NOVEL INDUCTION COIL SENSOR SYSTEM FOR CONTACTLESS INDUCTIVE FLOW TOMOGRAPHY

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Abstract: We present preliminary results of flow measurements for two different models of continuous casters using the contactless inductive flow tomography. In the first experiment we used a rectangular slab caster with a dominating two-dimensional flow structure under the influence of an electromagnetic brake. For the second experiment a round caster was used in which a magnetic stirrer around the submerged entry nozzle should create an unstable three-dimensional swirling flow.

1. Introduction

More than 95% of the world's steel is produced by means of continuous casting [1]. The steel flows from a tundish through a submerged entry nozzle (SEN) into the copper mould. The mould is cooled from the outside, so that the steel starts to solidify. A strand of steel with a liquid core is pulled continuously out of bottom of the mould. The flow structures in the mould are subject to many investigations, since they have a huge impact on the quality of the steel. The flow pattern in the melt can be influenced, e.g. by DC electromagnetic brakes (EMBr). The opaqueness and high temperature of the melt pose a huge problem to existing techniques for flow measurement. It is desirable to have a contactless method for measuring the structure of the velocity field of the melt. Contactless inductive flow tomography (CIFT) achieves this by reconstructing the flow in the mould from measurements outside the mould of the flow induced perturbations to an applied magnetic field [2].
In section 2 we give a short overview of the mathematical background for CIFT. After presenting the experimental setup in section 3 we show preliminary results for CIFT-reconstructed flows in the presence of a DC-magnetic braking field for a model of a slab caster in section 4. In part 5 we present preliminary results from experiments with a 3D-flow in a round caster.

2. Mathematical Background

A magnetic excitation field $\mathbf{B_0}$ is applied to the melt. From Ohm's law for moving conductors with the velocity **v** and electrical conductivity σ, one can calculate the induced magnetic field **b** at positions outside of the container using Biot-Savart's law. [2]

$$\mathbf{b}(\mathbf{r}) = \frac{\mu_0\sigma}{4\pi}\iiint_V \frac{[\mathbf{v}(\mathbf{r}')\times\mathbf{B}(\mathbf{r}')]\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}dV' - \frac{\mu_0\sigma}{4\pi}\oiint_S \varphi(\mathbf{s}')\frac{\mathbf{n}(\mathbf{s}')\times(\mathbf{r}-\mathbf{s}')}{|\mathbf{r}-\mathbf{s}'|^3}dS' \tag{1}$$

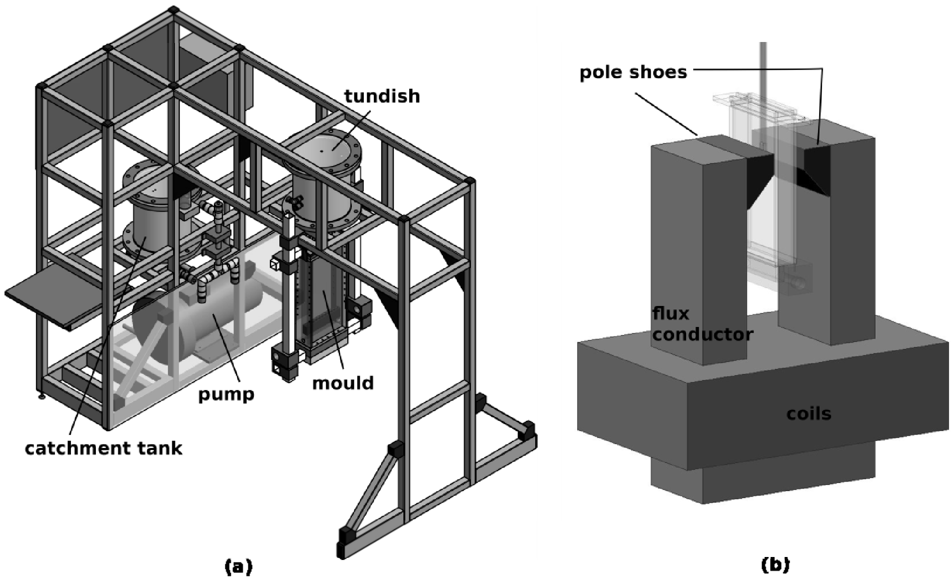
The measurement of the electric potential φ would require a direct electrical contact with the melt. This can be overcome by calculation of the potential from Poisson's law for divergence free current distributions.

$$\varphi(\mathbf{s}) = \frac{1}{2\pi}\iiint_V \frac{[\mathbf{v}(\mathbf{r}')\times\mathbf{B}(\mathbf{r}')]\cdot(\mathbf{s}-\mathbf{r}')}{|\mathbf{s}-\mathbf{r}'|^3}dV' - \frac{1}{2\pi}\oiint_S \varphi(\mathbf{s}')\frac{\mathbf{n}(\mathbf{s}')\cdot(\mathbf{s}-\mathbf{s}')}{|\mathbf{s}-\mathbf{s}'|^3}dS' \tag{2}$$

