Experimental modelling of continuous casting of steel in slab moulds using low melting liquid metals

K. Timmel, T. Wondrak and S. Eckert

HZDR, Bautzner Landstraße 400, 01328 Dresden, Germany

Corresponding author: k.timmel@hzdr.de

Abstract
Electromagnetic actuators are widely used in industry for contactless control of the steel flow in the continuous casting process. However, a real control of the flow structure by those actuators is a challenging task due to the lack of flow monitoring devices. Even a satisfying non real-time characterisation of the melt flow from plant measurements is missing. Beside numerical simulations, only a very few spatially and temporally limited measurements in liquid steel are available to investigate the actual action of the magnetic fields on the fluid. Therefore, model experiments with low melting point liquid metals are an important tool to investigate the flow structure and related transport processes in the mould of a continuous caster. Their advantage is the availability of a variety of measurement techniques for quantitative flow measurements. The application of the Ultrasonic-Doppler-Velocimetry (UDV) and the Contactless-Inductive-Flow-Tomography (CIFT) allows for a detailed characterization of the mould flow with a reasonable spatial and temporal resolution.

In recent experiments at HZDR, the systematic study on the influence of an electromagnetic brake on the mould flow in a slab caster was continued. The measurements were carried out using a 1:2 scaled model operated with SnBi and a 1:8 scaled model operated with GaInSn, respectively. The melt surface was partly measured by a laser scanner system. In particular, the immersion depth of the submergence entry nozzle (SEN) was varied during the experiments. It became obvious that changes in the mould flow had a strong influence on the free surface of the melt, where strong perturbations can significantly impair the surface quality of the final steel strands. Moreover, effects from the “artificial” clogging of one SEN-port or the injection of Argon gas at the stopper rod were investigated.

Key words: Continuous Casting, Liquid metal models, ultrasonic wave guides

Introduction
The persistent effort to achieve a better product quality and higher productivity of the continuous casting of steel implies the high importance of powerful capabilities to control the flow in tundish and mould, and the initial solidification in the mould. Numerous sophisticated numerical simulations concerned with the metal flow during the casting process need a fundamental experimental validation [1]. The use of water models has the advantage to save expenses and to be able to apply a number of well-proofed measuring methods. However, a generalisation of these results to liquid metal flows has to be considered as questionable because the realistic values of flow parameters (Re, Pr, Gr, Ha, etc.) are difficult to meet. In many cases, for instance liquid metal flows with strong temperature gradients, with an additional gaseous phase or under the influence of electromagnetic fields, the flow phenomena cannot reasonably be modelled by means of water experiments [1].

The application of electromagnetic fields provides a considerable potential to control the fluid flow in the mould and to influence the solidification in the strand. First strategies for EM applications in steel casting were mainly guided by simplified pictures of the magnetic field impact on the global flow field. Many numerical investigations have been reported until now to improve the understanding of the magnetic field influence on the mould flow (see for instance [2-5]). However, the problem has to be considered as challenging because of the complex geometry, the highly turbulent flow, and specific peculiarities occurring in case of MHD turbulence. Obviously, a validation of the numerical predictions by liquid metal experiments is indispensable. However, related experimental studies are rather scarce until now. Several plant trials were carried out [6, 7] to test the efficiencies of electromagnetic brakes in the real casting process. Because of the lack of suitable measuring techniques for liquid steel at 1500 °C such trials can provide only a limited gain of knowledge about the magnetic field effect on the flow. Only rough information might be achieved by visual observations of the surface velocity or by the application of imprecise local mechanical metering devices. First model experiments employing simplified mercury models have been reported [8-11]. For instance, Okazawa et al. [8] used a Vives-type sensor to investigate the effect of an electromagnetic stirrer on the fluid flow in the mercury model. With our work we want to continue the strategy of cold metal models. The main value of such cold metal laboratory experiments consists in the capabilities to obtain quantitative flow measurements with a reasonable spatial and temporal resolution. New techniques for measuring the velocity in liquid metal flows came up during the last decade allowing for a satisfying characterization of flow quantities in the considered temperature range up to 400°C. The main issue of the experimental program at LIMMCAST concerns investigations about the impact of the magnetic field on the flow in the continuous casting process.
Experimental setup

