Flow measurements in a continuous casting model using a low temperature liquid metal

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This paper describes experimental investigations of flow structures and related transport processes in the continuous casting mould under the influence of an external DC magnetic field at laboratory scale. Experimental results will be presented here which have been obtained using a physical model (mini-LIMMCAST) operating with the low melting point alloy GaInSn. The Ultrasound-Doppler-Velocimetry (UDV) was applied for measurements of the flow pattern in the mould. An array of ten transducers was attached to the narrow mould side, measuring the horizontal velocities in the region around the liquid metal jet. Further, with two sensors on the mould top, vertical velocities were recorded successively in the whole mould width. According to the concept of the electromagnetic brake the impact of a DC magnetic field on the outlet flow from the Submerged Entry Nozzle (SEN) has been studied up to Hartmann numbers of about 400. The effect of the magnetic field on the flow structure turned out to be manifold and rather complex. The magnetic field causes a deflection of the jet, at which the respective exit angle from the nozzle ports becomes more flat. Thus, both the penetration depth of the discharging flow into the lower part of the mould and the impinging velocity of the jet onto the side wall are reduced. A significant return flow occurs in the adjacent regions of the jet. Specific vortices are formed with axes being aligned with the magnetic field direction. Such vortical structures are typical for quasi-two-dimensional magneto-hydrodynamic (MHD) flows. The flow measurements do not manifest a general braking effect which would be expected as an overall damping of the flow velocity and the related fluctuations all-over the mould volume. Variations of the wall conductivity showed a striking impact on the resulting flow structures.

Keywords: Continuous steel casting, Liquid metal model, electromagnetic brake (EMBr)

1 INTRODUCTION

Magnetic fields are established in the continuous casting process for years for the purpose of flow control [1]. However, the turbulent flow of molten steel in a continuous casting mould under the influence of a DC magnetic field appears to be very complex and is not sufficiently understood yet. The impact of an electromagnetic brake (EMBR) on the mould flow was addressed by many numerical studies considering various magnetic field configurations or examining the influence of variations of different casting parameters on the magnetic field effect. However, a serious deficit of experimental data is noticed which could be employed for numerical code validations. Model experiments using low melting point alloys (e.g. [2]) are an important tool to provide a substantial database for the validation of respective numerical simulations [3], [4]. The main value of “cold” laboratory experiments consists in the capabilities to obtain quantitative flow measurements with a reasonable spatial and temporal resolution.

2 EXPERIMENTAL SET-UP

The continuous casting process was studied by means of the small-scale model facility mini-LIMMCAST [5]. The eutectic GaInSn-alloy was used as model fluid which is liquid at room temperature. The experimental mockup contains a tundish in the shape of a circular vessel made of stainless steel. A submerged entry nozzle (SEN) with an inner diameter of 10 mm was attached at the bottom of the cylinder. The liquid metal was poured through the SEN into a rectangular mould made of acrylic glass with a cross section of 140 x 35 mm^2 and a length of about 300 mm. Fig. 1 shows the setup of the mini-LIMMCAST facility.

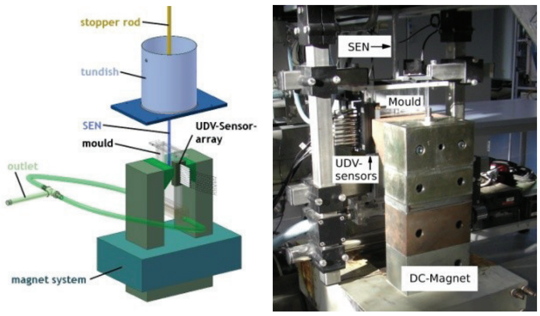


Figure 1: Sketch and photograph of the experimental setup mini-LIMMCAST showing the installed magnetic system and the ultrasonic sensors for flow measurements.

