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Real-time control of the mould flow in a model of continuous casting in frame of the TOMOCON project

T. Wondrak[1]*, U. Hampel[1], M. Ratajczak[1], I. Glavinic[1], F. Stefani[1], S. Eckert[1], D. van der Plas[2], P. Pennerstorfer[3], I. Muttakin[4], M. Soleimani[4], S. Abouelazayem[5], J. Hlava[5], A. Blishchik[6], S. Kenjeres[6]

[1] Helmholtz-Zentrum Dresden - Rossendorf, Bautzner Landstraße 400, Dresden, Germany
[2] Tata Steel, Wenckebachstraat 1, Velsen-Noord, The Netherlands
[3] Primetals Technologies Austria, Turmstrasse 44, Linz, Austria
[4] University of Bath, Claverton Down, Bath, United Kingdom
[5] Technical University of Liberec, Studentská 1402/2, Liberec, Czech Republic
[6] Delft University of Technology, van der Maasweg 9, Delft, The Netherlands

Corresponding author: t.wondrak@hzdr.de.

Abstract
In continuous casting, the flow structure of the liquid steel in the mould and the two-phase distribution in the submerged entry nozzle (SEN) are crucial for the quality of the produced steel. In order to effectively control the flow in the mould by electromagnetic brakes (EMBrs) and the injection of gas into the SEN, even a rough knowledge of the flow structure would be very helpful. In the framework of the TOMOCON project, the contactless inductive flow tomography (CIFT) and the mutual inductance tomography (MIT) will be integrated into a control loop for slab casters. This control loop will be developed and implemented at the Mini-LIMMCAST facility, which is available at the Helmholtz-Zentrum Dresden – Rossendorf. In this paper a short overview of this project will be given.

Key words: continuous casting, electromagnetic brake, inductive measurement techniques, flow control

Introduction

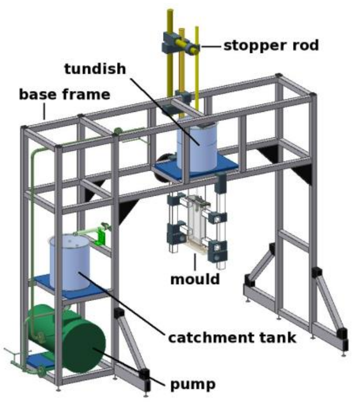
Continuous casting is widely used in the steel industry for the production of billets, blooms and slabs. Typically, the liquid steel flows from a tundish through a submerged entry nozzle (SEN) into the mould. A stopper rod or a sliding gate controls the flow rate of the melt. The walls of the mould are made of copper and are constantly cooled with water so that a shell solidifies at the walls. The partly solidified strand exits the mould at its bottom and is cooled further until it is solidified completely. For most steel grades, argon gas is injected into the SEN in order to prevent nozzle clogging and to catch inclusions.

The flow in the upper part of the mould affects the formation of inclusions and surface defects that affect the quality of the cast product [1]. For instance, the flow should enable the transport of bubbles towards the free surface to avoid inclusions in the solidified steel. In addition, too high velocities at the meniscus can lead to slag entrapment. On the other hand, too low velocities may lead to premature freezing of the steel at the meniscus, promoting surface defects. Thus, the flow pattern and flow velocity at the meniscus must be controlled within tight limits. Therefore, it is desirable to control the flow in the upper part of the mould during casting. Typically, electromagnetic stirrers (EMS) or electromagnetic brakes (EMBrs) are used for this purpose [2]. Ideally, the control loop of those actuators should take the current flow structure in the mould into account. However, up to now this is not feasible due to the lack of appropriate measurement techniques. Only a few local measurement techniques are available for specific plant trials because of the high temperatures of about 1500°C and the opaqueness of the liquid steel. Among them are the nail board dip test, the strain gauge method, mould flow control (MFC) sensors from AMPEA [3] or the evaluation of the oscillation mark shape [4]. Only recently, a new technique was proposed, based on temperature measurements in the meniscus area of the mould [5].

In the last decade two promising contactless measurement techniques were developed: contactless inductive flow tomography (CIFT) and mutual inductance tomography (MIT) which have the potential to be incorporated in a real-time process control loop. CIFT is able to reconstruct the flow structure in the mould by applying a magnetic field to the mould and measuring the flow induced perturbances of that field outside the mould. Based on these measurements, the velocity field is reconstructed by solving the corresponding linear inverse problem [6-9]. MIT is able to detect the conductivity distribution in one cross section of a pipe [10-14]. The sensor consists of an array of coils which are arranged around the pipe. From the measured mutual inductances between these coils the gas/liquid distribution is reconstructed by solving the corresponding non-linear inverse problem. It has been applied for imaging the distribution

of liquid metal and argon gas in the SEN of a small model [8] as well as of a pilot [11] and a full size plant [12].
In the framework of the EU project TOMOCON (smart TOMOgraphic sensors for advanced industrial process CONtrol) a new control mechanism based on these measurement techniques will be developed and demonstrated using the Mini-LIMMCAST facility, which is available at Helmoltz-Zentrum Dresden – Rossendorf [15]. It is a model of a slab caster and is operated at room temperature with the eutectic alloy GaInSn. It will be equipped with both measurement techniques and an EMBr. In this paper, a short overview about the project will be given. After a short description of the Mini-LIMMCAST facility, the two tomographic measurement techniques and a preliminary draft of the control loop are presented.

