Analysis of the Fluid Flow Behavior Within a Beam Blank Mold Using Submerged-Entry Nozzle With Three Exit Ports

Through the use of physical and mathematical modeling techniques, liquid flow inside a beam blank mold with a submerged valve consisting of three exit ports has been analyzed. The behavior of the slag metal interface was evaluated using water and an aqueous NaCl solution to simulate steel. Slag simulation was done using silicon oil. Increased casting speed results in increased free surface oscillation. For the fluid density of 1,000 kg/m³, oil entrainment started at a casting velocity of 0.98 m/minute. For a fluid density of 1,170 kg/m³, no entrainment was observed in any of the conditions studied.

To understand the fluid flow characteristics generated by the feeding system used in beam blank molds, it is important to define the best operating conditions, aiming at higher productivity, higher steel cleanliness and operational safety. In beam blank molds, the complexity of geometry makes quality control of the cast product more challenging. The use of two submerged-entry nozzles (SENs) enables the reduction of fluid flow asymmetry along the mold. However, this configuration leads to difficulties in the operation and design of the feeding system. Xuo and Zhu reported that the use of straight SENs results in a practically inactive free surface, which hinders the melting of flux powder and impairs the lubrication of the mold walls. On the other hand, the use of two SENs with lateral outlet ports allows for the development of a uniform flow of fluid and heat, generating a solidified shell of more homogeneous thickness and intensifying the superficial oscillation. Chen et al. observed a reduction in the impact depth of the liquid jet from this model of nozzle, facilitating the removal of non-metallic inclusions. Onishi et al. demonstrated that the cleanliness of the steel increases when replacing straight SENs with SENs with side ports.

Zhang et al. characterized the fluid flow inside the beam blank mold with open jet. In this case, a large entrainment of air bubbles and a significant change in velocity profile along the mold were observed. The immersion depth of the funnel has great influence on the impact depth of the bubbles and oscillation of the free surface.

When using an SEN with side ports, the configuration of the outlet ports also has a significant influence on the flow characteristics. Najjar et al. studied the influence of the angle of inclination, shape and thickness of the walls of the ports on the characteristics of the liquid jet, showing that all these factors affect the inclination of the liquid jet and consequently the behavior of the surface of the bath.

With respect to the behavior of the metal slag interface, Hibbeler et al. have shown that the slope of the liquid jet is one of the factors that affect the possibility of slag entrainment. Coverage slag entrainment is an important source of inclusions greater than 20 μm. Flow control and chemical composition of the slag are ways of controlling the emulsification. Deng et al. report that changes in the flux pattern generated by the magnetic field affect the behavior of the metal/slag interface. Among the phenomena...
that explain slag entrainment, one can highlight the swirling, high velocity of the fluid that shears the metal-slag interface and turbulence in the meniscus region.12

Usually, physical simulation of the metal/slag interaction does not accurately reflect actual behavior. Therefore, it is common to use different materials in order to predict the variation of interfacial behavior when the physical properties of the involved fluids are varied.13 By adding salt to the water, it is possible to vary the density of the same and consequently to evaluate the effect of the difference in density in the critical velocity of entrainment.

There are experimental procedures cited in the literature in which sodium chloride was used, increasing the water density to 1,170 kg/m³,14 and potassium carbonate to a density of approximately 1,400 kg/m³.15

This work aims to describe the fluid flow as well as the behavior of the interface between two immiscible fluids present in beam blank molds, which represent metal and slag, verifying the influence of viscosity, density difference and interfacial tension in beam mold blank poured by only one SEN with three side ports.

**Materials and Methods**

The analyses, through physical modeling, were performed in a 1-to-1 scale acrylic beam blank mold with dimensions of 499 mm X 415 mm X 125 mm and 1.5 m high. Fluid flows were kept at 100 L/minute, 125 L/minute and 150 L/minute, corresponding to the casting velocities of 0.78 m/minute, 0.98 m/minute and 1.2 m/minute, respectively. The immersion depths of the SEN were 200 mm and 250 mm. The proposed SEN design (Fig. 1a) shows three side ports spaced 120° from each other: two ports with smaller diameter (16 mm) and one with a larger diameter (47 mm) that is positioned toward the web. The larger port has a well of 20 mm. The angle of inclination of the ports (θ) was −5°. In the analysis of inclusion behavior, the data from this SEN was compared to the SEN with +5°.

**Fluid Flow Analysis —** In the physical simulations, some simplifications were performed. The steel solidification, the specific consumption of slag and the taper of the mold were disregarded.

