Mathematical Modelling and Numerical Simulation of the Multiphase Flow in the Main Trough of a Blast Furnace

R. V. P. Rezende[1], A. F. C. Silva[1], C. R. Maliska[1]
[1] SINMEC – Computational Fluid Dynamics Lab, Federal University of Santa Catarina, Brazil.

ABSTRACT: The use of computational fluid dynamics, CFD, is acquiring importance on metallurgical industrial sector, mainly due to the rising of the demand and the strong competition of the global market. By its nature, metallurgical processes are physically complex, conjugating many physical phenomena at high temperatures. Issues related to the multiphase flow of liquid metal are even more uncommon. Generally, analyses are done considering single phase flow. A critical unit operation where this assumption is not reasonable is the blast furnace withdraw, which has at least three phases: the cast-iron, slag and atmospheric air. As a first approach, this work presents a mathematical model that describes the two-phase flow of cast-iron and air, considering three-dimensional, transient and turbulent conditions. The temperature changing is not accounted for in the present work, since the main interest is in the flow patterns. The model has been solved with the commercial code ANSYS CFX. Results have shown that the multiphase approach accounting for the jet/free-surface interaction is more suitable. Details, as the oscillatory behaviour and the vortical and reverse flow, which have been seen only in experiments and industrial facility, were captured by the model.

1. INTRODUCTION

A critical operation of the steelmaking process is the tapping of the blast furnace into the main trough, whose the main function is to separate the slag from cast iron and feed the refinement operation with a clean metal. And, although that operation is a critical step of the steel making process, a few papers dealing with it is available. Among them, there are experimental and numerical approaches. The experimental analyses are generally made in a scaled physical model with water and oil, retaining the flow similitude (Froude and Reynolds numbers) [1-4]. Employing numerical approaches, one can cite the work of Gondolf et al. [5] and Luomala et al. [6]. Both analyses have the same assumptions: a steady state single-phase flow of a mixture of metal and slag, or only the liquid metal without the free-surface. At the air-liquid interface it is applied a wall with a free-slip condition, as is done in tundishes simulations [7, 8]. The liquid jet from the blast furnace is not considered, and its effect is accounting for only at the impact point on the free-surface, where the velocity and the sinking angle are prescribed at the free-slip wall.

As the industrial practice knows, and the experimental analyses have demonstrated, the interaction of the free-surface with the open jet plays an important role in the flow behaviour, mainly when the slag separation and the refractory lining wearing rate are accounted for. Hence, a single-phase assumption with no free-surface/jet interaction is limited in describing all fields involved, as velocity, turbulence and phase distribution because these fields are quite different in a confined flow when compared to an open-channel flow. Computational fluid dynamics, CFD, is acquiring importance in the metallurgy industries since it allows analyses of metallurgical processes with relatively low costs when it is compared with experimental methodologies. Analyses which are experimental prohibitive due to the physical conditions involved as high temperatures and thermal radiation can be done using CFD.

This works contributes in this area, presenting a mathematical model that describes the two-phase flow of cast iron and air, considering its three-dimensional, transient and turbulent conditions, considering the free-surface and the open jet and solving it numerically. The temperature changing is neglected. The model has been solved with the commercial code ANSYS CFX.

2. MATHEMATICAL MODEL

The model considers unsteady flow of gas-liquid; Newtonian fluids, isothermal, turbulent and isochoric flow; validity of the Boussinesq hypothesis; the wall law is not affected by the presence of other phase; no mass transfer; the superficial tension coefficient is constant and the velocity field is assumed continuous through the interface.

This set of hypothesis permits to apply an Eulerian formulation to the analysis employing the homogeneous models (VOF), where the velocity field is assumed continuous through the interface, what avoid the imposition of a closure model to the momentum interfacial transfer. Both phase, air and liquid metal, are considered continuous and the turbulence is modelled by *k*-ε model as is used in single-phase flow [9]. The interfacial tension force is modelled by CSF model [10].