Demonstrator setup
Fig. 1 shows a schematic and a photo of the Mini-LIMMCAST [15]. Here, instead of liquid steel, the eutectic alloy GaInSn is used whose material properties are described in [16]. The melt flows from the tundish via the SEN made of acrylic glass into the mould with a cross section of 140 x 35 mm^2. The position of the stopper rod controls the flow rate in the SEN. Additionally, argon gas is injected into the SEN via the tip of the stopper rod. The liquid flows from the bottom of the mould into a catchment tank from where it is pumped back into the tundish. The model will be operated in continuous mode allowing measurement times of several hours. For modelling the influence of an electromagnetic brake (EMBr) on the flow, a DC magnet is attached to the mould that produces a transverse magnetic field with a maximum field strength of 0.31 T. The pole faces of the magnet cover the wide side of the mould completely. The model has following actuating variables: the flow rate of the liquid metal by the position of the stopper rod, the flow rate of the argon gas and the strength of the EMBr. Additionally, the new inductive measurement techniques will be validated using ultrasound Doppler velocimetry measurements.



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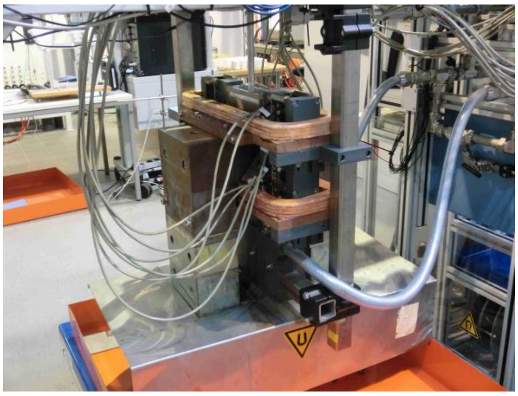
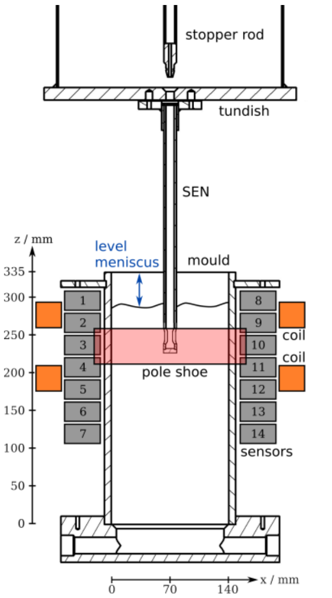


(b)

Fig 1.: Schematic (a) and photo (b) of the Mini-LIMMCAST facility

Contactless inductive flow tomography
Fig. 2a shows a schematic of the sensor arrangement for CIFT. Two rectangular coils generate the primary magnetic field of about 1 mT. Seven magnetic field sensors along each narrow face of the mould record the secondary field, which has a maximum strength of about 200 nT. Fig. 2b shows the reconstructed velocity for one instant in time without an electromagnetic brake. The typical double roll flow structure can be clearly identified. One challenge of this technique is the accurate measurement of the secondary magnetic field in the presence of the ferromagnetic pole shoes of the EMBr. These ferromagnetic parts possibly affect the secondary magnetic field and this alternation is not accounted for in the CIFT formulation. It was shown numerically that for the present sensor arrangement the impact of the pole shoes on the secondary magnetic field is negligible. Additionally, gradiometric induction coils are used with an alternating primary magnetic field [9]. The typical excitation frequency is in the range of a few Hz so that the skin effect is negligible and the magnetic field can penetrate all the liquid. Induction coils have the advantage that they are insensitive to all static magnetic fields. While in previous work the strength of the EMBr was constant during the entire measurement, the effects of a varying strength of the EMBr have to be investigated. The time resolution of the magnetic field measurement and the subsequent flow reconstruction will be about 1 Hz. For the integration of CIFT into a control loop, a real time reconstruction algorithm has to be developed.