In the integral equations (1) and (2), **B** is the superposition of the induced magnetic field **b** and the applied magnetic field $\mathbf{B}_0$. In metallurgical applications the magnetic Reynolds number Rm is much smaller than one, therefore the influence of **b** on $\mathbf{B}$ is negligible and we get a linear relation between **v** and **b**. The calculation of **v** from **b** is an ill-posed linear inverse problem, which can be solved using Tikhonov's regularization [2]. In our applications, the excitation field $\mathbf{B}_0$ is typically in the order of 2 mT at the position of the mould. The induced magnetic field **b** is in the order of 100 nT, but can be as small as a few Nanotesla. For the reconstruction of a mainly two-dimensional flow, like in a slab-caster, a single magnetic field is sufficient. For the reconstruction of a three-dimensional flow two magnetic fields in different directions need to be applied.

3. Experimental setup

0At the Helmholtz-Zentrum Dresden-Rossendorf a model of a continuous caster was created, called Mini-LIMMCAST (Mini Liquid Metal Model of Continuous Casting), see Figure 1 [3]. The eutectic alloy GaInSn is used instead of liquid steel. The GaInSn is pumped from a stainless steel catchment tank to the tundish. The stopper in the tundish is lifted and the GaInSn flows through an SEN into the mould. After passing a weir, which controls the position of the meniscus in the mould, the liquid metal flows back into the catchment tank. The flow rate can be adjusted by the position of the stopper rod. The mould and the SEN can be exchanged easily. We conducted experiments with rectangular slab caster and a round caster.



4. CIFT for a rectangular slab caster under the influence of an electromagnetic brake

Experiments were conducted with a slab caster mould with a rectangular cross section of 140 × 35 mm² and a height of 350 mm. The SEN had two oval shaped ports, pointing to the narrow faces of the mould [4]. In contrast to the previous measurements with Fluxgate probes, the induced magnetic field was measured with 2 × 7 cylindrical induction coils positioned to the narrow sides of the caster. Each induction coil has 340,000 windings with a conductor diameter of 25 µm. The signals from the coils were amplified between by 20 dB by differential amplifiers made by FEMTO before being digitalized by an AdWin 18-bit-Analog-Digital-

Converter system (ADC). Since the induction coils pick up the superposition of the excitation field and the induced field, it is crucial to have a highly linear signal processing system.
A ruler-type brake as depicted in Figure 0 (b) was used to generate a DC magnetic field with a field strength of up to 300 mT perpendicular to the wide faces of the mould and hence to the main flow direction. In this configuration the ferromagnetic parts (pole shoes) of the EMBr modify the applied and the induced magnetic field. Therefore, we measured the induced magnetic field in the presence of the pole shoes and reconstructed the velocity, before we switched on the DC magnetic field of the brake, as seen in Figure 1(b). It shows a typical double roll in accordance to previous measurements [4]. From UDV measurements [5], it is known that under influence of the brake the jet is moved upward and flows horizontally towards the narrow face of the mould. This can also be seen in the measurement of the induced magnetic field. The next task will be the reconstruction of the velocity for an active brake.

