Ultrasonic flow measurement in liquid metal models of continuous steel casting

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Model experiments with low melting point liquid metals are an important tool to investigate the flow structure and related transport processes in melt flows relevant for metallurgical applications. One very important industrial process is the continuous casting of steel. But there exist almost no measurement data of the inner mold flow from real casting plants and there are no satisfying measurement techniques available for those harsh conditions. By this, e.g. a detailed understanding of the action of electromagnetic brakes on the complex flow is missing. Therefore we built model experiments for the continuous casting process of steel by using low melting liquid metals and investigated the mold flow under different conditions. The main value of cold metal laboratory experiments consists in the capabilities to obtain quantitative flow measurements by ultrasonic flow measurements with a reasonable spatial and temporal resolution. Standard transducers were used at the model operating at room temperature with the eutectic alloy of GaInSn. Ultrasonic transducers for high temperatures and ultrasonic waveguide sensors were used at the big model, which uses the alloy Sn60Bi40 as model liquid and is operated at temperatures of 200-350 °C. Results from the mold flow measurement will be presented, showing the effect of a static magnetic field on the flow structure. It turned out, that the magnetic field can locally accelerate the flow, contrary to the expected action as a brake. The ultrasonic velocity measurement data were further used for validation and for comparison with other measurement techniques at the model experiment.

Keywords: Continuous casting of steel, electro-magnetic flow control, liquid metal models, applied Ultrasonic Doppler Velocimetry, ultrasonic wave-guides, high temperature transducers

1. 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 mold, and the initial solidification in the mold. Numerous sophisticated numerical simulations concerned with the metal flow during the casting process need a fundamental experimental validation. 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 generalization 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.

The application of electromagnetic fields provides a considerable potential to control the fluid flow in the mold 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 mold 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 cannot provide any reliable knowledge about the magnetic field effect on the flow in the mold. First model experiments employing simplified mercury models have been reported by Japanese [8, 9] and French [10] groups. 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. The key measurement technique for flow characterization in our experiments is the Ultrasonic Doppler Velocimetry. It reveals the mold flow structure under different casting conditions and allows a validation of new liquid measurement techniques, like the Contactless Inductive Flow Tomography [11,12].

2. Experimental facilities

The experimental program of the LIMMCAST facilities at HZDR aims to model the essential features of the flow field in the continuous casting of steel. Basically, these are the flow fields in the tundish, in the submerged entry nozzle (SEN) and in the mold cavity, the complex two-phase flow in SEN and mold due to argon injection as well as the effect of electromagnetic actuators at the mold. For this purpose, there have been build three experimental facilities dealing with the modelling of the continuous casting process.

A photograph showing an overall view of the

LIMMCAST facility is displayed in Fig. 1. All components are made of stainless steel, including the tundish, the SEN and the mold. The low melting point alloy Sn60Bi40 is used as model liquid. The liquidus temperature of 170°C allows for an operation of the facility in a temperature range between 200 and 350°C. The schematic sketch in Fig. 1 illustrates the setup comprising two test sections. A simple pipe test section is used for general testing of measurement techniques for hot liquid metals. The continuous casting strand contains the models of a tundish, a SEN and a mold. The test sections are filled with liquid metal from the storage tank by pressurized Argon. An unused test section can be sealed by valves (not displayed in the sketch). When the loop is filled, the melt is driven by an induction pump through the corresponding test section.

The investigations on continuous casting will be explicitly focused on the behavior of the isothermal melt flow. Argon gas bubbles can be injected with tunable flow rates through the stopper rod into the SEN resulting in a two-phase flow inside the nozzle and the mold. Pipe connections with flanges are realized at various locations within the loop allowing in principal a replacement of the particular components, which gives us a flexibility to modify the flow geometries for miscellaneous requirements.

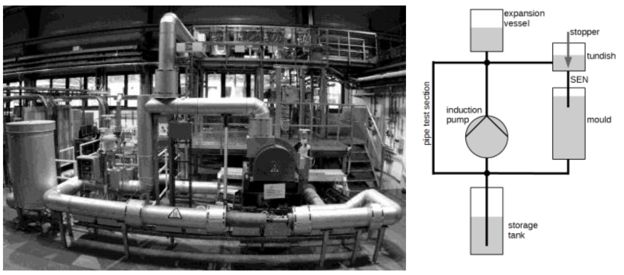

Fig. 1: LIMMCAST – large scale (250 °C) liquid metal experiment for continuous flow measurement in tundish, SEN and mold (left) and a schematic setup (right).

Fig. 2 shows the small-scale setup Mini-LIMMCAST, which is operated with the eutectic alloy GaInSn as model fluid. The experiments at this setup allow for flow measurements at room temperature (Liquidus temperature of the alloy is 10°C) and gained in valuable experiences for the detailed design of the larger LIMMCAST facility during its build-up.

