Continuous Casting - Comparison between Numerical Simulation and Experimental Measurement

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Abstract

We investigate experimentally, by means of both physical and numerical models, the behaviour of the internal flow of a mercury model, which shape is scaled to the shape of a continuous caster subjected to a continuous magnetic field.

Introduction

In continuous casting of steel, a ladle of molten steel is poured in a tundish, which level is kept constant. Then the molten metal flows through a submerged nozzle in a water-cooled mould: the caster. In the mould, steel solidifies in its one shell. Then, by means of rolls, the slab is bended horizontally to be cut and afterwards is taken away in order to be rolled. In order to control the flow in the mould and therefore the solidification of the steel, steelmakers tested various configurations of electromagnetic devices. The physical idea is the following. Moving in continuous (DC) magnetic field, the molten steel develops induced currents, generating a force which is generally directed against the flow.

The new topography of the flow in the EMBR (ElectroMagnetic BRake) configuration has been investigated by Harada et al. [1994][1] bringing to light the possible generation by the magnetic field of a counter flow around the jet.

To investigate such a flow, velocity measurements are performed in the mercury model in an EMBR geometry, using an ultrasonic velocimeter[3]. Numerical simulations are performed using the FLUENT6 code in which a MHD modulus and a specific turbulent model [4] were added.

1. Experimental set-up

The experimental arrangement is a hydraulic circuit working with mercury (density $\rho = 13.6 \times 10^3 kg/m^3$, electrical conductivity $\sigma = 10^6 (\Omega \cdot m)^{-1}$). The mercury flow rate is fixed to 22.4l/mn. The experimental cell (figure 1) is a Plexiglas rectangular tank of $l=480 mm$ width and $e=80 mm$ thick. A nozzle exhibiting two symmetrical ports feeds it. The immersion of the nozzle is 70 mm. The ports diameter is 22.4 mm and their angle is 20°. The DC magnetic field is generated by an electromagnetic coil with two polar pieces of vertical cross section 520mm x 20mm (width x high). The magnetic field exhibits a horizontal mean direction. Its maximum characteristic value measured in the air gap in the middle point of the polar pieces is: 0.465T. The axis of the ultrasonic probe is placed in the meridian plane of the ingot.
2. Experimental results

Figure 2 is an illustration of the experimental results. The presence of the magnetic field leads to a reorganisation of the flow.

- Near the port of the nozzle: the trace of the feeding jet is exhibited; the magnetic field of characteristic intensity $B_{\text{max}}/2$, leads to an acceleration of the liquid, when for the $B_{\text{max}}$ value the flow is bracked. With magnetic field, the jet is lower than without.
- in the middle of the ingot, the same behaviour is observed concerning the magnitude of the jet, but its vertical position is almost independent of the magnetic field
- near the small face, the direction of the flow is reversed by the magnetic field: the liquid goes upward when a magnetic field is applied, whether it was going downwards without magnetic field.

3. Numerical model

With the help of user-defined routines, the commercial software FLUENT6 has been extended to take into account Magneto-Hydro-Dynamic effects on the fluid flow for DC magnetic fields at low magnetic Reynolds number ($\mu \sigma BL \ll 1$, where $\mu$ is permeability of the fluid, $\sigma$ its conductivity, $B$ the magnetic field and $L$ a characteristic scale). In this case $B$ is not influenced by the flow field: it has been imposed here from measurements in the magnet.
without mercury. The additional routines implement the resolution of a Poisson equation for the electrical potential \( \phi \) and the calculation of the electrical current \( j \):

\[
eqn.1 \quad 0 = \nabla \cdot (\sigma \nabla \phi) - \nabla \cdot (\sigma \mathbf{U} \times \mathbf{B})
\]

with \( \phi = \phi_0 \) (imposed) on some boundaries, and \( \frac{\partial \phi}{\partial n} = (\mathbf{U} \times \mathbf{B}) \cdot \mathbf{n} \) on the others.

\[
eqn.2 \quad j = \sigma (-\nabla \phi + \mathbf{U} \times \mathbf{B})
\]

The partial derivative equation ensures the conservation of the current density \( j \), whereas the Neumann boundary condition ensures that there is no normal current across the corresponding boundaries (here, all the walls are insulating, and the bottom boundary is considered far enough to be without current). The Dirichlet condition serves as a potential reference and is imposed here at the fluid inlet (with \( \phi_0 = 0 \)).

