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MODELLING OF FLUID FLOW IN A PS CONVERTER WITH ONE AND THREE INJECTION POINTS

Aaron ALMARAZ[1], Erik SALAS[1], Miguel A. BARRON[2], Ricardo CUENCA[1], David JARAMILLO[1], Fidel REYES[3], and Gabriel PLASCENCIA[1*]

[1] CIITEC – IPN, Cerrada Cecati s/n, Col. Sta. Catarina, 02250 México, D.F., MÉXICO

[2] Departamento de Materiales, UAM-Azcapotzalco, Av. San Pablo 180, Col. Reynosa-Tamaulipas, 02200 México, D.F., MÉXICO

[3] Departamento de Ingeniería Química Metalúrgica, Facultad de Química, UNAM Edificio D. C.U., 04510 México, D.F., MÉXICO

*Corresponding author, E-mail address: g.plascencia@utoronto.ca

ABSTRACT

Copper and nickel converting is mainly conducted in Peirce-Smith converters. Such converter, in spite of its age has not experienced significant technological modifications. Extensive work has been conducted to understand fluid flow phenomena as air is injected into molten mattes. High momentum must be transferred from the gas to the melt in order to refine the metal. In this work, we present a CFD analysis of gas injection using one and three tuyeres. Results show that by increasing the number of injection points, the flow pattern within the converter change considerably. Such changes result in the development of large recirculation zones and localized eddy formation. Additionally, it was found that the gas plumes in the melt are asymmetrical thus flow paths constantly interfere between themselves.

NOMENCLATURE

p	pressure (Pa)
$\mathbf{u}$	velocity (m/s)
t	time (s)
g	gravitational acceleration (9.8 m/s^2)
G	filtering function
q	Phase
S	Source term (PISO algorithm)
α	volume fraction
ρ	density (kg/m^3)
μ	viscosity (Pa s)
ϕ	general form of LES equations
ξ	argument of a Gaussian distribution

INTRODUCTION

Copper (or nickel) conversion is defined as the selective oxidation of iron and sulphur with oxygen enriched air (up to 35 %vol. oxygen) injected laterally into a molten matte by means of a series of tuyeres aligned on one side of a cylindrical vessel named converter. Nearly all the copper and nickel obtained pyrometallurgically is processed in Peirce-Smith converters. In spite of its high productivity, the Peirce-Smith converter has some technical issues:

- Clogging of tuyeres as result of metal/refractory accretions growing on the tip of the tuyeres
- Localized thermal gradients resulting in erosion of the refractory lining around the tuyeres, thus shortening the service life of the refractory.
- Effective SO_2 capture in the off gases

In addition to its simplicity, this furnace has not experienced significant technological improvements over a century of operation, which opens the door for upgrading it (Navarra and Kapusta, 2009). This necessity can be overcome with the use of computational tools and physical modelling of such reactor.

On the other hand, gas injection is vastly used in process metallurgy; a significant amount of analytical and experimental work has been published on this subject. Extensive reviews by Brimacombe (1991, 1996), Kellogg & Díaz (1992), Mazumdar & Guthrie (1995) and more recently by Lehner & Samuelsson (2009) and Mackey & Campos (2001). In all these reports it has become evident the need to further explore fluid flow phenomena at operating conditions in order to minimize as possible the extent of refractory wear and accretion growth in Peirce-Smith converters.

MODEL DESCRIPTION

Fluid flow is described by Navier-Stokes (NS) equations, which in vector form are expressed as follows:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=-\nabla p+\mu\nabla^2\boldsymbol{u}+\rho\boldsymbol{g} \qquad (1)$$

where ρ is the fluid density, **u** is the fluid velocity (vector), t is time, p is pressure, μ is the fluid viscosity and **g** is the gravitational acceleration. To maintain the mass balance in the system, the continuity equation must be solved as well:

$$\frac{\partial \rho}{\partial t}=-\nabla\cdot\rho\boldsymbol{u} \qquad (2)$$

which under isothermal conditions can be simplified to:

$$\nabla\cdot\boldsymbol{u}=0 \qquad (2a)$$

In current industrial copper converter practice, turbulence is needed to increase copper matte mixing, thus mass, momentum and heat transfer are also increased. In order to model turbulence properly, the Large Eddy Simulation (LES) model was employed. It is well recognized that LES simulates turbulence in a better way than two-equations models such as the κ-ε. LES is applied to turbulent flows and consists of three steps: (i) filtering of NS equations, to remove small spatial scales, allowing for solving large eddies; (ii) use of a model to solve the stress tensor obtained after the filtering stage and (iii) conduct actual numerical simulations. (Ghosal & Moin, 1995). From the previous description, it is obvious that finding a proper filter to the NS equations is paramount in order to achieve good numerical results with LES. The filter selection comes from defining a scale length that can divide the eddies into large or small.