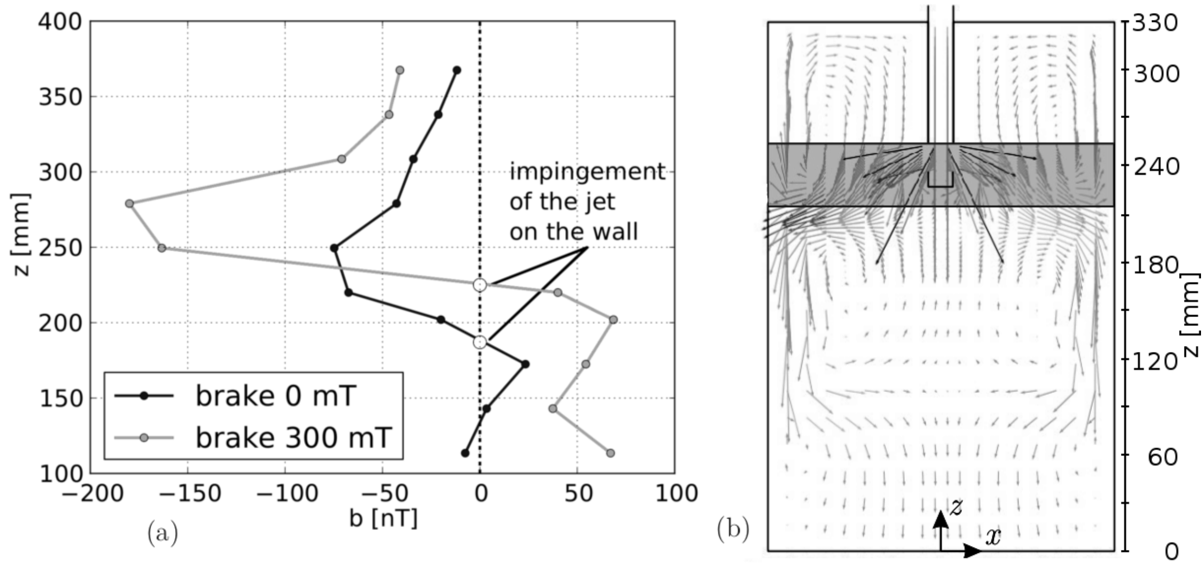
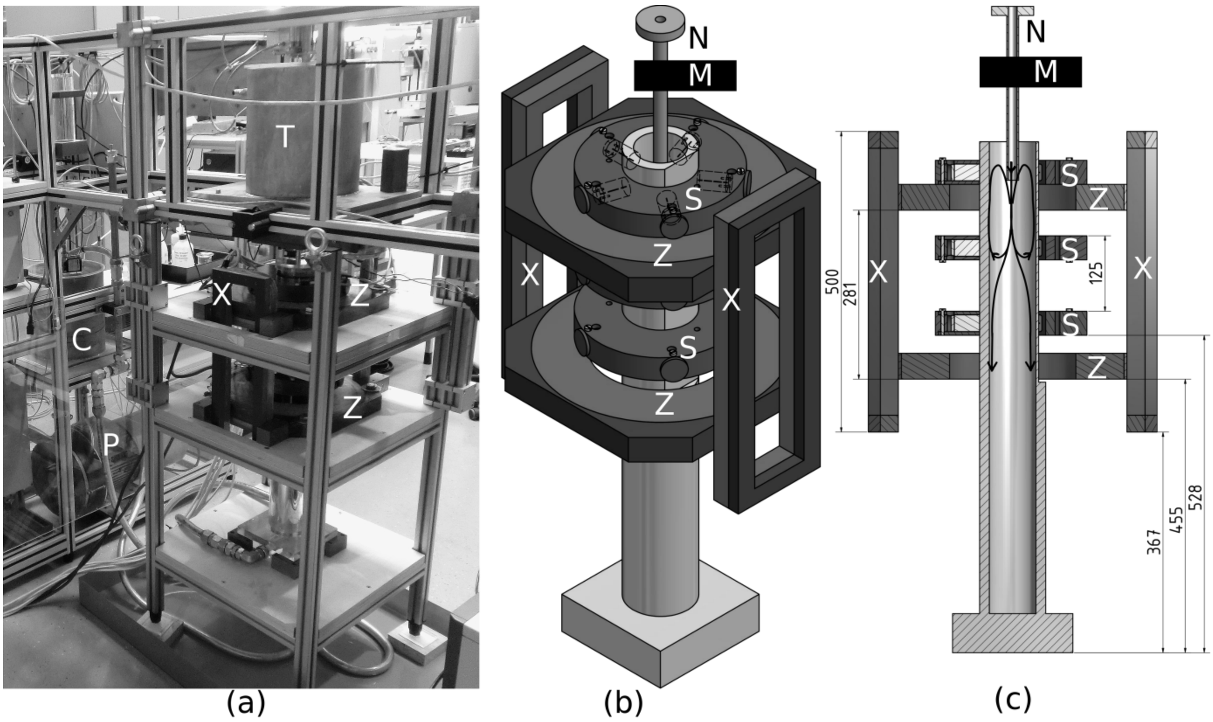


Figure 1: (a) Comparison of **b** along the left narrow face for active and non-active EMBr. (b) Reconstructed velocity field for non-active EMBr, showing a clear double-roll structure. The grey bar shows the position of the pole shoes.

5. CIFT for a round caster under the influence of a magnetic SEN-stirrer

In our cylindrical mould with a height of 800 mm and diameter of 80 mm, combined with a SEN with a downward faced outlet, a widening of the downstream and a poloidal upstream is expected. To influence the flow pattern we used a magnetic stirrer with two permanent magnets rotating around the SEN with a variable rotation rate of up to 50 Hz. The rotating magnetic field in the order of 500 mT gives rise to azimuthal velocity components in the SEN, which should create an unstable helical flow in the mould.