The tracking of a tracer after its injection into the SEN inlet has been used for fluid flow qualitative analysis. The free surface oscillation was measured using a set of ultrasonic sensors SICK UM30-21_118; the points (1 to 7) chosen for analysis are also shown in Fig. 1b.

A computer simulation was also carried out using the ANSYS CFX software version 17.1. The water was considered a Newtonian fluid, with constant temperature equal to 25°C. The applied model was k-ε, in which the continuity, Navier-Stokes and effective viscosity equations were solved, as well as the auxiliary equations for the determination of k (turbulence energy) and ε (kinetic energy dissipation rate).

The boundary conditions applicable to the problem were:

- **Walls —** Non-slip condition on the walls of the mold and of the SEN; condition of free slip wall on the free surface.
- **Mass flow at the entrance —** 1.667 kg/second; 2.083 kg/second and 2.5 kg/second for the casting speeds equivalent to 0.78 m/minute; 0.98 m/minute and 1.2 m/minute, respectively; **Outlet — Opening.**

The planes used in the analysis of the velocity profiles are represented in Fig. 1b by the lines AA and BB, which represent the plane of symmetry and the plane connecting the smallest diameter port to the corner of the flange, respectively. On the other hand, the line BC schematically represents the direction of the centerline of the liquid jet. In this direction, the
velocity of the fluid was evaluated. Some of the simulations were made in transient mode in order to enable verification of tracer dispersion inside the mold, as well as comparison with physical simulation.

**Metal Slag Interface Analysis** — In the physical simulation, the interface between the fluids was filmed from the position shown in Fig. 1b. The resulting sequence of frames was used to evaluate the behavior of the interface as a function of time.

The fluids used to simulate the steel were water and a saline solution. A 20-mm-thick oil layer simulated liquid slag. The physical properties of the applied fluids are presented in Table 1. As a limitation of the physical modeling, the ratio between the water/oil physical properties does not coincide with the ratio between the steel/slag properties. An example is the difference in density. Silicon oils have a density around 95% of the water density, while the slag density is around 35% of the steel density. Varying the properties of the fluids during simulations of interphase phenomena allows for the evaluation of the influence of each property individually on the interphase phenomena and the prediction of the expected behavior from the industrial point of view. The use of the saline solution allows for the evaluation of the influence of density of the fluid on the interphase phenomena, whereas the changes in the type of oil used would clarify the influence of the viscosity, since both oils have the same density.

The intensity oscillation of the free surface of the oil was also assessed, as described before for the case without simulation of slag.

For the purpose of metal slag interface analysis, the mathematical simulations were performed using ANSYS CFX 17.1 software, considering steady state. Although the interfacial phenomena are of a transient nature, studies have shown that permanent regime simulations enable the evaluation of the main parameters, besides saving the simulation time.\(^1\)

**Inclusion Removal Rate Analysis** — In order to simulate the flow of inclusions in the mold, 5 g of particles with sizes between 100 μm and 200 μm were injected into the inlet of the SEN and collected at the exit during a period of 5 minutes. After drying, the collected particles were weighed. The inclusion flotation rate is given by the difference between the collected and total injected. The equation that correlates the particles sizes in the model with the inclusions on the industrial equipment is given by:

\[
\frac{r_{p,M}}{r_{p,P}} = \lambda^{1/4} \left( 1 - \frac{\rho_{p,M}}{\rho_{L,M}} \right)^{1/4} \left( 1 - \frac{\rho_{p,P}}{\rho_{L,P}} \right)
\]

(Eq. 1)

where

- \( r_{p,M} \) and \( r_{p,P} \) = the radius in the model and in the industrial equipment, respectively, and
- \( \rho_{L,P} \) (7,000 kg/(m³)), \( \rho_{L,M} \) (1,000 kg/(m³)), \( \rho_{p,M} \) (900 kg/(m³)) and \( \rho_{p,P} \) (3,000 kg/(m³)) = the density of the steel, water, inclusions in the model and in the industrial trial, respectively.

For a scale factor (λ) equal to 1, the particles with a diameter between 100 μm and 200 μm are equivalent to inclusions in the metallic bath in the grain size range between 41.84 μm and 83.68 μm.

