Ultrasonic flow measurements in a low temperature liquid metal model of the continuous steel casting process

Klaus Timmel, V. Galindo, X. Miao, Sven Eckert and Gunter Gerbeth

MHD Department, Forschungszentrum Dresden-Rossendorf, P.O. Box 5101119, 01314-Dresden, Germany

Experiments have been performed at room temperature using a small-scale experimental set-up with the eutectic alloy GaInSn. The ultrasound Doppler method was applied for measuring the fluid velocity in the mould. An arrangement of 10 transducers was used to determine a two-dimensional distribution of the horizontal velocity component. 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. Our measurements deliver an authentic reproduction of the location and extension of the emergent jet and disclose the temporal behaviour of the flow inside the jet as well as in the recirculating zones. An important result of our study was the feature that a static magnetic field may give rise to non-steady, non-isotropic large-scale flow perturbations. The combination of cold liquid metal models and the ultrasound Doppler method as a powerful flow measuring technique in liquid metals appears as an important tool for an experimental investigation of the mould flow and provides valuable experimental data for the validation of numerical flow simulations.

Keywords: Ultrasound Doppler Method, liquid metal, continuous casting, mould flow, magnetic field

1 INTRODUCTION

Fluid flow in the mould cavity of the continuous casting process can be controlled by the application of magnetic fields. For instance, AC magnetic fields are employed as electromagnetic stirrers (EMS) for a homogenization of the melt and a promotion of the double-roll flow pattern in the mould, which is supposed to diminish many slab defects such as the entrapment of bubbles and non-metallic inclusions and to improve therefore the quality of the solidified steel strand [1, 2]. Another approach to ensure high quality slabs under high casting speeds is the utilisation of DC magnetic fields as electromagnetic brake (EMBR) [2, 3]. The DC field should directly reduce the velocity in the mould region and suppress recirculating flows which arise from the high intensity jet flow poured into the mould from the submerged entry nozzle (SEN). The EMBR technology had already been invented in the 1980’s and firstly applied to continuous casting plants in Japan and Sweden [4]. On one hand, second and third generation of EMBR’s are brought into industrial use meanwhile (see for instance [5]). On the other hand, the electromagnetic braking effect in highly turbulent, complex flow configurations is not fully understood until now. For instance, an experimental study has been published recently, which was concerned with the influence of a DC magnetic field on the liquid metal flow driven by rising gas bubbles inside a cylindrical column [6, 7]. A global damping of the flow was observed in the case of a vertical field aligned parallel to the main direction of the bubble motion. However, the application of a horizontal magnetic field causes intensive, non-steady and non-isotropic flow structures. This effect should be taken into account for a deliberate design of electromagnetic brakes for flow stabilisation.

A multitude of numerical studies have been carried out considering different magnetic field configurations [5, 8, 9] for the continuous steel casting, but the reliability of the numerical results is insufficiently confirmed by accompanying experimental activities. Experimental studies on industrial scale with hot metallic melts ($T \geq 600°C$) may require formidable effort and expense. The main drawback is the extremely limited availability of measuring techniques which are able to provide reliable quantitative data from the flow being relevant for numerical code validations. Cost-saving model experiments using low melting point metallic melts permit detailed investigations of the flow structure and related problems with a high grade of flexibility. The application of the Ultrasound Doppler Method enables for measurements of the flow field in opaque metallic liquids. Experiments at room temperature are possible using the ternary alloy GaInSn. That provides the possibility to avoid the usage of mercury for reasons of safety.