The experiments were conducted with a ruler type magnetic brake, which covers the whole width of the mould. The magnet was positioned in a height, where the liquid jet discharges from of the nozzle ports. Three cases were considered within this paper: a reference measurement without magnetic field and the application of the magnet field with either isolating or electrically conducting walls of the mould. To realize the situation of the conducting walls in the acrylic glass mould, thin brass plates were attached to the inner wide side of the mould. The narrow walls had to be kept free in order to enable the undisturbed application of the ultrasonic measurement technique. The thickness of the brass plates was chosen in such a way, that the wall conductance ratio C_W corresponds to the real case of the solidified steel strand in the continuous casting mould [6]. Further details about the experimental equipment can also be found in [6].

The liquid metal flow in the mould was measured by means of the Ultrasonic Doppler Velocimetry (UDV). This method is capable to measure the fluid flow around the discharging jet from the nozzle ports with a reasonable temporal and spatial resolution [6]. The UDV-method was applied non-invasively through the narrow mould wall. Ten transducers were mounted having a distance in between of 10 mm for detecting the horizontal velocities in the region of the nozzle ports.

In further experiments one sensor was placed on the top of the mould top at each side of the nozzle, to capture the vertical velocities. In contrast to the horizontal measurement through the wall, these sensors are dipped into the liquid metal. The sensors were shifted in steps of 7 mm yielding in 8 measuring lines.

Another UDV configuration consists of two ultrasonic transducers, placed opposite at the narrow side walls. The height was chosen in such a way, that the measuring line crosses the liquid metal jet.

The DOP2000 velocimeter (Signal Processing, Lausanne, Switzerland) was used in combination with 4 MHz ultrasonic transducers (TR0405LS, same producer). Velocity profiles delivered by the transducers were recorded in multiplexer mode.

3 RESULTS

3.1 Vertical Flow Field

The averaged vertical mould flow in the mid plane is depicted in Fig. 2. The magnitude of the velocity is plotted according to a colour scale (red corresponds to a downward flow meanwhile blue represents an upward flow). The position of the DC-magnet is indicated by the horizontal green lines. These lines represent the upper and lower edges of the pole faces.

(a)

(b)

(c)

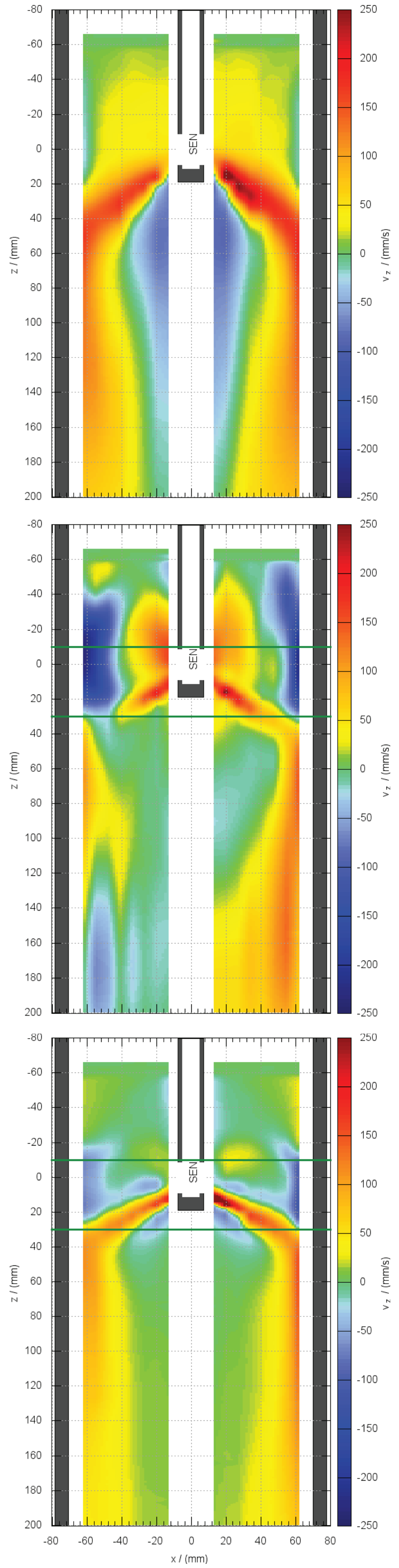


Figure 2: Mean vertical velocity without field (a); with applied DC-magnetic field between the horizontal green lines for isolating walls (b) and conducting walls(c).