2.1 Mass and Volume Conservation

$$\frac{\partial\left(r_\alpha \langle\rho_\alpha\rangle\right)}{\partial t} + \nabla\cdot\left(r_\alpha\langle\rho_\alpha\rangle\langle\mathbf{u}\rangle\right) = 0 \tag{1}$$

$$\sum_{\alpha=1}^{2} r_\alpha = 1 \tag{2}$$

where r_α represents the volume fraction of phase α. The operator $\langle\ \rangle$ represents the ensemble average of the property [11].

Momentum

$$\frac{\partial\left(\langle\rho\rangle\langle\mathbf{u}\rangle\right)}{\partial t} + \nabla\cdot\left(\langle\rho\rangle\langle\mathbf{u}\rangle\otimes\langle\mathbf{u}\rangle\right) = \nabla\cdot\left(\mu_{eff}\left\langle\nabla\mathbf{u}+\nabla\mathbf{u}^T\right\rangle\right) - \nabla\langle p\rangle + \left(\langle\rho\rangle - \rho_{ref}\right)\mathbf{g} + \mathbf{m}_i^\sigma \tag{3}$$

where $\mathbf{m}_i^\sigma$ is the interfacial tension force by unit of volume, and the effective dynamic viscosity, μ_{eff}, is given by $\mu_{eff} = \langle\mu_\alpha\rangle + \mu_T$. In the buoyancy term, ρ_{eff} is taken as the air density.

2.2 Turbulence

$$\frac{\partial\left(\langle\rho\rangle k\right)}{\partial t} + \nabla\cdot\left(\langle\rho\rangle\langle\mathbf{u}\rangle k\right) = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \left(\mu_T\left\langle\nabla\mathbf{u}+\nabla\mathbf{u}^T\right\rangle : \nabla\langle\mathbf{u}\rangle - \langle\rho\rangle\varepsilon\right) \tag{4}$$

$$\frac{\partial\left(\langle\rho\rangle \varepsilon\right)}{\partial t} + \nabla\cdot\left(\langle\rho\rangle\langle\mathbf{u}\rangle \varepsilon\right) = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \left(C_{\varepsilon 1}\mu_T\left\langle\nabla\mathbf{u}+\nabla\mathbf{u}^T\right\rangle : \nabla\langle\mathbf{u}\rangle - C_{\varepsilon 2}\langle\rho\rangle\varepsilon\right) \tag{5}$$

where the eddy viscosity is given by $\mu_T = C_\mu \langle\rho\rangle k^2/\varepsilon$ .The constants are taken from [9].

2.3 Mixture Properties

The ensemble averaged mixture properties in Eq. (3) are given by

$$\langle\varphi\rangle = r_{iron}\langle\varphi_{iron}\rangle + r_{air}\langle\varphi_{air}\rangle \tag{6}$$

where ϕ represents any physical property.

2.4 Initial conditions

As the system is assumed at rest, the velocity field is null and the volume fraction of metal have a known initial height, h^o, inside the channel, given by

$$r_{iron} = 0.5\tanh\left(\frac{h^o - y}{\delta_i}\right) + 0.5$$
$$r_{air} = 1 - r_{iron} \tag{7}$$

The variable δ_i represents the thickness of interface, what guarantees a soft transition of the properties through interface, enhancing the numerical stability.

2.5 Boundary Conditions

The boundary conditions are given in Tab. 1. The Fig. 1 presents the domain and it's the regions where the boundary conditions were applied.

Local	Description	Condition
Tap hole	inlet	7.5 m/s with 10 degree inclination
Refractory wall	wall	No-slip for momentum and wall-law for *k* and ε
Cast-iron outlet	Opening Pressure and Direction	$p=0$ Pa; $r_{air}=1$; $I_{turb}=1$ %
Far field	Opening with Static Pressure for Entrainment	$p=0$ Pa; $r_{air}=1$; $I_{turb}=10$ %

Tab. 1: Boundary conditions.

