vis}} \frac{k^2}{\varepsilon} \).

These equations were solved together with the standard \( k-\varepsilon \) turbulence model of Launder and Spalding\(^{10}\) through the volume finite method.

2.1. The Standard \( k-\varepsilon \) Turbulence Model

The equations for turbulent energy \( k \) and dissipation rate \( \varepsilon \) are given by:

\[ \frac{\partial \rho}{\partial t} \left( \frac{\partial k}{\partial t} \right) + \frac{\partial}{\partial x_j} \left( \rho \frac{\partial k}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \frac{\partial \phi}{\partial x_j} \right) G_k - \rho \varepsilon \]  

(3)

\[ \frac{\partial \rho}{\partial t} \left( \frac{\partial \varepsilon}{\partial t} \right) + \frac{\partial}{\partial x_j} \left( \rho \frac{\partial \varepsilon}{\partial x_j} \right) = \frac{1}{\varepsilon} \frac{\partial}{\partial x_j} \left( \rho C_{\mu \varepsilon} k \frac{\partial \varepsilon}{\partial x_j} \right) - C_{\mu \varepsilon} \frac{\varepsilon}{k} G_k + \frac{\varepsilon}{k} \rho \varepsilon^2 \]  

(4)

The recommended values of the constant proposed by Launder and Spalding\(^{10}\) were: \( C_1 = 1.44, C_2 = 1.92, C_{\mu \text{vis}} = 1.3, \sigma_k = 1.0, C_{\mu \varepsilon} = 0.09 \).

2.2. Volume of Fluid Multiphase Model

For the modelling of the multiphase system steel-slag-air composed of immiscible fluids, the Volume of Fluid (VOF) model was used.\(^{11–13}\) This model is an Eulerian method that uses a volume fraction indicator to determine the location of the interfaces of different phases in all cells of a computational domain. The model introduces a VOF function \( \alpha \) to define the fluid region. In particular, a unit value of \( \alpha \) corresponds to a cell full of molten steel, while a zero value indicates that cell contains no steel. Cells with \( \alpha \) value between zero and unity must then contain the free surface.

In order to minimize the effects of the inaccurate interpolation for some physical quantities, the model needs equations accounting for the variation of density as well as of viscosity. If it is considered incompressible, immiscible fluids, no phase change between fluids, then the variable density and viscosity present at each cell can be expressed on the base of their fraction as shown below

\[ \rho_{\text{mix}} = \alpha_{p} \rho_{p} + (1 - \alpha_{q}) \rho_{q} \]  

(5)

\[ \mu_{\text{mix}} = \alpha_{p} \mu_{p} + (1 - \alpha_{q}) \mu_{q} \]  

(6)

The tracking of the interphases between the phases is accomplished by the solution of a continuity equation for the volume fraction. For the \( q \)th phase, this equation has the following form:

\[ \frac{1}{\rho_q} \frac{\partial}{\partial t} (\alpha_q \rho_q \mathbf{v}) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}) = S_{\alpha_q} + \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) \]  

(7)

The mass transfer from phase \( p \) to phase \( q \) and from phase \( q \) to phase \( p \) is given by the right side of the equation, where \( S_{\alpha_q} \) is a source term.

The volume fraction equation will not be solved for the primary phase; the primary phase volume fraction will be computed based on the following constraint:

\[ \sum_{q=1}^{n} \alpha_q = 1 \]  

(8)

The volume fraction equation is solved through an explicit time discretization method and the employed reconstruction based scheme was the Geo-Reconstruct. In this approach, the standard finite-difference interpolation schemes are applied to the volume fraction values that were computed at the previous time step.

\[ \alpha_{q+1} = \frac{\alpha_{q} \rho_{q}^{n+1} - \alpha_{q} \rho_{q}^{n} }{V + \sum_{j} (\rho_{p} U_{x} \alpha_{q j}^{n})} \]  

(9)

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The momentum equation, shown below, is dependent on the volume fraction of all phases through properties \( \rho \) and \( \mu \).

\[ \frac{\partial}{\partial t} (\rho_{\text{mix}} \mathbf{v}) + \nabla \cdot (\rho_{\text{mix}} \mathbf{v} \mathbf{v}) = \nabla \cdot \left( \mu_{\text{mix}} \nabla \mathbf{v} + \mathbf{v} \mathbf{v} \right) \]  

(10)

The last term of this equation is a momentum source related with balance or forces arising by surface tension characteristics.

