Large Eddy Simulation of Bubbling-Jetting Transition in a Bottom Blown Copper Converter

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Abstract - In this work the isothermal transition from bubbling to jetting regime in a bottom blown Peirce-Smith copper converter is numerically studied, varying the air jet injection velocity from 5 to 100 m s\textsuperscript{-1}. Large Eddy Simulation turbulence model is employed in the computer simulations to obtain transient, rather than averaged, phase distributions. For low injection velocities the bubbling regime is present, however the jet behavior evolves from bubbling to jetting regime as injection velocity is increased. For high injection velocities jetting behavior arises. In this case splashing is severe, however the bulk metal becomes little stirred due to the low momentum transfer.

Keywords: Bubbling-jetting transition, copper converter, large eddy simulation, multiphase flow, Peirce-smith converter.

1 Introduction

Blister copper is the raw material for manufacturing high purity electrolytic copper. Today more than 90\% of the world’s blister copper is obtained by means of Peirce-Smith converters (PSC), which are long cylindrical horizontal chemical reactors where air is injected into a copper matte through submerged tuyeres\textsuperscript{[1]}. Fluid flow in PSC is turbulent in nature given that high momentum transfer is required to get fast chemical reaction rate and heat transfer. Many works have been reported regarding fluid flow in Peirce-Smith converters. Early seminal works of Brimacombe\textsuperscript{[2,3]} deal with physical experiments which pretend elucidate the transition from bubbling to jetting flow regimes and the effects of high pressure injection. Conditions for bubble-to-jet transition regimes in submerged jets are analyzed by Payne and Prince\textsuperscript{[4]} and Sundar and Tan\textsuperscript{[5]}. Liow and Gray\textsuperscript{[6]} analyze the influence of bath depth and tuyere submergence on the formation of standing waves in PSC by means of water modeling. In the last few years, with the advent of fast computers with huge memory capacity, numerical simulations through Computational Fluid Dynamics software have been carried out to study the fluid mechanics in PSC. In this context, Vaarno et al\textsuperscript{[7]} solve the isothermal flow field in a PSC, and their numerical results are corroborated with $\frac{1}{4}$ scale water model. They report that relatively large bubbles increase the turbulence in the molten metal. Recently, two works of Valencia et al.\textsuperscript{[8,9]} analyze the fluid dynamics in a Teniente copper converter by means of physical and Computational Fluid Dynamics modeling. These authors identify the bubbling and jetting flow regimes by means of a dimensionless Froude number and report the natural oscillation frequency of the bath surface as a function of the bath and tuyere submergence depths.

In this work the isothermal transition from bubbling to jetting regime is numerically studied for an industrial-like PSC with a fixed bath depth of 1 m, varying the injection velocity from 5 to 100 m s\textsuperscript{-1}. Computational Fluid Dynamics commercial software is employed to solve the transient 3D Navier-Stokes equations. Large Eddy Simulation and Volume of Fluid models are employed to simulate turbulence and multiphase flow, respectively.

2 Mathematical Model

The momentum and mass conservation for an isothermal incompressible Newtonian fluid are expressed by means of the Navier-Stokes and continuity equations, respectively\textsuperscript{[10]}:

\begin{equation}
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu_{\text{eff}} \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) \quad (1)
\end{equation}

\begin{equation}
\frac{\partial u_i}{\partial x_i} = 0 \quad (2)
\end{equation}

where $\rho$ is the fluid density, $u_i$ is the $i\textsuperscript{th}$ component of the fluid velocity, $t$ is time, $x_i$ is the $i\textsuperscript{th}$ spatial coordinate, $p$ is pressure, and $\mu_{\text{eff}}$ is the effective fluid viscosity. In recent years, Large Eddy Simulation (LES) turbulence model has been employed in engineering applications to analyze complex transient fluid flows. On the contrary to the $K-\varepsilon$ turbulence model which yields time-averaged results, LES yields fine details of the time-dependent flow structures\textsuperscript{[11]}. To carry out properly its task, LES requires extremely fine grids and very small time steps which significantly increases the computational effort. In LES only the turbulent flow eddies which can be resolved by the computational grid are computed, and those which are unresolved are only modeled. To model the unresolved flow structures, in this work the Smagorinsky sub-grid scale (SGS) model is employed. The SGS stresses are given by
\[ \tau_{ij} = 2\mu_i S_{ij} \text{ where } \mu_i \text{ and } S_{ij} \text{ are the turbulent viscosity and the resolved strain tensor, respectively, and they are defined as follows}\] [11]:

\[ \mu_i = \rho C_s \left(S_{ij} S_{ij}\right)^{1/2} \] (3)

\[ S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \] (4)

In Eq. (3) \( C_s = 0.1 \) and \( L = \left(\Delta x \Delta y \Delta z\right)^{1/2} \).

To tackle the multiphase flow in the copper converter, the Volume of Fluid model is employed. This model relies in the assumption that two or more phases are not interpenetrating. For each additional phase, \( p \), its volume fraction, \( x_p \), is introduced as a variable. In each control volume the volume fractions of all phases sum to unity. Tracking of the interface between the phases is accomplished by solving the continuity equation for each phase\([12]\):

\[ \frac{\partial x_p}{\partial t} + \mathbf{v} \cdot \nabla x_p = \frac{S_{xp}}{\rho_p} \] (5)

where \( S_{xp} \) is a source term for the \( p \) phase.