The experimental programme of the LIMMCAST facility at HZDR aims to model the essential features of the flow field in the continuous casting of steel, namely the flow field in the tundish, in the submerged entry nozzle (SEN) and in the mould cavity. Experimental setups were built up for this purpose and two of them will be introduced in this section: the LIMMCAST and the Mini-LIMMCAST facility. The investigations in both setups will be explicitly focused on the behaviour of the isothermal melt flow. Although the two experiments exhibit different scaling in length, the basic geometric features of submerged entry nozzle and mould are the same. The SEN is a bifurcated one with two side opening port openings and the mould represents the geometry of a slab caster, i.e. it has a rectangular cross section. The experimental setups were used to investigate intensely the action of electromagnetic fields on the liquid metal flow. An electromagnetic brake (EMBr) of the ruler type was used in the experimental series presented in this paper, i.e. the pole faces of the magnet covered the whole width of the mould. In principle, it is possible to replace the important parts of the loops in a reasonable amount of time (especially at Mini-LIMMCAST). For example, the action of an electromagnetic stirrer (EMS) on the flow in a round mould at Mini-LIMMCAST can be found in another paper of this proceeding by Schurmann et al.

The bigger experimental facility is called LIMMCAST and an overall view of this facility is shown in Figure 1. All components are made from stainless steel. The low melting point alloy Sn60Bi40 is used as model liquid, whose temperature-dependent material data are reported by Plevachuk et al. [12]. The liquidus temperature of 170°C allows for an operation of the facility in a temperature range between 200 and 350°C. An electromagnetic pump is used for continuously transporting the liquid metal in the experimental loop. The actual mould has a cross section of 500 \( \times \) 100 mm\(^2\) and offers measurement access for Ultrasonic-Doppler-Velocimetry (UDV) from the top by using ultrasonic wave guides and from the narrow side walls using high temperature ultrasonic transducers. This resulted in a well time resolved measurement of the mould flow. Complementary, the entire mould flow can be also observed with the Contactless Inductive Flow Tomography (CIFT) [13].

\[\text{Figure 1: Overview of the LIMMACST facility.} \quad \text{Figure 2: Mini-LIMMCAST with all the main parts.}\]

The second setup is called Mini-LIMMCAST and is illustrated in Figure 2. This setup is been filled with eutectic alloy of GaInSn as model liquid. This alloy is liquid at room temperature and its material properties are reported by Plevachuk et al. [14]. The experiments reported here were conducted in a discontinuous way, i.e. firstly the model tundish was filled by the liquid metal and secondly after opening the stopper rod the model fluid flows just by gravity through the assembly back into the storage tank. The mould was made of acrylic glass and has a rectangular cross section of 140 \( \times \) 35 mm\(^2\). The mould flow was measured with the UDV using up to 10 transducers in multiplexer mode for a well time and spatial resolved flow mapping in the jet region. Standard transducers can be used due to the operation at room temperature. The global flow in the entire mould can be obtained by CIFT [15-16]. The CIFT-technique and some measurement results are presented in a separate paper in this proceeding, e.g. Ratajczak et al.

The effect of the EMBr was investigated at Mini-LIMMCAST under different electrical boundary conditions in the mould. The standard acrylic glass mould denotes an electrically insulating wall. In some experimental series, brass plates were inserted into the mould and attached to the wide mould walls. The brass plates modelled the solidified steel and represent electrically conducting walls. The thickness was chosen in that way, that it satisfies the wall conductance ratio, as introduced in [17]. The LIMMCAST facility with mould walls made of stainless steel always represents electrically conducting boundary conditions.