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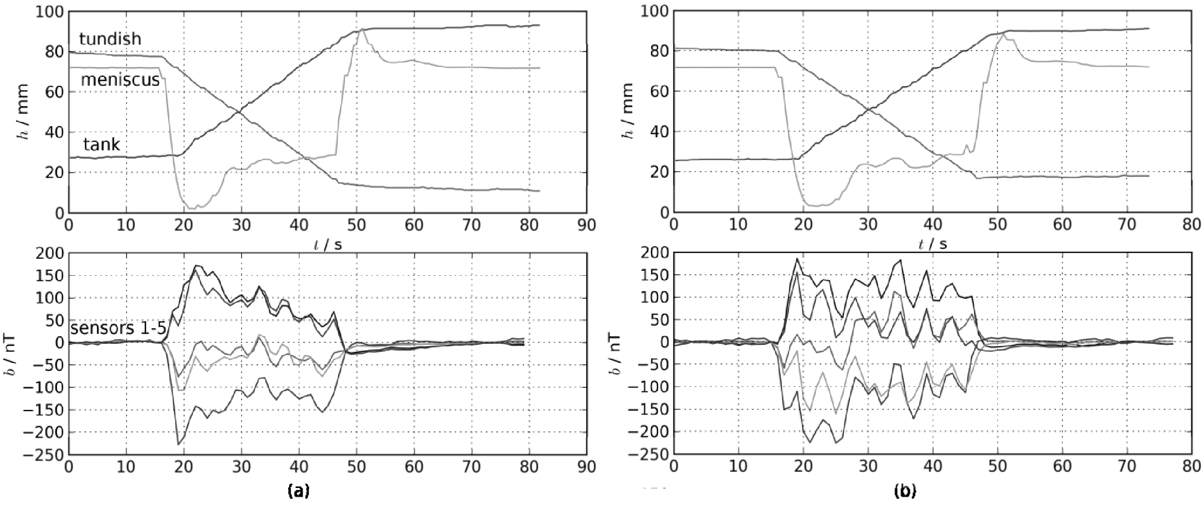
To reconstruct a three-dimensional flow, two magnetic fields in different directions are needed [2]. For a cylindrical mould, these can be a transversal and an axial field, $\mathbf{B_x}$ and $\mathbf{B_z}$, respectively. In contrast to the previous measurements on the demonstration facility [2], we are now able to measure the induced magnetic field for both applied magnetic fields simultaneously by choosing two different AC frequencies. For an adequate separation we used for $\mathbf{B_x}$ 7 Hz, and for $\mathbf{B_z}$ 3 Hz, thus avoiding the undesirable skin effect.

0We used 15 induction coils to measure the magnetic field. The induction coils were facing



the surface of the mould and are placed in three 12.5 cm spaced z-positions close to the mould at the imaginary corners of a pentagon (see Figure 1). In addition to the induction coils used in the experiments with the EMBr, we are now able to use gradiometric coils which are measuring the radial gradient of the induced magnetic field due to the new 24-bit ADC system from LTT Tasler. As expected, gradiometric coils are much more robust to distortions of the environmental magnetic field, e.g. generated by the magnetic stirrer around the SEN.
Nevertheless, after digitizing the induced voltage from the pickup coils with 10 kS/s, digital filtering was needed if the stirrer was switched on. In this case a Chebyshev-inverse low pass filter of degree 5 was applied, before the amplitude of the sinusoidal signal was extracted using the quadrature demodulation (QDT). If the rotation rate of the stirrer was close to the frequency of the applied magnetic field, additional filtering in form of a moving Gaussian filter was required.
In order to evaluate the new measurement system for a cylindrical mould, we applied only $\mathbf{B_x}$ and measured the induced magnetic field for the experiments with active and non-active stirrer around the SEN. The recorded magnetic field at the uppermost sensor array is shown in Figure 4 for those experiments. In comparison to the measurement without stirrer (Figure 4a), the induced magnetic field in the case of an active stirrer is much more fluctuating which can be attributed to a more unstable flow in the mould (Figure 4b). The next task will be the implementation of the inversion algorithm for calculation of **v**.

6. Discussion and outlook

In this paper, we showed that CIFT is able to measure the induced magnetic field **b** of 100 nT in the presence of a 300 mT DC-magnetic braking field and ferromagnetic materials at a liquid metal model of a slab caster. Significant differences in **b** can be measured if the EMBr is used, indicating a changed flow pattern.
In addition we showed that measurement of **b** is possible when the flow in a round caster is influenced by a magnetic SEN stirrer. When the stirrer is switched on, the measured magnetic field shows increased variations, indicating fluctuations in the flow. The reconstruction of the velocity field and data analysis for two applied magnetic fields, needed for a full 3D-reconstruction, are yet to be done.

7. Acknowledgements. The research is supported by the German Helmholtz Association in frame of the Helmholtz-Alliance LIMTECH.

8. References

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