### 3 Numerical Results

Bubbling to jetting transition in submerged injection has been widely studied by Hoefele and Brimacombe\([2]\) and Payne and Prince\([4]\), who affirm that this transition primarily depends on a balance between the inertial forces of the gas flow through the hole and the gravity forces of the liquid surroundings the orifice. Sundar and Tan\([13]\) report that the bubbling to jetting transition is best represented by the Kutateladze number, \( Ku \), given that this dimensionless group includes the basic forces that determines transition, namely gas inertial forces, bubble buoyancy forces, liquid gravity forces and tension forces. Kutateladze number is defined as follows\([13]\):

\[ Ku = \frac{U \sqrt{\rho_g}}{\sigma \left(\rho_l - \rho_g\right)^{1/2}} \] (6)

where \( U \) is the orifice gas velocity, \( \rho_g \) is the gas density, \( \rho_l \) is the liquid density, \( \sigma \) is the liquid surface tension and \( g \) is gravity.

In this work, in order to reduce the computational effort, just a slice of an industrial-like copper converter with bottom injection is employed in the numerical simulations, as is shown in Fig. 1. The dimensions of the slice are as follows: 4 m of diameter, thickness of 0.5 m and nozzle diameter of 0.05 m. A bath depth of molten copper of 1.0 m is assumed. In order to observe the bubbling to jetting transition flow regime three injection velocities of the air jet are considered: 5, 50 and 100 m s\(^{-1}\). Besides, to reduce the computational effort, just 4 s of integration time is considered in the computer experiments. In the 3D transient numerical simulations two phases are taken into account, namely copper matte and air. Physical properties of the copper matte are shown in Table 1. A mesh of around 1.5x10\(^6\) elements and time step of 1x10\(^{-5}\) s are employed in the computer simulations. Boundary conditions are as follows: symmetry in the virtual vertical planes, and non-slip condition in the physical cylindrical wall.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tr>
<td>Density</td>
<td>5200 kg m(^{-3})</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.004 kg m(^{-1}) s(^{-1})</td>
</tr>
<tr>
<td>Surface tension</td>
<td>1.2 N m(^{-1})</td>
</tr>
</tbody>
</table>

Fig. 2 shows the distribution of phases for several times in the middle plane of the slice for an injection velocity of 5 m s\(^{-1}\). In this figure red phase is molten copper and blue phase is air. Bubbling regime is clearly observed.

![Figure 2](image-url) Distribution of phases in the middle plane of the slice for an injection velocity of 5 m s\(^{-1}\). (a)1.0 s, (b)2.0 s, (c)3.0 s, (d)4.0 s. Red phase is molten copper and blue phase is air.
In Fig. 3, little stirring and small waves at the tridimensional matte surface are appreciated. Bath stirring is confined to the vicinity of the bubbling jet.

When the jet injection velocity is raised from 5 to 50 m s\(^{-1}\) a transition regime is present, as is shown in Fig. 4. Elongated bubbles, larger in size than those obtained with 5 m s\(^{-1}\) of jet velocity, are formed and explode at the matte surface. Stirring of the bath is intense and considerable molten metal is upwards splashed. A tridimensional view of the matte surface is shown in Fig. 5, where strong swelling is observed.

For an injection velocity of 50 m s\(^{-1}\), Fig. 4 clearly shows jetting behavior for 0.5 s of elapsed time. Fig. 6(d) shows bubbling behavior for 0.8 s indicating jet instability. Given that computer simulations are time-consuming it could not be corroborated if this behavior is just transient or steady. A tridimensional view of the matte surface is depicted in Fig. 7, where severe splashing is detected. However, the bath stirring is confined to the vicinity of the air jet and the bulk of the molten metal remains almost at rest. This means that when jet injection velocity is very high, a gas tunnel is formed and transfer of momentum from the incoming jet to the bulk metal is low.

For an injection velocity of 100 m s\(^{-1}\), Fig. 6(c) clearly shows jetting behavior for 0.5 s of elapsed time. Fig. 6(d) shows bubbling behavior for 0.8 s indicating jet instability.
Kutateladze numbers corresponding to the considered jet velocities are shown in Table 2. In accordance with the jet velocities considered in this work, transition from bubbling to jetting regime occurs for $K_u > 3.4832$.

Table 2. Kutateladze numbers.

<table>
<thead>
<tr>
<th>Jet velocity</th>
<th>Kutateladze number</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0 m s$^{-1}$</td>
<td>0.3483</td>
</tr>
<tr>
<td>50.0 m s$^{-1}$</td>
<td>3.4832</td>
</tr>
<tr>
<td>100.0 m s$^{-1}$</td>
<td>6.9664</td>
</tr>
</tbody>
</table>

4 Conclusions

Transition from bubbling to jetting regime in a bottom blown Peirce-Smith copper converter is numerically studied in this work. An injection velocity of the air jet of 5 m s$^{-1}$ causes a bubbling regime and little stirring of the bulk metal. When jet injection velocity is raised to 50 m s$^{-1}$ significant stirring of the bulk metal and splashing are observed, however bubbling regime persists. For 100 m s$^{-1}$ of injection velocity jetting behavior arises and severe splashing is present, however the bulk metal remains almost at rest due to formation of a gas tunnel which prevents momentum transfer.

5 References