The typical double roll flow pattern, which is usually the desired flow pattern, can be observed in the situation without applied magnetic field in the uppermost plot. The jet is exiting from the ports and is directed towards the narrow mould wall, where it splits into an upper and lower roll.

The flow undergoes a tremendous change as soon as a DC-magnetic field is applied. The mean flow becomes clearly asymmetric between the left and right mould sides with electrically isolating walls. An additional small roll is created just below free surface.

The installation of conducting walls at the wide sides of the mould results in another flow regime. A small roll is created just below and above the jet and near the nozzle, resulting in a return flow in the vicinity of the jet. The roll below the free surface is still present, as in the case with isolating walls. These features are related to the transition from a double roll structure to a multi roll pattern in the mould. The new flow structure is caused by the alignment of eddies parallel to the magnetic field direction and the creation of return flows close to a free liquid metal jet in the case of a DC-magnetic field [7]. In the lower parts of the mould a plug flow is generated showing rather low velocity values.

The application of a DC-magnetic field at the marked position obviously destroys the double roll flow pattern. Further eddies were created with isolated walls as well as with conducting walls. The zone of the jet appears rather confined and a perceptible reduction of the flow intensity in the jet cannot be recognized.

3.2 Two-dimensional velocity vectors

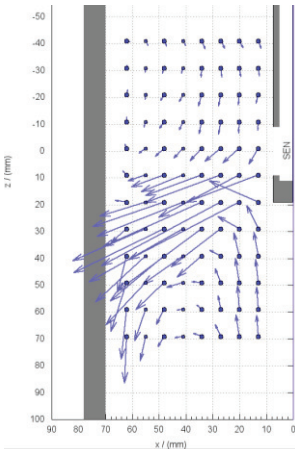
The combination of horizontal and vertical measurements allows for the calculation of velocity vectors at the intersection points. The result of the 80 intersection points is depicted in Fig. 3, again for all three investigated conditions. The location of the DC-magnets pole faces is highlighted in green.

The jet emanating from the SEN and the downward flow near the narrow wall is clearly visible in all three cases. The return flows of the lower and the upper roll can be well observed in the reference case without magnetic field. The upward stream of the upper roll is concentrated close to the narrow wall and merely adequately caught by the measurement.

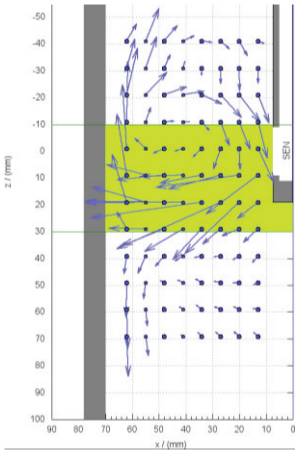
The application of a static magnetic field enforces a recirculation zone close above the jet under isolating conditions. Actually, velocities are increased in this region, contrary to the usual expectations with respect to the action of an electromagnetic brake.

The placement of conducting walls damps the recirculation zone above the jet. A further recirculation zone below the jet becomes visible. These recirculation zones can also be identified in Fig. 2(c) as blue stripes directly beside the liquid metal jet.

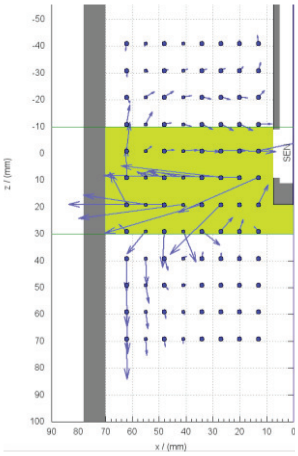
In addition, the exit angle of the jet was flattened and the impinging point was shifted upwards in presence of a magnetic field.



(a)



(b)



(c)

Figure 3: Velocity vectors in the crossing points of vertical and horizontal ultrasonic measurement: without field (a); with applied DC field for isolating walls (b) and conducting walls(c).