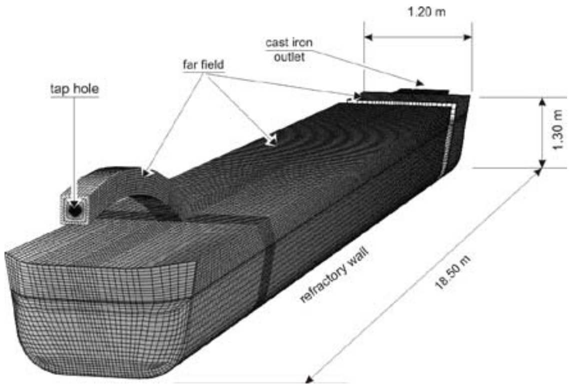


Fig. 1: Boundary conditions, geometry configuration and dimensions of the calculation domain.

2.6 Physical Properties

The physical properties are given in Tab. 2.

$\langle \rho_{iron} \rangle$	$\langle \rho_{air} \rangle$	$\langle \mu_{iron} \rangle$	$\langle \mu_{air} \rangle$	$\langle \sigma_{\alpha\beta} \rangle$
7000 kg/m³	1.185 kg/m³	5.0 x10^{-3} Pa.s	1.83 x10^{-5} Pa.s	1,35 N/m

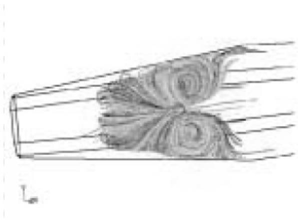
Tab.2: Cast iron and air physical properties.

3. NUMERICAL METHOD

The model has been solved with commercial code ANSYS CFX employing a hexahedral mesh with 375k elements and 400k nodes. The numerical approach applies adaptative time step, coupled solution, paralleling processing with relaxation in overlapping regions. The physical time was made equal to 35 seconds.

4. RESULTS

The single-phase steady flow simulation results were compared with the data from Gondolf et al. [5] and Luomala et al. [6]. The two-phase flow is also presented and the comparison between the two approaches is discussed. In Fig. 2 and Fig. 3, it is presented the Gondolf et al. [5] results. According to these figures, two symmetric recirculation zones appear around the sinking point. Downstream this region, the flow is almost a plug flow.



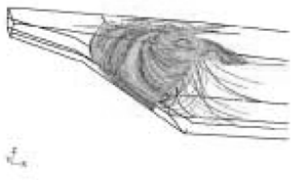


Fig. 2: Upper view of channel [5]. *Fig. 3: Side view of channel [5].*

Qualitatively, these same results were obtained in this work and are presented in Fig. 4. According to the figure, the same behaviour is found: two symmetric recirculation zones around the impingement point.

According to Fig. 5, when the unsteady multiphase model is employed, one can see the same recirculation zones, but now with a transversal oscillatory behaviour, associated to a streamwise oscillation that, in its turn, collides with the recirculation zones in the impingement zone in a periodic way.

In Fig. 6 is presented the vector field extracted from work of Luomala et al. [6]. The flow is reverse and faster close to the lateral walls, and the same qualitative vector field has been found in this work according to Fig. 7. There is a reverse flow towards the lateral walls.

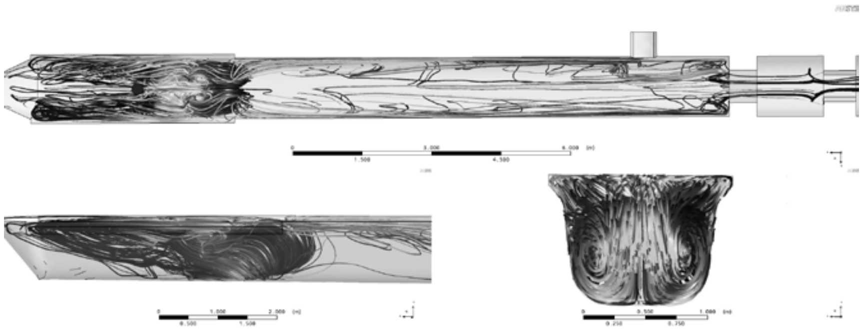
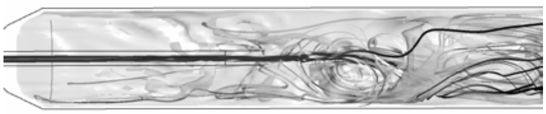
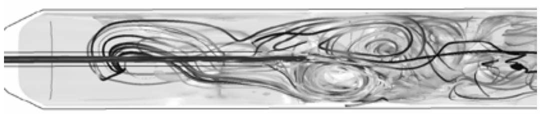


Fig. 4: Results from this work: streamlines from single-phase flow without free-surface.