The fluid flow is calculated using classical Reynolds-Averaged momentum equations with a Lorentz force \( \mathbf{f} = \mathbf{j} \times \mathbf{B} \), and the continuity equation \( \text{div} \mathbf{U} = 0 \). We use the k-\( \varepsilon \)-\( \alpha \) turbulence model described in [4], which is essentially a k-\( \varepsilon \) model modified to take into account the anisotropy induced by the magnetic field. The new variable \( \alpha \), defined from second-order correlations, measures the anisotropy of the fluctuation field. Its value is 1/3 for 3D isotropic turbulence and tends towards 0 when the turbulence is highly elongated along the magnetic field lines (3D fluctuations invariant along \( \mathbf{B} \), improperly called “2D turbulence”).

The mercury model and the inner part of the nozzle are meshed together with a total of 180000 cells, refined near the inner walls of the nozzle and the small faces of the container. The nozzle is extended 300mm above the mercury surface (~10 inner diameters), and a uniform velocity corresponding to the real flow rate is imposed at inlet. All the walls and the surface are electrically insulating (they are in plexiglass in the experiment, except the lower part of the container in stainless steel, but at this point the electrical potential is weak). The surface is flat, electrically insulating and without friction. The outlet (bottom part of the container) is at constant pressure.

A stationary simulation in the presence of DC magnetic field \( (\mathbf{B}_y(x,z) \text{ from measurements at } B_{\text{max}}) \) has been performed and compared to a stationary simulation without magnetic field. All the models are the same in these two calculations.

4. Numerical results

The velocity field inside a slab caster is very complicated when no magnetic field is applied. The jets coming out of the ports can impact the small faces as in figure 3, and create one recirculation in the upper part on each side of the nozzle (double-roll regime). In other conditions, the jet kinetic energy can be dissipated before the small face, so that the fluid coming out of the nozzle raises up to the surface and circulates towards the small faces, then down along the small faces (single roll regime). The flow can oscillate between these regimes and the steady solution, when it exists, is not exactly symmetrical, as can be seen on figure 3.

When the magnetic field is applied, the flow becomes two-dimensional, i.e. it is almost invariant along the thickness (figure 4). The upper recirculation is damped, and therefore the flow at the free surface is weaker: the mean absolute velocity at the surface is 7.1 cm/s whereas it was 13.3 cm/s without magnetic field.
figure 3 – Velocity field at B=0: horizontal planes z=0(surface) & z=0.2m(below the ports); vertical planes near small faces (x=± 0.24m). Vectors are not drawn where |V|>0.5m/s

figure 4 – Velocity field at B_{max}: horizontal planes z=0(surface) & 0.2m(below the ports); vertical planes near small faces (x=± 0.24m). Vectors are not drawn where |V|>0.5m/s

figure 5 – Velocity in the midplane (y=0) at B=0. Vectors are not drawn where |V|>0.5m/s

figure 6 – Velocity in the midplane (y=0) at B_{max}. Vectors are not drawn where |V|>0.5m/s
The non-symmetrical behaviour can also be noticed on figure 5 and 6: the upper recirculation on the right side of the figure is smaller than the other one. Comparing these two figures, it can be seen that the magnetic field causes the jets to raise, what was seen on the experimental data. This can be attributed to the vanishing vertical momentum of the upper recirculation (near the nozzle) when the magnetic field is applied, whereas this recirculation pushes the jets towards the bottom when there is no magnetic field.

![Graph](image)

**Figure 7** – vertical velocity (>0 downwards) at |x|=4,8,20 cm in the midplane (y=0) at B=0.

The vertical velocity distribution is plotted in figure 7 for B=0, on lines corresponding to the measurement locations, together with results on symmetrical lines (on the other side of the nozzle). The dissymmetry is visible and gives an order of the uncertainty on numerical results. However, the variation of these profiles can be used to analyse the effect of the magnetic field: the curves obtained for B=0 and B_{max} are compared in figure 8 to the

![Graph](image)

**Figure 8** – numerical and experimental results at x=4cm(on the left) and x=20cm(on the right) for B=0(first line) & B_{max}(second line)
experimental data, showing that the effect of the magnetic field is qualitatively rendered by
the numerical model. In particular, the jet location near the nozzle is raised by the magnetic
field, and the velocity along small faces is affected in the same manner, i.e. the zone of
uniform downwards velocity along the small face is extended towards the surface.

Quantitative comparison of calculations and experiments can hardly be done because
the real geometry of the nozzle was not taken into account in the calculation, due to meshing
problems and lack of time. The qualitative agreement is promising for further calculations,
that will include more precisely the experimental conditions.

Conclusion

The mercury model of a slab caster, existing at the EPM laboratory, is able to provide
detailed information on the flow field and its modification by magnetic fields. A numerical
model has been developed to describe such flow and the associated MHD effects, including a
special non-isotropic turbulence model described in [4]. The first numerical results are
promising, and can be further improved by a better description of the experimental geometry,
and by the adjunction of special laws of the wall as described in [5]

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