2 EXPERIMENTAL SETUP

Fig. 1 shows the small-scale setup, which is operated with the eutectic alloy GaInSn as model fluid. A stainless steel cylinder serves as the tundish which contains about 3.5 l of the GaInSn alloy. The melt is discharged through a Plexiglas tube as SEN with an inner diameter of 10 mm into the mould with a rectangular cross section of $140 \times 35\ mm^2$ also made of Plexiglas. Two nozzle ports are situated about 80 mm below the free surface in the mould. From the mould the liquid metal flows through a U-bend channel into a storage vessel. The vertical position of the vessel inlet controls the free surface level in the mould. An electromagnetic pump conveys the melt from the vessel back into the tundish. The experiments presented here were performed in a discontinuous mode, i.e. after filling the tundish with the melt the stopper rod was lifted to drain the fluid into the mould. During this process the liquid level of both the tundish and the mould were monitored using a laser distance sensor. The liquid flow rate has been derived from the descent of the surface level in the tundish.

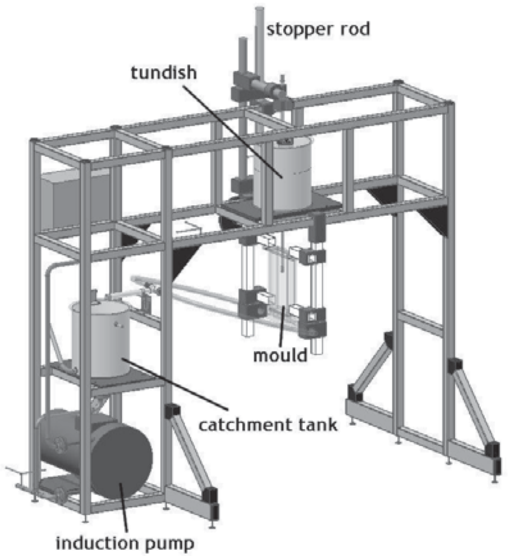


Figure 1: 3D-scheme of the small-scale GaInSn model.

A DC magnet supplies a transverse magnetic field. Measurements of the field strength have shown that the field is homogenous between the pole faces within a tolerance of about 5%. The pole faces of the magnet cover the wide side of the mould completely. The vertical extension of the pole shoes is 40 mm, whereas the position of the upper edge of the pole faces coincides with the nozzle outlet.

The Ultrasound Doppler Method was used for measuring the fluid velocity in the mould. This method is based on the pulse-echo technique and delivers instantaneous profiles of the local velocity along the ultrasonic beam and can be applied to attain experimental data from a bulk flow in opaque liquids [10]. In the last twenty years the ultrasound Doppler technique became an accepted method for flow investigations in various liquid metals (see for instance [6, 11, 12]). In the present study we have applied the DOP2000 velocimeter (model 2125, Signal Processing SA). A line array of ten 4MHz transducers (TR0405LS, acoustic active diameter 5 mm) was assembled with a distance of 10 mm between two adjacent sensors. As shown in Fig. 2, this array was vertically arranged at the outer wall of the mould aligned with the midsection of the narrow mould face. The internal multiplexer of the DOP2000 has been used for a sequential acquisition of data from all sensors with an overall scan rate of 5 Hz. The midpoint of the SEN at the height of the nozzle ports has been chosen as point of origin for our coordinate system.

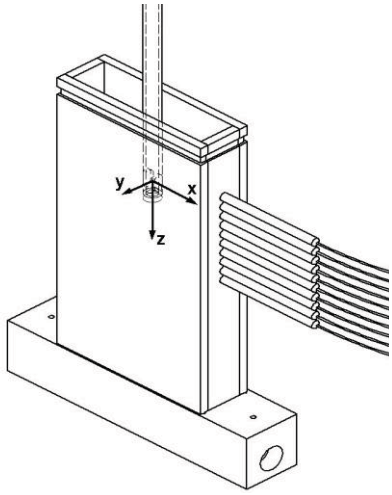


Figure 2: Mould with submerged entry nozzle (SEN) and the linear arrangement of 10 ultrasonic transducers for flow measurements along the vertical midsection.