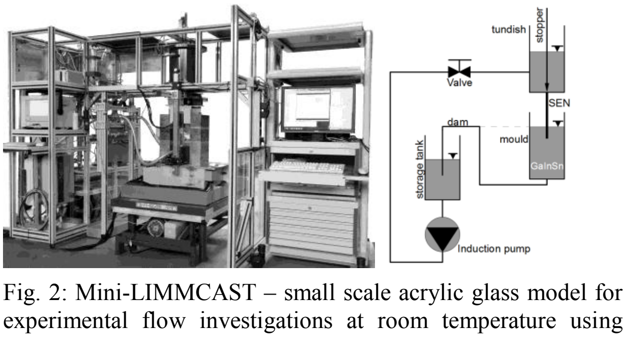

Fig. 2: Mini-LIMMCAST – small scale acrylic glass model for experimental flow investigations at room temperature using GaInSn (left) and a sketch of the operation principle (right).

The results of this setup were gained at a discontinuous operation. The melt was conveyed from the storage tank into the tundish by an induction pump. When the tundish was filled, the stopper rod was pulled and the melt was flowing through the SEN into the mold. From the mold the melt is flowing over a dam back into the storage tank. Meanwhile, a continuous operation of this setup is also possible, but the quality of ultrasonic signal for velocity measurements is degrading in this operation mode due to increased damping of the ultrasonic signal.

The third setup, the X-LIMMCAST, is specialized in visualization of liquid metal – Argon two-phase flows by X-ray imaging. It will be therefore not considered in this paper.

Velocity measurements by the Ultrasound Doppler Velocimetry were done at LIMMCAST and Mini-LIMMCAST by using the devices DOP2000 or DOP3010 from Signal Processing. Different kinds of transducers were applied, like standard ones, high temperature transducers and transducers equipped with a wave-guide. The quantity of operated transducers in multiplexer mode ranged from two to the maximum possible of ten. The next section will give an overview on the measurement conditions and present some measurement results.

3. Experimental results

3.1 Mini-LIMMCAST – room temperature

Previous experiments showed a dramatic influence of a static magnetic field on the liquid metal flow in the mold [13]. 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. This strong upward flow was measured now in the vertical velocities with the Ultrasonic-Doppler-Velocimetry (UDV) [14]. Two standard transducers with an acoustic diameter of 5 mm and an ultrasonic frequency of 4 MHz were used (TR0405LS).

During the measurement, the two transducers were in direct contact with the liquid metal. They dipped from top through the free surface into the melt. The challenge was the lift of the free surface of several centimeters between the rest and the running condition. The transducers were floating above the free surface at the start of the experiment, where the melt is at a rest. When the experiment and melt flow starts, the liquid metal level in the mold rises due to the hydrodynamic resistance in the whole outflow pipe as the outflow is driven only by gravity. Oxides at the free surface laid themselves on the transducers face and blocked the acoustic coupling into the liquid metal. A gadget with a covering plate had to protect the transducers faces and had to be pivoted away once the liquid metal level rose above the transducers contact face. With this gadget it was than possible to measure the vertical flow in the mold from the top. A measurement in vertical direction from the bottom through the bottom wall was not possible because of the high thickness of the bottom wall, the great measurement distance from the bottom towards the jet flow and the settling of particles / impurities at the bottom which block the ultrasonic coupling into the melt.

The two ultrasonic transducers (labeled with “US” in Fig. 3) were mounted one in each mold half symmetrically with respect to the mid-plane or the SEN, respectively. The mean vertical velocity profile along the narrow mold wall recorded with this configuration is shown in Fig. 3.

The liquid metal jet emerging from the SEN is impinging at the narrow wall and splitting in a strong downward stream and a weaker upward stream under the reference condition without magnetic field. The splitting can be well detected in the measurement of vertical velocity next to the narrow wall in Fig. 3 by a change in flow direction. The static magnetic field is causing a local increase in the upward velocity which is very obvious in Fig. 3. The feature of increased upward flow was found in numerical simulations of the mold flow, too [15]. The standard configuration at Mini-LIMMCAST represents electrically isolating boundary conditions as the mold is made of acrylic glass. The rigid and conducting shell of already solidified steel at the mold wall has been modelled with thin brass plates. This brass plates had a strong influence on the temporal behavior of the jet flow (see [13]), but the strong upward flow along the narrow mold is still present (Fig. 3).