The surface tension arises as a result of attractive forces between molecules in a fluid that is required to maintain the equilibrium at the surface. This value was considered as a constant along the interface between each pair of phases and it is considered as a source term in the momentum equation.

2.3. Prototype Description and Model Considerations

Figure 1 shows the tundish prototype dimensions including the geometries of the CLS and innovative DLS. The fluid flowing into the tundish is considered having Newtonian behaviour and is under isothermal and unsteady state conditions. The governing equations are discretized and solved by the computational segregated-iterative method. The non-linear governing equations were linearized using the implicit approach, in combination with the explicit VOF method to define sharp interfaces, and the discretization was performed using the second-order upwinding scheme. The
PRESTO scheme was used for pressure interpolation. The algorithm used for pressure-velocity coupling is known as PISO. Convergence criterion was obtained when the residual of the output variables reached values equal or smaller than 1 \times 10^{-4}. The computational mesh is about 2 000 000 structured cells.

2.4. Initial Conditions and Boundary Conditions
The conditions to simulate the tundish level fluctuation were: Firstly, the steel flow patterns were simulated up to achieve steady state conditions keeping constant the tundish bath level. Then, the ladle change-over operation began by making the incoming flow rate equal to zero to decrease the amount of steel inside the tundish from 32 Ton to 19.6 Ton (minimum bath level position). At this point, the incoming flow rate is increased to 9.5 Ton/min until the steel bath level is increased to the normal operating level. Finally, when the normal operating steel level was reached, the steel flow was simulated for another 100 seconds.

To achieve the above procedure a normal incoming flow rate equal to 5 Ton/min was employed before and after the ladle-change over operation at the ladle shroud entry by a boundary condition of velocity entry. The tundish exit was also considered with a boundary condition of velocity entry. The mathematical model was run during 300 seconds to reach steady state conditions; subsequently, the ladle change-over operation was simulated. To be able to simulate the tundish bath level movement, a pressure inlet condition is applied at the tundish top (P=101 325 Pa) to simulate the effects of a system open to the atmosphere. Typical no-slip conditions were applied at all solid surfaces. The physical properties of each phase employed on the simulations are presented in the Table 1. For the simulation, additionally to the CLS, two DLS were considered, the first with smaller chambers (DLS-S) than the second (DLS-B).

3. Results and Discussion
3.1. Model Validation
Validation is an essential stage of multiphase mathematical modelling in order to trust the numerical results. To achieve this point, a one third scale water model was previously built, where a water-oil-air system was employed to study the transient period of the ladle change-over operation; then, using the same multiphase system, a mathematical model was developed using CFD techniques in order to understand and to analyse in more detail the transient phenomena of the oil emulsification and the oil aperture. The results of these works have demonstrated that the present mathematical model predicts with good accuracy these phenomena allowing the model validation and to continue to the next stage where the real multiphase steel-slag-air system is considered.

3.2. Ladle Shrouds Behaviour during Steady State Period
Before the analysis of the transient phenomena, it is necessary to observe how the dissipative ladle shrouds affect the bulk flow patterns during the steady state period before the tapping of a new ladle. For this, the fluid-dynamic results, using the three ladle shroud designs, are analysed once 300 second of the unsteady state simulation was reached since at this time the quasi-steady state condition was achieved. Figures 2 and 3 show velocity vector profiles and velocity contours, respectively, in three planes: at the central longitudinal position, at the steel-slag interface, and in the transversal position at the ladle shroud entry. It is evident that three ladle shroud designs show similar flow characteristics: once the steel is delivered to the tundish, it entries with high velocity impinging the tundish floor and breaks into two main streams; one of this moves toward the left side of the tundish, and it impacts the tundish left lateral wall changing sharply its direction upward to the slag layer forming a strong recirculation in this zone. The other main stream moves in direction towards the tundish exit; this stream moves close the tundish floor reaching almost the half length of the tundish, but this is slowed down for another stream in an opposite direction. To understand the origin of this contrary flow, it is necessary to follow the steel flow arriving the slag interface at the left tundish side, which reaches the interface with a higher velocity compared with the rest of the flow at this level, however, when this stream gets the ladle shroud position encounters another streams coming from the frontal and posterior walls inducing the formation of many recirculation; in addition, this last flow moves in part toward the exit very close to the indicated walls and leaving the tundish centre with an inadequate flow feed, which is why both streams comes back toward the ladle shroud generating the opposite flow stream mentioned before.