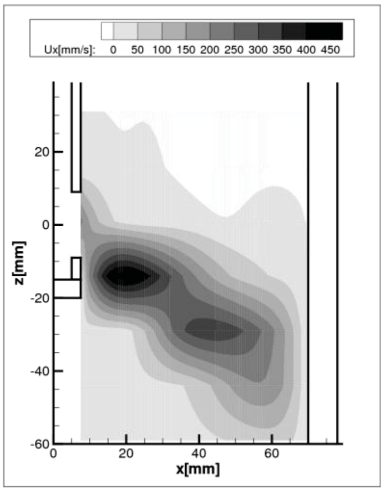
3 RESULTS

3.1 Numerical calculations

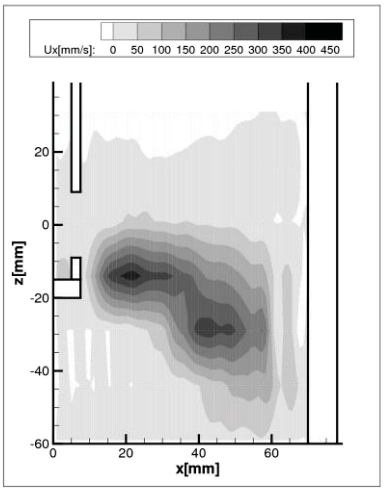
The open source tool OpenFOAM® was used to simulate the fluid flow in the mould cavity. The Navier-Stokes equation was solved numerically in a steady state incompressible regime. The flow solver provides several turbulence models such as the SST-k - ω model, which was used in the calculations presented here. As boundary condition a turbulent velocity profile with a given flow rate value was imposed at the nozzle inlet. The liquid metal free surface in the mold was modeled as a stress-free interface with a zero vertical velocity component. The velocities measured by the Ultrasound Doppler method represent a mean value taken over the lateral extension of the ultrasonic beam. Therefore, for comparing the calculated velocity $u_x(x,z)$ with the experiment it was necessary to average the numerically obtained velocity profiles over a circular cross section with a diameter of 5 mm.

3.2 Flow measurements

The discharging flow from the nozzle ports impinges on the narrow face of the mould where it forms two vortices in the upper and lower mould region. Profiles of the horizontal velocity were recorded at the midsection along the wide side of the mould between the side wall and the submerged entry nozzle. The comparison between the results obtained from the numerical calculations and the flow measurements in Fig. 3 shows a very good agreement. The simulations provide an authentic reproduction of the location and extension of the emergent jet and the magnitude of the flow velocity as well.



(a)

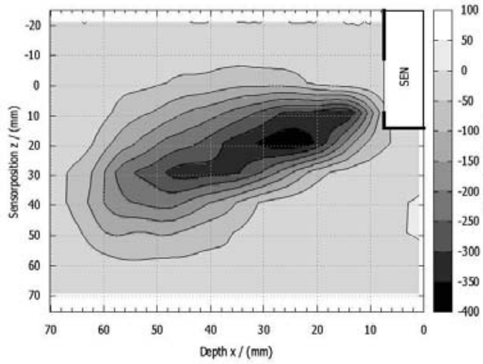


(b)

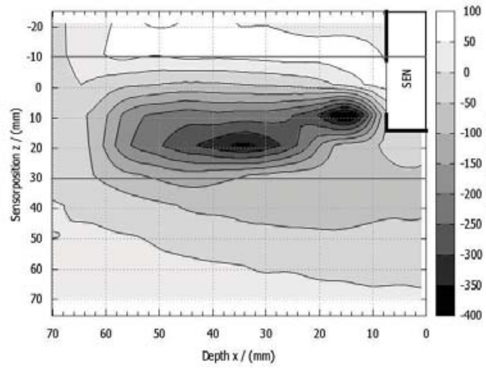
Figure 3: Time-averaged, horizontal flow at the nozzle outlet: (a) numerical results, (b) flow measurements.