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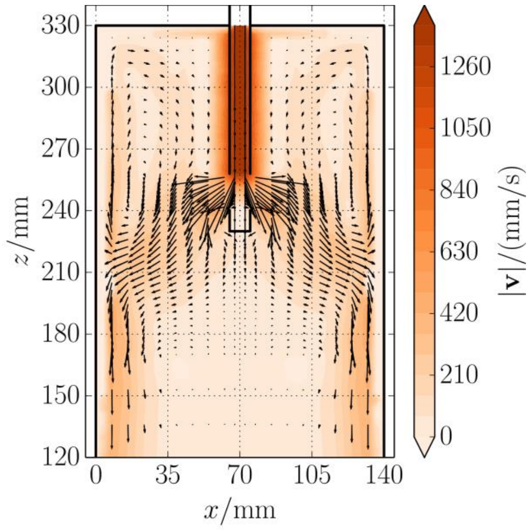
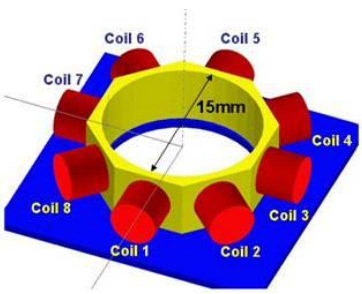


(b)

Fig 2.: Schematic of the sensor arrangement for CIFT and one flow reconstruction without EMBr

Mutual inductance tomography

MIT is able to reconstruct the conductivity distribution in one cross section of the SEN, and thereby to distinguish between liquid metal and argon in case of a two-phase flow. Existing systems typically use an array of 8 coils around the SEN and operate with a frame rate of 20 to 40 frames per second [8,14]. After measuring the mutual inductances between the 8 coils, the non-linear inverse problem has to be solved. Fig. 3 shows a schematic sketch of an MIT sensor and the reconstructed liquid metal distribution at the Mini-LIMMCAST facility [8,14]. These experiments showed that the outer surface of the liquid metal strand in the SEN was reliably detected. However, it was difficult to identify bubbles inside the liquid jet. Additionally, the high velocity of about 1.4 m/s of the melt requires a high frame rate to visualise bubbles of the size of 5 mm. A proposed solution could be the combination of the electrical capacitance tomography (ECT) with MIT. The MIT part will be operated with low frequencies for imaging the interior of the liquid metal jet and ECT will be used to detect the outer shape of the jet [18].



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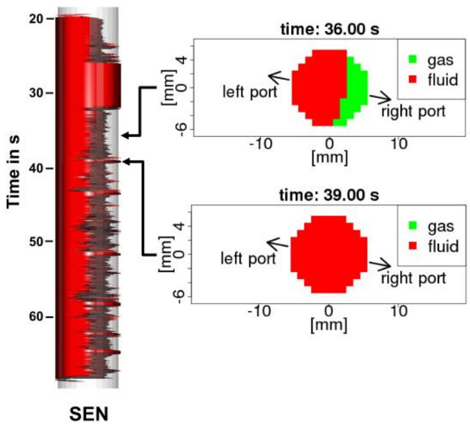

(b)

Fig 3.: Schematic (a) of an MIT sensor and reconstructed argon/GaInSn distribution (b) in the SEN at the Mini-LIMMCAST facility (see [8])

Control loop

In order to combine both tomographic measurement systems with the available actuating variables of the demonstrator, a control loop is proposed which is shown in Fig. 4. The challenge is the design and implementation of the controller. Advanced control designs from the class of model-based control (MBC) strategies are most likely to cope successfully with this challenge. In the first step, a variety of numerical flow simulations have to be carried out in order to identify the special features of the flow which are suitable for the control mechanism. The numerical simulation will be validated by experiments at the Mini-LIMMCAST using both tomographic sensors as well as ultrasound Doppler velocimetry measurements and X-ray radiographic measurements for two-phase flows. These results will form the basis for the design of the controller. A specific challenge for the control loop may be that process adaptations should not occur too often, as these may result in initial instabilities.

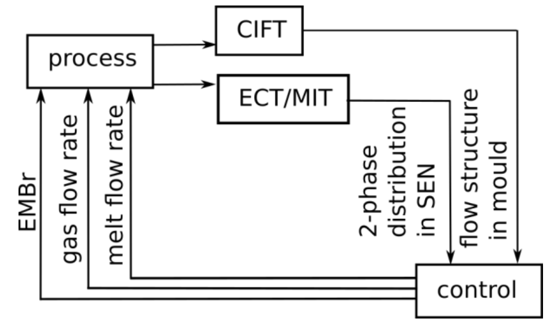

Fig 4: Proposed control loop

Conclusions

Both measurement techniques, CIFT and MIT, allow the measurement of the current state of the flow regime in the SEN as well as in the mould for the first time. Additionally, both tomographic techniques have the potential to be applied robustly in the harsh environment of an industrial caster. The detailed knowledge of the flow enables to implement a control mechanism, which is capable to properly react in a timely manner on changes in the flow in order to achieve sufficient product quality. However, the development of the control loop is a challenging task due to the complexity of the flow. In the TOMOCON project, a first control loop will be designed and will be implemented at a model of a continuous caster to show the feasibility of this approach.

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