Time = 10 s



Time = 15 s



Time = 20 s

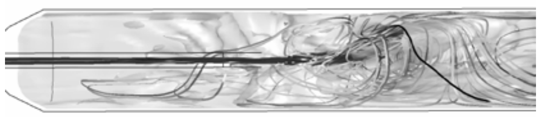


Fig. 5: Results from this work: upper view of streamlines from the two-phase unsteady model considering the free-surface and the open jet in three distinct times.

In the multiphase unsteady model, this reverse and symmetric flow occurs only after the impingement and for a short period of time. After that period, the streamwise oscillations and waves travelling through the channel induce the interchanging of the main vortices, and the reverse flow surges periodically in each wall, as is shown in Fig. 8. The period for this to happen is nearly 5 seconds.

In the single-phase approach these results do not depend on the inlet conditions. A changing on the velocity magnitude, or even on the angle, alters just the vortices position, not the physical behaviour.

A comparison between the experimental work of Begnis et al. [4] and the two-phase model of this work demonstrates a good result, according to Fig. 9 and Fig. 10. In both, there is the eruption of air bubbles captured by the jet in the sinking zone. The authors have reported the same reverse flow.

In Fig. 11 the air entrainment is presented. The mixture among air and the cast iron can be very well seen.

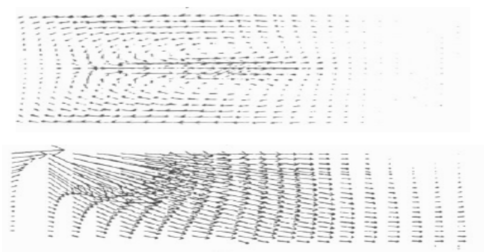


Fig. 6: Upper and side view of vector field from Luomala et al. [6].

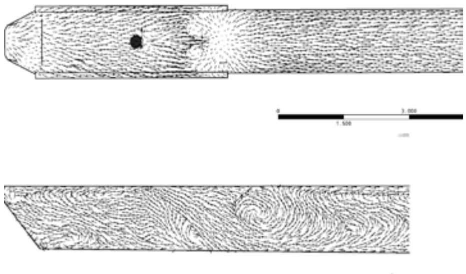
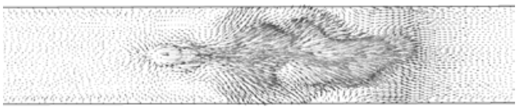
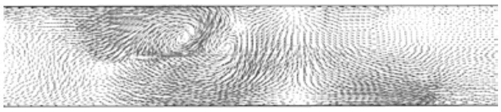


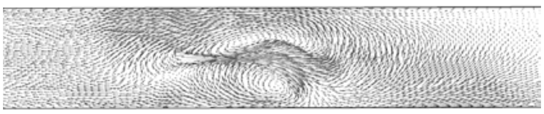
Fig. 7: Results from this work: upper and side vector field from single-phase steady model.



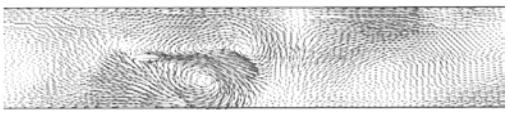
Time = 2 s



Time = 30 s



Time =15 s



Time = 35 s

Fig. 8: Results from this work: upper view of vector field from two-phase unsteady model considering the free-surface and the open jet for four distinct times.

Fig. 9: Experimental results presenting eruption of bubbles[4]

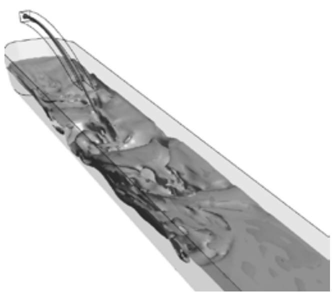


Fig. 10: Two-phase flow: dynamic of free-surface and air.