Fig. 4 contains time-averaged plots showing the flow measurements of the horizontal velocity field for the case without magnetic field and a transverse field of 0.31 T, respectively. These two-dimensional plots were obtained by using the line array of ten transducers as described in section 2. The application of the magnetic field provokes the occurrence of a remarkable recirculating flow at the upper part of the nozzle outlet. The inclination angle of the jet becomes flat. The impingement point at the opposite side wall is shifted upwards by about 20 mm. However, the intensity of the velocity within the jet is only slightly reduced.

The arrangement of the ultrasonic transducers has been modified to measure the velocity distribution in the narrow cross section of the mould. Three transducers were positioned at the midsection (y = 0) and at a distance of 13 mm at either side of the central sensor. The vertical position corresponds to the bottom end of the SEN. Fig. 5(a) shows the situation without magnetic field. The maximum of the jet appears approximately at the central point of the measuring plane. Fig. 5(b) represents the case if a magnetic field of 310 mT was applied. Besides a slight reduction of the maximum velocities, the imposition of the magnetic field provokes a broadening of the jet width along the magnetic field lines.



(a)



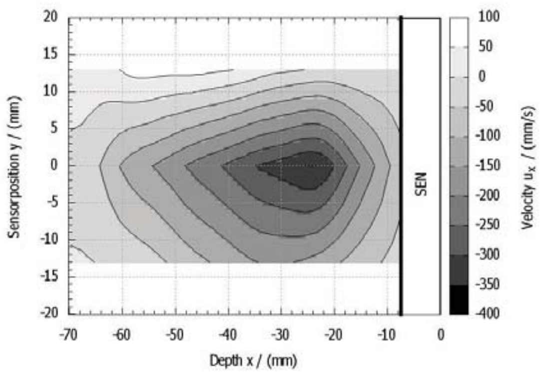
(b)

Figure 4: Flow measurements of the horizontal flow at the nozzle outlet (vertical arrangement of 10 transducers): (a) without magnetic field, (b) B = 0.31 T.

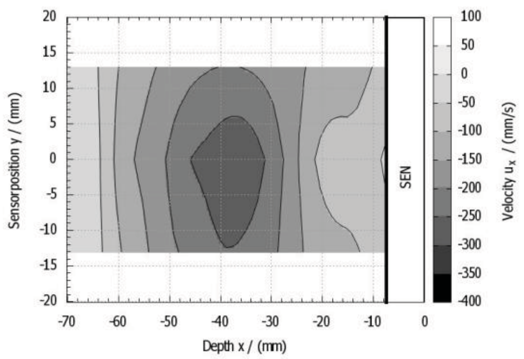
Fig. 6 displays time series of the velocity recorded at a position near the nozzle outlet. The sensor detects a turbulent flow with strong irregular velocity fluctuations if no magnetic field is applied. A slowdown of the velocity fluctuations due to the magnetic field effect cannot be observed. The measurements show large-scale oscillations of the local velocity which probably arise from an alternating up-and downturn of the jet flow.

4 SUMMARY

The application of tailored magnetic fields is the key issue for an effective optimisation of the continuous casting process, but it requires further investigations of the interplay between the mould flow and the magnetic field, in particular experimental data are needed to verify the electromagnetic braking effect and to prove respective numerical predictions.



(a)



(b)

Figure 5: Horizontal flow at the nozzle outlet (horizontal arrangement of 3 transducers): (a) B = 0, (b) B = 0.31 T.

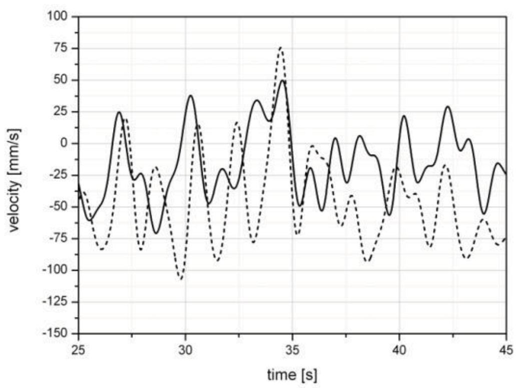


Figure 6: Time series of the horizontal velocity recorded at the position x = 24.5 mm and z = 49 mm for B = 0 (solid line) and B = 310 mT (dashed line).