In general terms, LES equations have the form:

$$\bar{\phi}(x) = \int_D \phi(x') \cdot G(x, x')\, dx' \qquad (3)$$

Where G is the filtering function with domain (-∞, +∞). Some commonly used filters (Aldama, 1990) are the "top hat" filter:

$$G(\xi) = \begin{cases} 1, \ if\ |\xi| \le 0.5 \\ 0, \ otherwise \end{cases} \qquad (4)$$

and the Gaussian filter:

$$G(\xi) = \sqrt{\frac{2}{\pi}} \exp\left(-2\xi^2\right) \qquad (5)$$

For the present work, we decided to use equation (5) as a filter.

Additionally, another model is needed to tackle the multiphase flow in the copper converter. The Volume of Fluid (VOF) formulation relies on the assumption that two or more phases are not interpenetrating. For each additional phase (q) its volume fraction α_q is introduced as a variable. In each control volume, the volume fraction of all phases sums up to unity. The tracking of the interface between the phases is accomplished by solving the continuity equation for each phase (Fluent, 2003):

$$\frac{\partial \alpha_q}{\partial t} + \vec{v} \bullet \nabla \alpha_q = \frac{S_{\alpha q}}{\rho_q} \qquad (6)$$

where $S_{\alpha q}$ is a source term for the q phase. Finally, the Pressure Implicit Splitting Operation (PISO) algorithm was employed in the transient simulations for the pressure-velocity coupling given that it maintains stability despite the larger time steps (Fluent, 2003).

More recently, Liovic and Lakehal (2012), have developed better modelling procedures that involve the effect of surface tension on multiphase flow. This new approach is based upon the increasing the accuracy of the numerical method by modifying the curvature of the gas-liquid interphase as it moves. The soundness of the resulting simulations is improved as the gas-liquid curvature is smoothed, by suppressing the surface shape functions. Also important is the discretization of the bi-phasic curvature, which can lead to considerable errors or increased computational time.

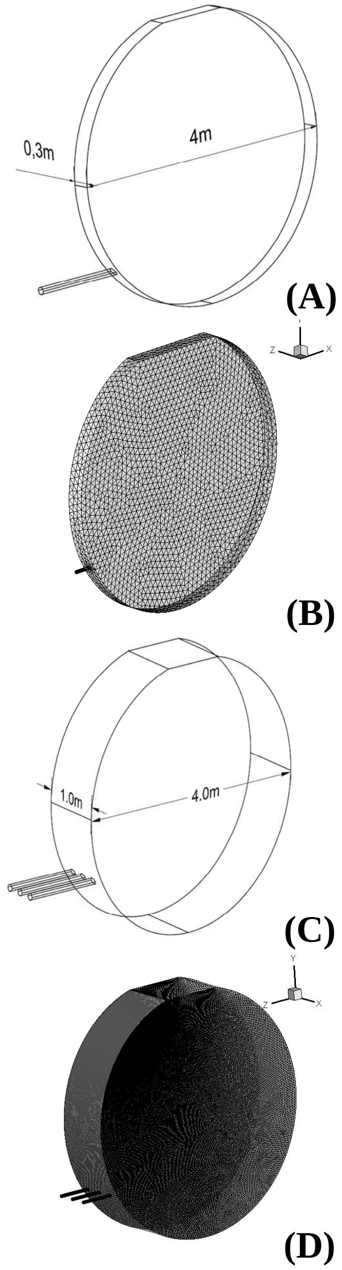


Figure 1: Schematic diagram of the geometries used in this work. (A) Dimensions of the one tuyere geometry. (B) Mesh used in (A). (C) Dimensions of the three tuyeres geometry. (D) Mesh used in (C).

In addition to the curvature refinement conditions, the use of more stable filters have also allowed for improving the exactitude of the simulations conducted with the LES model.

Geometry and boundary conditions

To conduct our numerical simulations a slice of a Peirce-Smith converter was used. Figure 1 show the computational domains used; whereas Table 1 shows the specific features of each of the geometries used for calculations.

Domain	Number of tuyeres	Slice diameter (m)	Slice width (m)	Tuyere diameter (m)
1	1	4.0	0.30	0.05
2	3	4.0	1.00	0.05

Table 1: Model features.