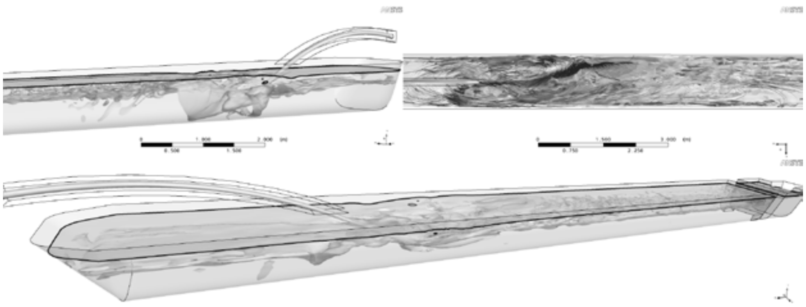


Fig. 11: Two-phase flow: air entrainment into cast iron. The line represents a volume fraction of 0.5.

5. CONCLUSIONS

A two-phase, unsteady, turbulent and three-dimensional model of the flow through the blast furnace main trough was proposed and numerically solved. The results demonstrated a qualitatively good agreement with others works. The results obtained demonstrated that the multiphase approach accounting for the jet/free-surface interaction is more suitable than the single-phase steady approach when the dynamic of free-surface is important, as in slag separation, or for predicting the wear rate of the refractory lining. Many details, as the oscillatory behaviour, vortices predictions and reverse flow that have been seen only in experiments and/or in the industrial facilities were captured by the model.

6. ACKNOWLEDGMENTS

The authors would like to thank CNPq and FINEP for the scholarship for the first author and to MAGNESITA and ESSS for the technical support.

7. REFERENCES

[1] He, Q., et al., Flow characteristics in a blast furnace trough. ISIJ International, 2002. 42(8): p. 844-851.

[2] He, Q., et al., Flow characteristics of a blast furnace taphole stream and its effects on trough refractory wear. ISIJ International, 2002. 42(3): p. 235-242.

[3] Kim, H., B. Ozturk, and R.J. Fruehan, Slag-metal separation in the blast furnace trough. ISIJ International, 1998. 38(5): p. 430-439.

[4] Begnis, J.S.S., E. Brandaleze, and R. Topolevsky. Simulación del canal del alto forno nº2 por medio de modelos físicos. in 5ª Conferencia de Redución del IAS. 2005. Argentina.

[5] Gondolf, M., J.P. Randal, and M.S. Lange. Numerical modeling of the wear in blast furnace main troughs. in The Unified International Technical Conference on Refractories. 2001. Mexico.

[6] Luomala, M.J., et al., Modelling of fluid in the blast furnace trough. Stell Research, 2001. 72(4): p. 130-135.

[7] Daoud, I.L.A., et al. Nova Metodologia Numérica para Obtenção de Tempos e Volumes Característicos em Distribuidores de Lingotamento Contínuo in XXXVII Seminário de Aciaria - Internacional. 2006. Porto alegre: ABM - Associação Brasileira de Metalurgia.

[8] Silva, R.F.A.F., et al. Aplicação de Ferramentas de Otimização e Dinâmica dos Fluidos Computacional em um Distribuidor de Lingotamento Contínuo. in XXXVII Seminário de Aciaria - Internacional. 2006. Porto Alegre: ABM -Associação Brasileira de Metalurgia.

[9] Launder, B.E. and D.B. Spalding, The Numerical Computation of Turbulent Flows. Computer Methods in Applied Mechanics and Engineering, 1974. 3: p. 269-289.

[10] Brackbill, J.U., D.B. Kothe, and C. Zemach, A continuum method for modeling surface tension. Journal of Computational Physics, 1992. 100(2): p. 335-354.

[11] Drew, D.A., Mathematical flow modeling of two-phase flow. Annual Review of Fluid Mechanics, 1983. 15: p. 261-291.