The generic problem of an initially axisymmetric jet, which is affected by a uniform, transverse magnetic field, was considered by Davidson [13]. The imposed field causes regions of reverse flow on both sides of the central jet. Furthermore, an elongation of the jet cross-section parallel to the field lines occurs. These general features with respect to a reorganization of the flow pattern were also observed in our continuous casting model. An experimental study with respect to a bubble-driven liquid metal flow in a transverse magnetic field has been published recently [6, 7]. An outcome was the feature that a static magnetic field may give rise to non-steady, non-isotropic large-scale flow perturbations. Likewise, the flow measurements presented here did not confirm the expectation of a smooth reduction of the velocity fluctuations at the nozzle outlet due to the magnetic field. This problem requires further investigation, because the concept of an EMBR in the continuous casting process relies on a reliable damping effect of the applied magnetic field. The availability of liquid metal cold models appears as an important tool for an experimental investigation of such open questions. Moreover, these model experiments will provide valuable experimental data for the validation of numerical flow simulations.

Acknowledgement

The research is supported by the Deutsche Forschungsgemeinschaft (DFG) in form of the SFB 609 “Electromagnetic Flow Control in Metallurgy, Crystal Growth and Electrochemistry”.

REFERENCES

[1] Okazawa K, Toh T, Fukuda J, Kawase T, Toki M: Fluid flow in a continuous casting mold driven by linear induction motors, ISIJ Int. 41 (2001), 851-858.
[2] Takeuchi S, Kubota J, Miki Y, Okuda H, Shirayama A: Recent trend of molten steel flow control technology in a continuous casting mold by electromagnetic force, 4th Int. Conference on Electromagnetic Processing of Materials (2003), Lyon (France), 145-150.
[3] Toh T, Takeuchi E, Matsumiya T: Recent advances in MHD applications to steelmaking processes, 5th Int. Conference on Electromagnetic Processing of Materials (2006), Sendai (Japan), 21-25.
[4] Nagai J, Kojima S, Suzuki KI, Kollberg S: Steel flow control in a high-speed continuous slab caster using an electromagnetic brake, Iron Steel Eng. 61 (1984), 41-47.
[5] Bal D, Brockhoff J, Damen W, Peeters T: Numerical modeling of an FC-II mould in a vertical bending continuous caster, 5th Int. Conference on Electromagnetic Processing of Materials (2006), Sendai (Japan), 108-113.
[6] Zhang C, Eckert S, Gerbeth G: The flow structure of a bubble-driven liquid metal jet in a horizontal magnetic field, J. Fluid Mech. 575 (2007), 57-82.
[7] Zhang C, Eckert S, Gerbeth G: Modification of bubble-driven liquid metal flows under the influence of a DC magnetic field, ISIJ Int. 47 (2007), 795-801.
[8] Takatani K, Nakai K, Kasai N, Watanabe T, Nakajima H: Analysis of heat transfer and fluid flow in the continuous casting mold with electromagnetic brake, ISIJ Int. 29 (1989), 1063-1068.
[9] Cukierski K, Thomas BG: Flow control with local electromagnetic braking in continuous casting of steel slabs, Metall. Mater. Trans. 39B (2008), 94-107.
[10] Takeda Y: Development of an ultrasound velocity profile monitor, Nucl. Eng. Design 126 (1991), 277-284.
[11] Takeda Y, Kikura H: Flow mapping of the mercury flow, Exp. Fluids 32 (2002), 161-169.
[12] Eckert S, Gerbeth G, Melnikov VI: Velocity measurements at high temperatures by ultrasound Doppler velocimetry using an acoustic wave guide, Exp. Fluids 35 (2003), 381-388.
[13] Davidson PA: Magnetic damping of jets and vortices, J. Fluid Mech. 299 (1995), 153-186.