When the comparison is made, it is clear that the dissipative ladle shroud designs induced a considerable reduction...
Fig. 2. Velocity vectors fields in three positions of the tundish: at the central longitudinal plane, at the steel-slag interface, and at the ladle shroud entry. [a), d), g)] CLS, [b), e), h)] DLS-S, and [c), f), i)] DLS-B.

Fig. 3. Velocity contours in three positions of the tundish: at the central longitudinal plane, at the steel-slag interface, and at the ladle shroud entry. [a), d), g)] CLS, [b), e), h)] DLS-S, and [c), f), i)] DLS-B. (Online version in color.)
on the steel velocity all along the tundish and that this velocity decrement increases as the chambers of the ladle shroud increases in size which can be easily observed in Fig. 4, this is shown through velocity contour and velocity vectors fields inside the three ladle shroud. This velocity reduction has been demonstrated that is due to an energy dissipation that takes place inside each chamber by Solorio-Diaz et al.9) which is why the steel entries to the tundish with less kinetic energy as shown by Garcia-Hernandez et al.15) In consequence, this velocity reduction will highly contribute in the slag emulsification and slag aperture control during the ladle change-over operation as will be shown next.

3.3. Steel Flow Behaviour during the Ladle Change-Over Operation

Once the new ladle shroud opens and the tundish bath level recovery starts the entry mass flow rate is three times the normal steady state steel flow rate, because of that, this entry jet with high kinetic energy promotes a very turbulent steel bath in the entry zone during the first few seconds without a defined flow pattern. In the next seconds the flow remains with high levels of turbulence but starts to develop a pattern; for that, velocity vectors fields and velocity contours are determined and shown in Figs. 5 and 6, respectively, at the central symmetrical plane of the tundish for four representative times of the studied period: 5, 15, 20, and 50 seconds considering the three ladle shroud designs. Firstly, it is clear that the dissipative ladle shrouds reduce the steel velocity even with this tripled mass flow rate and again the one with the bigger chambers is who achieves more efficiently this velocity reduction. Nevertheless, some flow characteristics are observed: it is evident that the steel movement tries to recover the steady state general pattern since the recirculation in the tundish left side appears and the opposite flows in the right side emerge, however, both flow patterns show a considerable higher velocity in comparison with what was observed during the steady state. It
should be noticed that this velocity increment in the recirculation surely will promote slag aperture and entrainment since the velocity vectors show a downward trend at the slag interface. It can be equally considered at the right side that the flow movement will strongly push the dragged slag promoting the emulsification phenomenon. In order to confirm this hypothesis, an analysis of the slag emulsification phenomenon is required.

3.4. Slag Emulsification Phenomenon

In order to obtain a better understanding of this detrimental phenomenon, a qualitative and quantitative analysis was carried out. The first is done by observing numerical video images at different times of the tundish bath level recovery of the air and slag phases been dragged into the steel bath, the results are shown in Fig. 7 for the three ladle shrouds. The second was achieved by calculating the amount of air and slag that were inside the steel bath at each moment of this transient period and the results are shown in Fig. 8.

It was determined that during the first three seconds only air is dragged inside the bath forming bubbles. Since the air density is much smaller than steel density, the air gets quickly uncoupled from the steel rising up to the slag interface after its impact with the tundish floor. Because of this, during the first three seconds it was detected a very chaotic and turbulent steel fluid dynamics. From the fourth to twenty fifth second, it was observed an emulsification phenomenon composed of air, slag, and steel mixture, but after this period and until the forty second the emulsion was just among slag and steel.

During the period when the air and the slag were dragged inside the tundish bath, the air phase reached its maximum values before the seven second for all cases while the slag phase did it at around the eighteen second. It was for this reason that at the ten second the transient flow in the tundish started to recover the general flow pattern of the steady state since the amount of air inside the bath has decreased significantly allowing the steel flow initiated to show a pattern. On the other hand, considering the same instant, even when the amount of slag inside the steel has increased considerably, the steel flow continues developing a pattern since the slag moves coupled with the steel phase. Around the thirty second, it was observed that there was not more slag being dragged and it was determined that from this point until the end of the emulsification phenomenon the slag participating was that remained emulsified with the steel.