In each case tetrahedral elements were used for meshing, to ensure convergence, the time step was set at 10^{-6} s.

As it can be in Figure 1, different geometries were used to simulate the fluid flow within the PS converter. The reason for increasing the width of the element used for simulating the fluid flow relies on the number of tuyeres used for injecting air into the molten matte. Typically a PS converter has up to 35 tuyeres placed along its axis. The tuyeres are equally spaced and the distance between tuyere's centres typically is of about 25 to 30 cm.

Earlier simulations (Väarno et al, 1997) with one injection point used a symmetry that did not considered the effect of adjacent plumes on the flow pattern developed by the simulated tuyere. Consequently, it's been assumed that the resulting plume present certain symmetry features that describe a particular flow pattern. However, results from Rosales (1999) show that there is a strong interaction between adjacent tuyeres that modify the flow trajectories described by a central tuyere. Such interaction result in flow patterns that not necessarily are symmetrical as it can be assumed based upon the actual location of the tuyeres on the converter. Considering Rosales's results; in this work, it has been decided to investigate the effect of adjacent tuyeres. To do that, it is needed to increase the size of the element used for the simulation of the gas injection; by adding two extra injection points, the width of the section of a PS converter used for simulating the gas plume has to increase three times that of the element used for simulating just one injection point.

In addition to increase the symmetry used for simulation, in principle, it can be assumed symmetry planes next to a centralized injection point and thus decrease the number of elements used to conduct the simulations, however, this approach could result in inaccurate flow patterns, since there is has been observed (Rosales 1999) strong interaction between the different gas injection points.

Table 2, shows the properties of the fluids used for our calculations:

Fluid	Density (kg/m^3)	Viscosity (Pa s)	Kinematic viscosity (m^2/s)
Air	1.225	1.79×10^{-5}	1.46×10^{-5}
Copper matte	4800	1.00×10^{-3}	2.08×10^{-7}

Table 2: Properties of the fluids used in our calculations.

RESULTS AND DISCUSSION

Figure 2 shows the evolution of the plume as gas is injected into the matte with just one tuyere. The morphology of the plume indicates that it is symmetrical and that in principle there would be no effect from the tuyeres placed in each side of the injection point.

In terms of fluid flow, it can be noticed in Figure 2, that shortly before one second of jetting, the air reaches the surface of the matte causing flow of the melt towards the wall over the tuyere and also in the direction opposite to that of the injection point. Before bursting into the surface, it shows little disturbance by the gas being injected.

After the initial second of blowing, the free surface of the melt becomes disturbed by the continuous gas input. Waving phenomena takes place. As the gas enters the matte, the liquid is pushed away by the former so when the latter reaches the opposite wall of the converter it returns towards the injection point. Such motion results in continuous crashing with the "new" liquid pushed by the gas. As a consequence of the melt collisions, splashing and the development of circular flow pattern within the melt occur. Both of these effects are undesirable. In terms of the gas, it is shown that due to the motion of the liquid a bubbling regime establishes. From time to time, and depending upon the bubbling frequency, an open jet appears.

Figure 3, shows the flow within the converter when three tuyeres are used to inject air instead of just one. In the early stages of the gas flowing into the matte, the flow looks symmetrical; there is no indication of any effect of the flow from the lateral tuyeres on that of the central one. However, as the injection time approaches 1 second, the gas reaches the free surface of the melt. As time elapses more disturbances into the melt surface occurs. Waving is more evident and energetic when using three tuyeres. It is also evident a larger amount of splashing.

As with the injection with one tuyere, a bubbling regime establishes. Bubble frequency is similar among the different tuyeres. The interference of the different gas streams change the local residence time of the gas plume in adjacent tuyeres; consequently, the bubbling frequency is altered. Additionally, some open jet regime establishes because of the stream interference.

It is also expected that as the number of tuyeres providing gas increases, the flow pattern within the converter should change as well. Figure 4, depicts the flow lines in the vessel when injecting with one and three tuyeres.

In the case of gas blowing with one tuyere, a well-defined recirculation zone at the centre of the vessel develops. Such recirculation zone nearly occupies one half of the total volume available for matte conversion. This zone is undesirable since it prevents the full use of the converter to conduct the refining reactions. However, as the number of tuyeres for gas injection increase to three, the flow patterns in the vessel become more chaotic.