**Results and Discussion**

**Flow Analysis** — Fig. 2 depicts the fluid flow in the beam blank mold by dispersing a tracer for different casting speeds. It can be seen that the jet of liquid directed toward the web spreads upon reaching the surface of the opposing flange, with a portion flowing toward the free surface while the remainder moves downward, forming a recirculation zone approximately 600 mm from the meniscus. In addition, a portion of this fluid rapidly reaches the mold outlet (considering the mold height of 800 mm). This feature may

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**Table 1**

Properties of the Fluids Used in the Simulations

<table>
<thead>
<tr>
<th>Properties of fluids</th>
<th>Value (unit)</th>
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<tbody>
<tr>
<td>Density of water</td>
<td>1,000 (kg/m³)</td>
</tr>
<tr>
<td>Viscosity of water</td>
<td>0.00088 (Pa*s)</td>
</tr>
<tr>
<td>Density of salt solution</td>
<td>1,170 (kg/m³)</td>
</tr>
<tr>
<td>Viscosity of salt solution</td>
<td>0.00156 (Pa*s)</td>
</tr>
<tr>
<td>Density of oil 1</td>
<td>950 (kg/m³)</td>
</tr>
<tr>
<td>Density of oil 2</td>
<td>950 (kg/m³)</td>
</tr>
<tr>
<td>Viscosity of oil 1</td>
<td>0.475 (Pa*s)</td>
</tr>
<tr>
<td>Viscosity of oil 2</td>
<td>0.19 (Pa*s)</td>
</tr>
<tr>
<td>Interfacial tension water-oil 1</td>
<td>0.0357 (N/m)</td>
</tr>
<tr>
<td>Interfacial tension water-oil 1</td>
<td>0.0337 (N/m)</td>
</tr>
<tr>
<td>Interfacial tension salt solution-oil 1</td>
<td>0.0401 (N/m)</td>
</tr>
<tr>
<td>Interfacial tension salt solution-oil 2</td>
<td>0.0397 (N/m)</td>
</tr>
</tbody>
</table>
facilitate the entrapment of inclusions present in the steel.

The strong fluid spreading on the opposing flange implies slow fluid recirculation in the lower region. The jet of liquid from the smaller-diameter ports reaches the flange tips near the SEN and then spreads along the surface and the fillet. The portion passing through the fillet encounters the upward flow of the jet of liquid passing through the web, and both descend along the jet of liquid passing through the web.

Mathematical simulations in transient regime conditions for the tracer dispersion also allow for evaluation of the behavior of the fluid, with results similar to those obtained through physical modeling, according to Fig. 3.

Fig. 4 shows the velocity profile along planes AA and BB for different flowrates. Changes in casting speed are not involved in significant variations in velocity profile. In the AA plane, a vortex formation can be observed near the free surface in the recirculation region of the upward fluid. In the lower region of the mold, a recirculation zone is also observed near the mold outlet. The velocity profile in the BB plane allows one to assess that the jet of liquid coming from the smaller-diameter ports upon reaching the surface spreads itself, generating two vortices, involving rapidly filling the region as highlighted in Figs. 2 and 3. The liquid jets from the smaller ports mainly feed the upper region of the flange where the nozzle is positioned.

Fig. 5 compares the velocities at the center of the liquid jets by data obtained via computational fluid dynamics (CFD). The velocity of the liquid jet at the exit of the smaller ports is about 10% lower than that of the port directed to the region of the web. The velocity gradient in the liquid jet from the smaller port is higher as a function of the small distance from the surface of the flange on which the nozzle was positioned. Already the jet of liquid from the larger port passes through the web before it reaches the surface of the flange.
opposite to it. Gabriel et al.\textsuperscript{17} demonstrated that the velocity values obtained by the CFD technique (using the setup described in this work) are corroborated by the data obtained by physical model simulation using the particle image velocimetry (PIV) technique.

**Analysis of the Metal/Slag Interface** — Fig. 6 shows details of the water-oil interface along the mold, comparing the influence of casting speed and viscosity. Note that when the casting speed increases, there is greater entrainment of oil in the pool emulating the liquid steel. For the flowrates of 100 and 125 L/minute, no significant changes were observed in the interface, varying the viscosity of the oil, while for the higher flowrate, the drag of the oil with lower viscosity was higher, causing a greater eye opening in the region of the opposite flange. For the 500 cSt oil, the eye aperture was only on the corners of the flange opposite to the SEN.

Fig. 7 presents the water-oil (500 cSt) interface for different flowrates and time. For the flowrate of 100 L/minute, the occurrence of liquid entrainment was not observed. Comparison of Fig. 7 and Fig. 6 shows a good agreement in the interfacial aspects obtained by computational and physical simulation.