All the above explains how the emulsification phenomenon develops, nevertheless, the advantages of using the dissipative ladle shroud designs has not been pointed out. From Fig. 7 is qualitatively evident that these designs reduce efficiently the slag emulsification phenomenon being the dissipative ladle shroud-big the one that reduce the most this phenomenon. From a quantitative point of view, the dragged air is reduced from 39.58 kg with conventional

![Fig. 6. Velocity contours at the central longitudinal plane of tundish at 5, 15, 20, and 50 seconds of the bath level recovery, a) CLS, b) DLS-S, and c) DLS-B. (Online version in color.)](image-url)
ladle shroud to 24.81 kg with dissipative ladle shroud-small and to 15.21 kg with dissipative ladle shroud-big comparing maximum values which will represent a considerable reduction on the amount of dissolved oxygen, preventing the inclusion generated by steel re-oxidation. Concerning the slag, the conventional ladle shroud drags 57.60 kg in its
maximum value which is reduced to 30 kg with the dissipative ladle shroud-small and to 21.89 kg with the dissipative ladle shroud-big. This dragged slag was not only emulsified with the steel but also it reached out of tundish in the next total amounts: 51.26 kg with the conventional ladle shroud, 34.47 kg with the dissipative ladle shroud-small, and 2.78 kg with the dissipative ladle shroud-big. Considering that a total of 4,786 kg of steel were cast, it is calculated that: using the conventional ladle shroud and the dissipative ladle shroud-small values of 1% and 0.72% in total steel weight were obtained respectively, which determinate that both ladle shroud designs will provide steel out of specification during this operation; in contrast, using the dissipative ladle shroud-big a value of 0.05% in total steel weight is achieved which will represent a diminishment in the amount of declassed steel to a less demanding application or the possibility of using this steel for target grade.

These results indicate that using the dissipative ladle shroud-big the dragged slag can be reduced by 63% and the dragged air by 44% representing a reduction in the emulsification phenomenon in more than a 50% all in comparison with the conventional ladle shroud. Additionally, this design could decrease significantly the amount of downgraded steel generated by the ladle change-over operation.

3.5. Slag Aperture

During this tundish transient operation, the slag and the air are not only dragged into the steel bath by the high turbulent flows but also the slag layer is opened in different magnitudes and positions as a function of the time needed to recover the bath level. Since this slag layer aperture represents another detrimental phenomenon for the steel re-oxidation, the slag aperture was studied using tundish upper view images taken at different times along the bath level recovery period, as shown in Fig. 9; additionally, this phenomenon was quantify as a function of time and it is shown in Fig. 10.

The results show that the slag layer aperture initiates immediately after the new steel enters in contact with the remnant steel in the tundish due to the dragged air which quickly leaves the bath. During the first eight seconds there was a great amount of dragged air using the conventional ladle shroud which is reflected in a higher slag layer aperture in comparison with the other two designs. After this period and until the twenty five second, the slag layer aperture continues increasing with an irregular pattern; this irregularity, even when the steel has initiated a flow pattern, is a consequence of the great amount of slag that is coming out from the bath. Nevertheless, it is evident that due to the high flow velocities, at which the steel arrives to the steel-slag

![Fig. 9. Top view of the slag layer aperture at many times during the Ladle Change-Over operation.](image-url)
results.

(2) The amount of emulsified slag that reaches out of tundish is also reduced by using the dissipative ladle designs as follow: From 51.26 kg with the conventional ladle shroud to 34.47 kg with the dissipative ladle shroud-small and to 2.78 kg with the dissipative ladle shroud-big. This represents a reduction from 1% to 0.72% and to 0.05% in total steel weight, respectively, which will represent a diminishment in the amount of declassed steel to a less demanding application.

(3) This new ladle shroud design can decrease the re-oxidation by the reduction in the amount of dragged air but also will reduce the steel re-oxidation by the considerable reduction of the slag layer aperture from 30% with the conventional ladle shroud to 15% with the dissipative ladle shroud-small and to 6.2% for the dissipative ladle shroud-big, representing a decrement of 55% and 80% respectively.

(4) The use of the dissipative ladle shroud technology can efficiently reduce the high turbulent flows, induced by the three time flow rate required to recover quickly the tundish bath level, that produce the dragging of a great amount of air and slag which spend more than thirty seconds to leave the steel bath and generate a permanent aperture of the slag layer.

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