It is evident from figure 4, that a recirculation zone also develops in the centre of the vessel; this recirculation zone is similar in size and shape as that developed with just one tuyere. However, the flow paths are more affected by the gas injected with the adjacent tuyeres, so the flow is more difficult to describe. The effects of the high turbulence are even clearer. Efficient stirring and mixing of the melt are compromised by the presence of localized eddies; such eddies definitely affect the mass transfer between the gas bubbles and the melt.

It is observed with both models (one and three tuyeres) that the gas jet does not penetrate considerably the melt. Furthermore, as the blowing time increases, the jet seems to move towards the wall behind the injection point. Such effect may have something to do with the force balance that establishes between the gas and the melt.

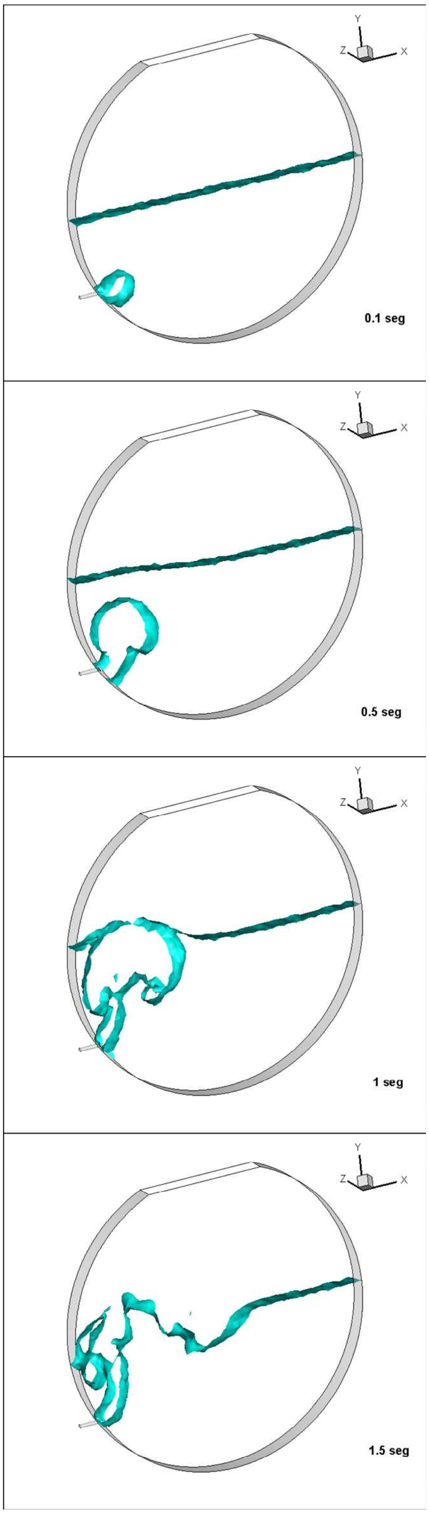
The density difference between the gas and the melt increases as iron and sulphur are selectively removed from the matte. Typically the matte density is 4800 kg/m^3, this value increases to nearly 9000 kg/m^3 as iron and sulphur are oxidized, leaving behind the metallic copper. This density increase means that the specific weight of the melt doubles. Such large difference has to influence the buoyancy forces acting on the system. Additionally, the recirculation of the matte/copper within the vessel has to contribute at some extent to the jet penetration.

Vaarno et al. (1997, 1998) used the simpler κ-ε turbulence model to simulate the flow in a Peirce Smith converter. Their results are similar to those shown in this paper for one injection point. They also found that the modified Froude number does not fulfil the geometric similarity criteria of the gas plumes. Such observation explains why the gas penetration decreases as the melt increases its density (after iron and sulphur removal).

In a different study, Rosales et. al. (1999), conducted the numerical simulation of an entire Teneinte converter. Such converter is similar in shape to the Peirce-Smith one.

