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Recent progress on contactless inductive flow tomography for continuous casting in the presence of strong static magnetic fields

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Abstract
The flow structure of liquid steel in the mold of a continuous caster has huge impact on the quality of the produced steel. In order to influence the flow during the casting process electromagnetic brakes (EMBr) are used. Even a rough knowledge of the flow field would be highly desirable. The contactless inductive flow tomography is a technique for reconstructing the velocity field in electrically conducting melts from externally measured induced magnetic fields. For a physical model of a mold with a cross section of 140 mm x 35 mm we present preliminary measurements of the flow field in the mold in the presence of a magnetic brake. In addition, we show first reconstructions of the flow field in a mold with the cross section of 400 mm x 100 mm, demonstrating the upward scalability of CIFT.

Key words: flow measurement, contactless inductive flow tomography, continuous casting

Introduction
In continuous casting any kind of flow monitoring of the liquid steel in the mold would be highly desirable for increasing the efficiency of the process and the quality of the final product. The flow field in the upper part of the mold is most critical for the quality of the produced steel. Here, some unfavorable flow conditions can lead to slag entrainment and surface defects [1]. In order to control the flow structure in the mold electromagnetic brakes (EMBr) or electromagnetic stirrers are frequently used [2]. Yet, the specific effects of those magnetic actuators are poorly understood due to the lack of adequate flow measurement systems.

One possible measurement technique is the contactless inductive flow tomography (CIFT) [3,4,5] which provides at least a rough picture of the flow by applying primary magnetic fields to the melt and by measuring the flow induced magnetic field perturbation outside the fluid volume. These measurements are utilized to infer the flow field by solving a linear inverse problem. Appropriate regularization methods, like Tikhonov regularization in combination with the L-curve technique, are necessary in order to mitigate the non-uniqueness problem.

In order to demonstrate the applicability of CIFT for continuous casting, a measurement system for a 1:10 scale model (Mini-LIMMCAST) of a continuous slab caster has been set-up at Helmholtz-Zentrum Dresden - Rossendorf (HZDR) [6,7]. In a variety of experiments the CIFT-reconstructed GaInSn flow in the mold was shown to agree reasonably with corresponding UDV measurements [8,9]. In these first experiments we used a static excitation magnetic field and recorded the magnetic field by Fluxgate probes with a dynamic range of 6 orders of magnitude. However, these measurements with DC excitation were extremely sensitive to external interferences.

An AC excitation field with low frequency is recommended to make the CIFT measurements more robust to fluctuations of the environmental magnetic field. This allows for separating the flow induced magnetic field from the environmental noise. The typical excitation frequency is in the range of a few Hz, so that the skin effect is negligible and the magnetic field can still penetrate all the liquid. In the AC case, induction coils can be used which are well applicable in high temperature environments. A further advantage of induction coils is that they do not saturate in strong static magnetic fields, which are widely used in the continuous casting process for the purpose of electromagnetic braking [10].

In this paper we will present the latest developments for the CIFT measurements in the presence of a strong magnetic field generated by an electromagnetic brake.

Experimental setup and CIFT
At HZDR, several liquid metal facilities have been set-up for the systematic investigation of the flow structures as they are typical for the continuous casting process, and of various means for controlling them [6]. Figure 1(a) shows a schematic sketch of the mold of the smaller of these facilities, called Mini-LIMMCAST (scale 1:10), which is operated with the eutectic alloy GaInSn that is liquid at room temperature. The tundish is represented by a stainless steel cylinder which contains about 3.5 l of the metallic alloy. The melt is discharged through an acrylic glass tube (SEN), with the inner diameter of 10 mm, into the mold with a rectangular cross section of 140 x 35 mm² (also made from acrylic glass). From this mold the liquid metal flows over a dam into a storage vessel. The vertical position of the dam controls the free surface level in the mold. The experiments presented here were performed in a discontinuous mode. The liquid
level in the tundish and the mold were monitored using a laser and an ultrasonic distance sensor, respectively. The liquid flow rate can be derived from the descent of the surface level in the tundish. Additionally, a magnetic ruler type brake was installed along the wide faces of the mold in order to validate the functioning of CIFT for such a configuration (Fig. 1(b)). The brake comprises pole shoes which increase and form the magnetic field of the brake and are made of material with very high magnetic permeability. The effects of this type of magnetic brake were already examined using Ultrasound Doppler Velocimetry (UDV) and compared to numerical calculations [11,12,13].

CIFT relies on inverting an integral equation system which can be derived from Ohm’s law for moving conductors by applying Biot-Savart’s law and solving the arising Poisson equation for the potential for insulating boundaries [3,4]. The intrinsic non-uniqueness problem of the emerging linear inverse problem, which mainly concerns the detailed depth-dependence of the velocity, is circumvented by utilizing the so-called Tikhonov regularization by minimizing, in parallel to the mean magnetic field deviations, the kinetic energy of the flow [4,14].