Physical simulation for the oil with a viscosity of 200 cSt also presented entrainment for the flows of 125 and 150 L/minute. Fig. 8 presents details of the water-oil (200 cSt) interface for different flowrates and time. It is noticed that for lower flowrates, little deformation of the interface occurs and that, near the fillet, the formation of a protuberance begins, but detachment did not occur. For the higher flowrates, the oil droplets were observed mainly in this region. For the flowrate of 150 L/minute, an inconsistency between the results of physical and mathematical simulation was observed, since in the first one there was a greater drag of the oil to the region of the web.

**Figure 5**

![Velocity values in the center of the jet: larger-diameter port (a) and smaller-diameter port (b).](image)

**Figure 6**

![Analysis of the water-oil interface as a function of flowrate and oil viscosity: 500 cSt oil (a–c), 200 cSt oil (d–f).](image)
For the other conditions, a good agreement between the results has been observed. To evaluate the effect of density on interfacial phenomena, water was replaced by NaCl solution with a density of 1,170 kg/m³. Fig. 9 shows the solution-oil 500 cSt interface for the different flowrates. It can be seen that no oil entrainment occurred even when the immersion depth was reduced to 200 mm with the highest flowrate of 150 L/minute. Based on this analysis, it is expected that in the same operating conditions there will be no entrainment in the industrial equipment since the density difference between slag and steel is higher than between the solution and the oil. This may make it possible to work with a smaller immersion depth, which is important for the development of the solidified shell. The computational analyses also presented similar results. Fig. 10 shows the NaCl-oil 500 cSt interface obtained by CFD, in which it can be noticed that there is no significant oscillation at the interface.

Regarding the free surface oscillation intensity, the highest values are found in the region near the flange opposite the nozzle, just around the corners (position 6). This is the region in which the first eye opening was observed. When the viscosity of the oil is reduced, there is an increase in the fluctuation intensity (Fig. 11a and 11b). The increase of the density of the fluid used to simulate the steel and the depth of immersion of the SEN reduce the intensity of oscillation on the free surface (Fig. 11c and 11d).

Inclusion Removal — Fig. 12 shows the influence of the slope of the exit ports on the percentage of floated inclusions. It is observed that increasing the inclination of the ports increases the number of inclusions floated. This may
be related to the reduction in jet inclination, a fact that would facilitate inclusions to reach the surface of the fluid pool in the meniscus region. Gabriel et al.\(^1\) observed that the +5° nozzle produced a smaller jet slope.

Increasing the casting speed results in a reduction in the percentage of floated inclusions. Zhang et al.\(^7\) performed tests on beam blank mold with two straight SENs at a casting speed of 1 m/minute, and found inclusions removal rates of 25% and 27% for nozzle internal diameter of 30 mm and 40 mm, respectively.

Onishi et al.\(^6\) observed that the use of nozzles with lateral outlets increases the efficiency in the removal of inclusions in beam blank mold.

### Conclusions

Using physical and mathematical modeling, analysis of the fluid flow inside a beam blank mold fed with only one SEN with three lateral ports had the following results:

**Figures 10 and 11**

Comparison of the free surface float intensity for the analyzed flows and immersions: water-oil 500 cSt (a), water-oil 200 cSt (b), and saline solution-oil 500 cSt (c) and (d).
The authors would like to thank FAPEMIG and CAPES of Brazil for financial support for this research project.

Figure 12

<table>
<thead>
<tr>
<th>Flowrate (L/min)</th>
<th>Inclusion Removal %</th>
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<tbody>
<tr>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>125</td>
<td>20</td>
</tr>
<tr>
<td>150</td>
<td>25</td>
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- Fluid recirculation in the mold is slow due to the spreading of the liquid jet in the opposite flange.
- The jet of liquid from the smaller ports mainly feeds the upper region of the flange where the submerged nozzle is positioned. This jet impinges on the surface of the flange.
- The velocity of the liquid jet at the outlet of the lower diameter ports of the SEN corresponds to approximately 90% of the velocity in the larger-diameter port. However, the gradient ahead of the smaller-diameter ports is much larger.
- Increasing the casting speed implies an increase in the intensity of superficial oscillation in the meniscus region.
- The inclusion removal rate for this submerged nozzle model is higher than that found for beam blank molds poured with two tubular submersible nozzles.
- Reducing the casting speed and increasing the angle of inclination of the outlet ports of the submerged nozzle increases the rate of removal of inclusions.
- Reducing the viscosity of the oil results in increased drag of the same in case of higher casting speed.
- The increase in density of the steel emulsifying liquid from 1,000 kg/m³ to 1,170 kg/m³ resulted in a significant change in interfacial behavior.

Acknowledgments

The authors would like to thank FAPEMIG and CAPES of Brazil for financial support for this research project.

References