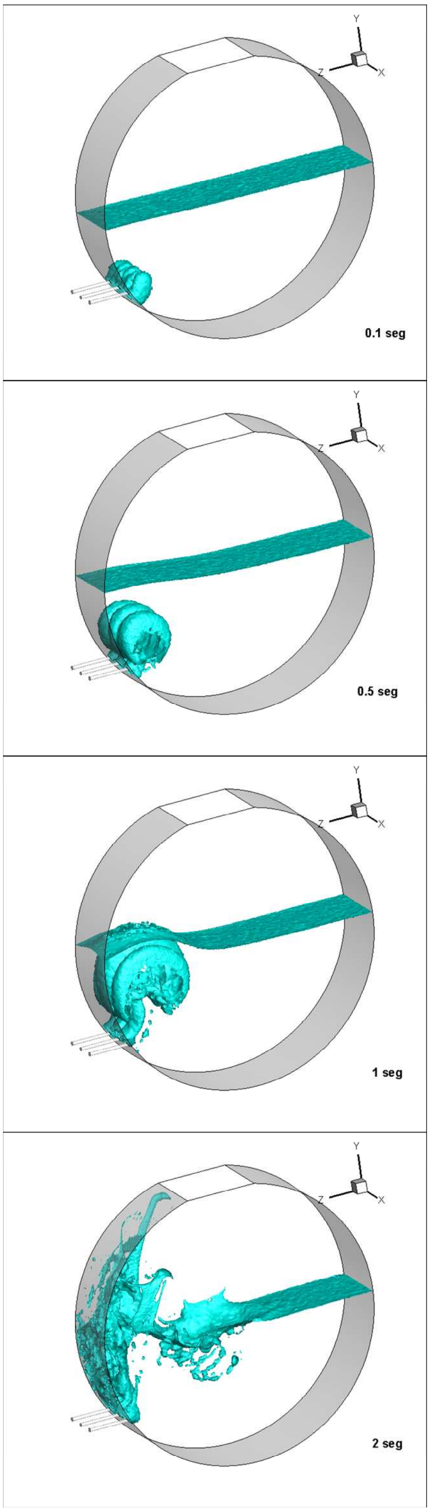
The observations done by Rosales et. al. agree with our observations of three injection points. As more injection points are added to the flow simulation, the more evident is their interaction. Non-uniform flow patterns develop along the injection axis, furthermore, the flow lines become more complex to determine and so is the net effect of the turbulence induced by the presence of bubbles during blowing. Waving phenomena becomes intense, thus rendering the capacity to transfer momentum from the jet to the molten matte.

This effect proves that even though the different tuyeres are located symmetrically alongside the converter axis, and the air injected into the matte is supplied under controlled velocity and pressure, the flow within the converter does not follow a constant path. Flow paths are greatly affected to several phenomena occurring simultaneously in the reactor as copper is refined. Among them: melt density increase, surface tension changes, gradients in viscosity develop, localized turbulent effects. Gas emission as the sulphur is removed from the matte. All of these effects and the confinement of the metal in the converter account for the complexity of the flow behaviour.



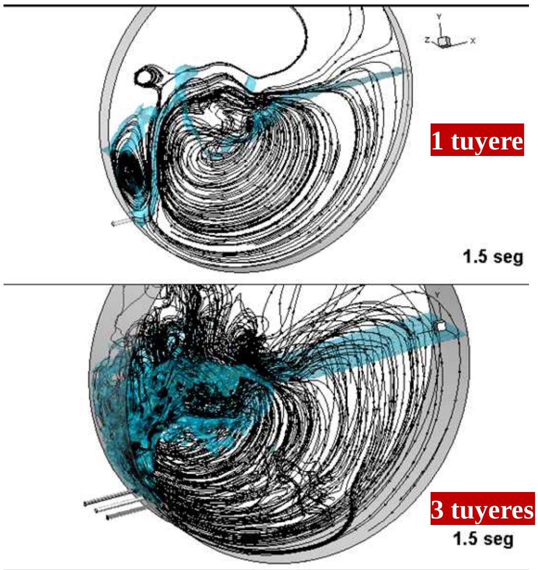
$$\mu_{matte} = 0.001 \text{ Pa s}$$

Figure 2: Evolution of the plume as air is injected into the matte with one tuyere.



μ_{matte} = **0.001 Pa s**

Figure 3: Evolution of the plume as air is injected into the matte with three tuyeres.



μ_{matte} = **0.001 Pa s**

Figure 4: Comparison of flow lines within the vessel when injecting with one and three tuyeres.

CONCLUSION

Numerical simulations of air blowing into a copper matte have been conducted. The effect of the number of tuyeres used to inject the gas was studied. As more tuyeres are used to blow the gas, the more chaotic the fluid flow within the vessel it becomes. Turbulent effects are magnified due to different flow paths, resulting in localized eddy formation; as the number of eddies increases so do the fluid flow dead zones. Consequently, mass transfer rates are greatly affected. Additionally, bubbling regimes established during blowing are also affected.

New simulations with the improved techniques proposed by Liovic and Lakehal must provide a better understanding of the fluid flow interactions within the PS reactor.

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