Experimental results

Previous experiments showed a dramatic influence of a horizontal, static magnetic field on the liquid metal flow in the mould [17]. Low frequency oscillations of the horizontal jet flow were detected as well as a local acceleration of the flow. The jet is deflected upwards by the static magnetic field resulting in a strong upwards flow near the narrow wall. In this paper, the strong upward flow was measured in the vertical velocities by UDV.

Figure 3 is depicting the mean vertical flow in the upper recirculation zone close to the narrow mould wall for different
strengths of the electromagnetic brake. It can be clearly seen, that the upwards flow is greatly increased by the application of the static magnetic field. This is in contrast to the otherwise assumed and simplified action of a static magnetic field as an overall brake on the mould flow. Besides some braking, the magnetic field is reorganizing the flow field and can lead locally even to an acceleration of the flow.

Similar experiments were conducted at Mini-LIMMCAST. Two ultrasonic transducers were mounted symmetrically - one in each mould half - and dipped from top through the free surface into the melt. The mean vertical velocity profile recorded with this configuration along the narrow mould wall is shown in Fig. 4. The splitting of the liquid metal jet in a strong downward stream and an upward stream is clearly recognizable by a change in flow direction of vertical velocity and it is in accordance with common picture of the mould flow as a double roll pattern. The static magnetic field is causing a local increase in the upward velocity which is very obvious in Fig. 4 and in accordance with the findings from LIMMCAST. The feature of increased upward flow was found in related numerical simulations of the mould flow, too [18]. The increase in vertical velocity due to the magnetic field is present for insulating and the conducting case as well. However, the electrical boundary conditions have a strong influence on the temporal behaviour of the jet flow (see [17]).

When the strong upward flow is reaching the free surface, it can affect the shape of the melt surface. This is illustrated in Figure 5. This Figure compares snapshots of the free surface for different boundary conditions. These snapshots show strong differences. The case with EMBr under insulating walls presents the creation of a strong bulge, meanwhile the surface under reference and conducting conditions is rather smooth. Beside the shape, the flow and the magnetic field can also change the temporal and oscillation behaviour of the melt surface.
right mould half. Figure 6(a) is depicting the upward flow of the upper recirculation zone under normal conditions. The blue colour is indicating a melt flow in upwards direction. Figure 6(b) is showing the flow under the condition of artificial clogging of the left nozzle port. The upwards flow close to the narrow mould wall is enforced under this circumstances as the outflow from the nozzle is concentrated on the shown mould half. Additionally, one can see a stronger downward flow for the locations closer to the nozzle.

![Figure 6](image)

**Figure 6:** Vertical mould flow at LIMMCAST under normal conditions (a) and with artificial blocking of the left nozzle port (b). Measurements were performed by ultrasonic transducer with wave guides through the top lid of the mould.

**Conclusions**

For physical modelling of the continuous casting process, it is essential to use liquid metals for conducting the experiments when regarding special effects, e.g. in case of two-phase flows or magnetic fields. To provide an experimental tool for these cases, the experimental facilities of the LIMMCAST-family were built up at HZDR. This paper shortly presented two of these experimental setups.

The experimental setups demanded for an appropriate velocity measurement technique applicable to liquid metals. This technique is the UDV-method. Different kinds of ultrasonic transducers were used in the experiments: standard, high temperature and ultrasonic wave guides. Selected results from each of the different transducer types were presented.

The selected results from velocity measurements showed a strong influence of the static magnetic field on the mould flow near the face of the narrow mould. The flow intensity was locally increased, which is in contradiction to the supposed action of a static magnetic field as contactless brake. Additionally, the detected change in the mould flow becomes recognisable in the free surface shape. The increase in flow intensity can lead to an unstable, fluctuating surface profile.

The presented results were achieved from two different facilities with different length scales, but similar scales in dimensionless numbers. The measurement results of the liquid metal experiments represent a valuable data base for the validation of numerical models, e.g. [18-20].

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