3.3 Time dependent flow

The time dependent flow profiles of the oppositely placed ultrasonic transducers can be viewed in Fig. 4. The horizontal velocity is plotted over the measuring depth and time. Positive values (red colours) indicates a flow towards the middle of the mould, meanwhile negative velocities (blue colours) represent a flow towards the narrow walls. The crossing of the jet trough the measuring line can be observed very well in all diagrams.

The impact of the wall conductivity becomes especially manifested by analysing the transient behaviour of the mould flow. The magnetic field triggered low frequent flow oscillations in case of isolating mould walls. The jet is disappearing from the measuring line temporarily and a reversal of flow direction can be detected (Fig. 4(b)). This is related to an up and down bending of the jet [6] and the creation of recirculation zones, as already described before. The oscillation seems to be linked between the two mould halves to appear opposite in phase, with a prominent jet on the one side and a damped jet, or even flow reversal, on the other side. The unequal temporal distribution of the flow regimes between the mould halves is the reason for the asymmetry in the averaged flow field, like in Fig. 2(b).

The low-frequent oscillations are damped, when the conducting brass plates have been inserted into the acrylic glass mould (Fig. 4(c)). In addition the liquid metal jet was constricted concerning his extension. A change in flow direction was observed near the SEN, which is again a sign for the creation of recirculation zones.

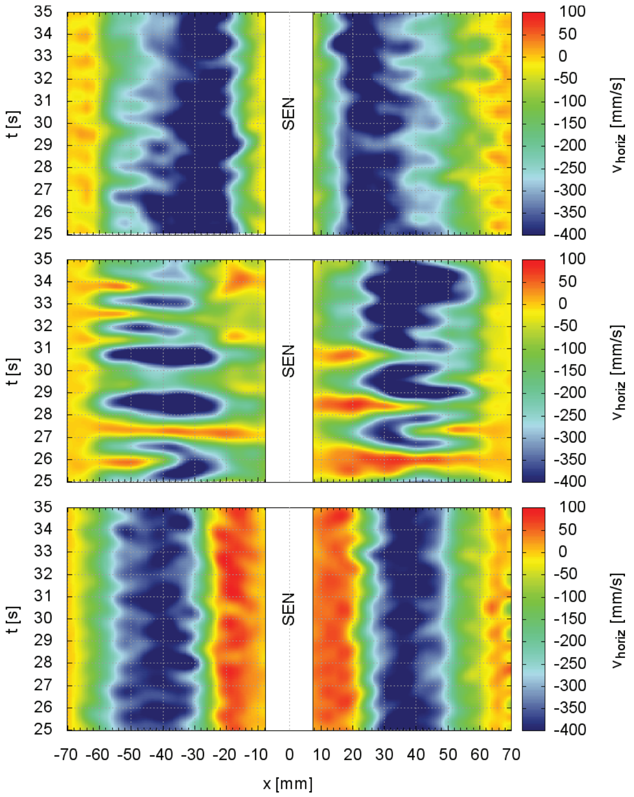


Figure 4: Time series of the horizontal velocity in the jet region (z=+19mm) without field (a); with applied DC-magnetic field and isolating walls (b) and conducting walls(c).

SUMMARY

The liquid metal models proved to be an appropriate and important tool for the investigation of flow phenomena occurring in the continuous casting process. In particular, the application of the Ultrasonic Doppler Velocimetry method allows for the observation of global flow structures, profiles of the local velocity and flow fluctuations. Moreover, the combination of such liquid metal models and measurement techniques are inevitable for the analysis of the magnetic field effects on the flow behaviour.

The applied DC-magnetic field causes strong modifications of the flow structure in the continuous casting mould. An overall damping of the mean flow was not observed in our experiments. The magnetic field may reduce the flow locally, but contrary to that the flow is accelerated at other locations or inversions of the flow direction occur. Another finding is that a steady magnetic field may give rise to flow oscillations in the mould.

The measurements illustrated the importance of the electrical boundary conditions. The electrical conductivity of the mould wall had a dramatic influence on the temporal behaviour of the flow. This feature has to be considered accurately in numerical modelling.

The experimental results provide a valuable database for a validation of numerical models and enable a better understanding of the mould flow and the related phenomena.

ACKNOWLEDGEMENT

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