For the restricted problem of inferring the flow in the mold of continuous slab casting it is sufficient to reconstruct only the two-dimensional flow field parallel to the wide faces of the mold, since this represents the dominant and most interesting flow structure [7]. In the presented case the applied magnetic field is generated by two rectangular coils which are mounted above and below the pole shoes of the electromagnetic brake, as seen in Fig. 1(b), in order to be closest to the region of the jet. The magnetic field sensors are placed along the centreline of the narrow faces of the mold, since the strongest induced magnetic field is located there. The measured induced field component is directed normal to the wall. For the application of an AC excitation magnetic field we are using 7 pickup coils with a diameter of 28 mm and 340 000 turns along each narrow face of the mold [10]. The induced voltages of the pickup coils are recorded by a 24-bit analog-digital converter system from Labortechnik Talsler. In the post-processing step the amplitude and the phase of the signal in comparison to the current through the excitation coil is calculated using the quadrature demodulation. The typical excitation frequency is in the range of a few Hz, so that the skin effect is negligible and the magnetic field can still penetrate all the liquid. Another important advantage of AC excitation is the reduction of the sensitivity of the measurement system to fluctuations in the environmental magnetic field.

CIFT in the presence of an electromagnetic brake
Due to the high magnetic permeability and the high electrical conductivity of the pole shoes strong eddy currents are induced by the excitation magnetic field, even at low frequencies in the order of 1 Hz. These eddy currents, in turn, generate an additional magnetic field which can be detected by the pickup coil. Fortunately, due to the fact that the
magnetic field of the eddy currents has a phase angle of 90 degree relative to the current in the excitation coil, this contribution to the measured induced magnetic field can be filtered out. In this way, we can safely calculate the magnetic field inside the mold as resulting exclusively from the excitation coil.

To make matters even more complicated, flow oscillations generate a strongly varying induced magnetic field under the influence of the strong static magnetic field of the electromagnetic brake, too. If the frequency of the typical flow oscillations is in the same order as that of the CIFT excitation current, both signals superimpose and cannot be separated. This problem can be circumvented by using a higher excitation frequency which is in our case 20 Hz. We measured the magnetic field for two different cases when the electromagnetic brake is switched off and when generating a static magnetic field of 310 mT. It is known from UDV measurements [13] that for an active magnetic brake with insulating walls the jet leaves the SEN horizontally and becomes very unstable, whereas with the brake switched off the flow remains rather stable. Figure 2 shows the fields of the sensors 1–7 for these two cases. For the brake being switched off, Fig. 2(a) shows the time dependent signals. One can clearly see that each sensor has a constant mean value with superimposed slight oscillations and a very precise reference at the beginning. If the magnetic brake is switched on (with insulating walls), we get an unstable double-roll flow structure in the mold, which is clearly mirrored in the measured induced magnetic field (Fig. 2(b)). Intense long-term fluctuations with periods in the order of several seconds are also observed, in particular in sensors 6 and 7. These measurements demonstrate that it is indeed possible to measure safely the induced magnetic fields which are 6-7 orders of magnitude smaller than the magnetic field of the brake. The next step will be the reconstruction of the velocity.

![Fig. 2: Measurement of the induced magnetic field in the case of the EMBr switched off (a) and the EMBr switched on with a static magnetic field of 300 mT with insulating walls (b) using an excitation frequency of 20 Hz.](image)

**LIMMCAST**

Motivated by those promising experiments at the Mini-LIMMCAST facility (scale 1:10), we have started to implement CIFT at the larger LIMMCAST facility (scale 1:2). One goal is the demonstration of the scalability in order to make sure that CIFT is able to reconstruct the flow in a real casting machine. The LIMMCAST facility is operated with SnBi at 250 °C. An electromagnetic pump is used to convey continuously the liquid metal into the tundish from which the melt pours through a pipe with an inner diameter of 21 mm into the mold with a cross section of 400 x 100 mm². The flowrate is controlled by a stopper rod [6]. Fig. 3(a) shows a schematic sketch of the excitation coil and the magnetic field sensors which are arranged in a very similar manner as for Mini-LIMMCAST, except that for the first tests we mounted the sensors only along one side of the mold, as depicted in Fig. 3(a). Special thermal insulation had to be installed to prevent the sensors from heating [10].

The excitation current for CIFT had a frequency of 3 Hz and an amplitude of 17 A. Interestingly, in spite of the lower electrical conductivity of SnBi (about 0.4 of the conductivity of GaInSn) and the larger distance of the sensors of about 10 cm from the fluid, the induced magnetic field is in the same order of magnitude as in case of GaInSn. Fig. 3(b) shows the reconstructed velocity in one half of the mold for an averaged time span of 100 s. For that purpose, we have
artificially mirrored the measured magnetic fields from one narrow face to the other. The jet pouring out of the SEN can clearly be identified. This preliminary result gives us confidence that CIFT should also be applicable for the total flow in the large LIMMCAST facility.

Conclusions

In this paper, we have demonstrated the suitability of CIFT for flow measurements in two model experiments related to the continuous casting of steel. Also in the case of an active electromagnetic brake, the induced magnetic field is measurable. The ultimate goal is to employ the method to the hot melts in real steel casters, but this is still a long way to go.

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References