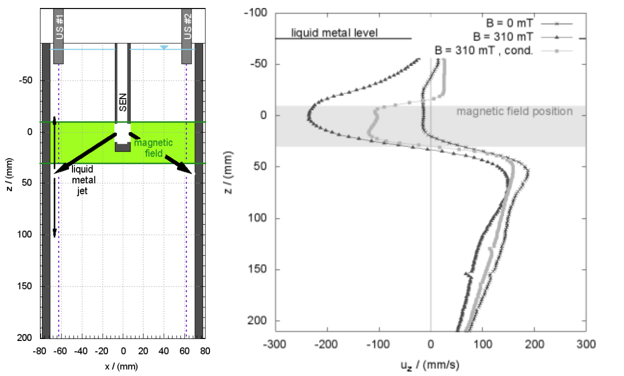

Fig. 3: Measurement configuration for mean vertical velocity along the narrow mold wall at the Mini-LIMMCAST setup (left) and corresponding results of one sensor for different experimental conditions (right).

Experiments at Mini-LIMMCAST for a closer look on the connection between jet flow and free surface shape are ongoing at the moment.

3.2 LIMMCAST – high temperature experiments

The LIMMCAST facility operates at temperatures of 200 to 350 °C. The facility comprises two test sections. The horizontal section is a closed pipe loop and serves as test section of liquid metal measurement techniques for velocity or flow rate, for instance. The UDV-method with high temperature transducers (TR0405LTH) has been tested at this section for the operation with the tin-bismuth alloy at about 200 °C.

The ultrasonic transducers were mounted with special adapters and holders with a Doppler-angle of 45° to the stainless steel pipe with an inner diameter of 54.5 mm. The measurement was performed through the stainless steel wall of the measurement adapter.

The velocity profile in the pipe flow is shown in Fig. 4. The velocity profiles had to be corrected at both ends. At the beginning, the ultrasonic echo from the melt is superimposed by the much stronger signal of multiple echoes inside the wall. The velocities at the first 5 mm are therefore much too low. At the other end, the velocity remains too high and did not converge to a wall velocity of almost zero. This is related to the existence of multiple echo paths from the scattering particles to the ultrasonic transducer with different time of flights or different apparent positions. Additionally, the measurement volume is relatively large compared to the thickness of the boundary layer. By this and because of the inclined ultrasonic path of 45°, the measurement in the region of strong velocity gradients within the measurement volume can become complicated. Therefore, the measured profile did not necessarily converge with the perfect theoretical velocity profile of a pipe flow. The measured profiles were corrected at the first and the last 5 mm by stetting the velocity directly at the wall to zero and by an interpolation to the next measured velocities at a greater distance than 5 mm to the wall. The resulting velocity profiles in the pipe are shown in Fig. 4.

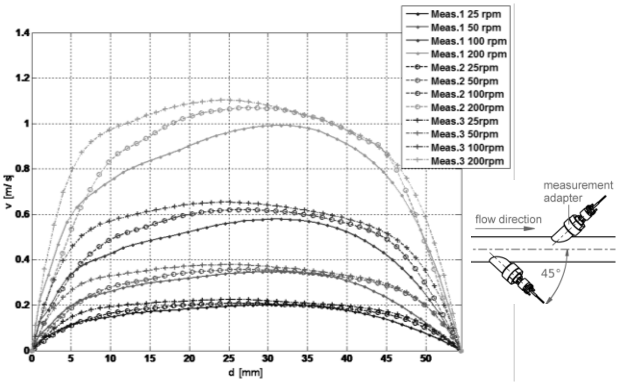

Fig. 4: Velocity profiles of the pipe flow at the horizontal test section of the LIMMCAST facility for different pump speeds.

The second test section comprises the continuous casting modelling. It is again a liquid metal loop containing the main parts of a continuous casting machine, which are the tundish, the SEN and the mold. There are free melt surfaces in the tundish and the mold, just like in the real casting process. The effect of a static magnetic field was investigated at the big LIMMCAST facility too. The mold is made of stainless steel and represents electrically conducting boundary conditions therefore. The vertical velocity was measured again with the UDV-method. This time transducers with wave-guides (TR0408W30) had to be used due to the higher temperature of the melt in the LIMMCAST facility.

Before putting the transducers with wave guides into operation, the contact face of the wave guide has to be prepared. Just like in soldering, impurities and oxides have to be removed from the surface (mostly done by an acid). Afterwards a thin initial layer of the operating metal was deposited on the cleaned facing by dipping the sensor in a liquid melt pool with clean free melt surface. The LIMMCAST facility is operating with an alloy of tin-bismuth, so the same alloy was used to produce the initial wetting of the wave guide. The ultrasonic wave guides were than mounted at the top lid of the model mold with a special compression type fitting. The melt is rising in the mold from the bottom to the top just like at Mini-LIMMCAST although it has other reasons at LIMMCAST. This time, no special gadget was used to protect the wave guide face from impurities on the free surface. Potential impurities have to be flushed away from the sensors facing by the liquid metal flow itself.

Fig. 5 shows the result of the velocity measurements with the mean vertical velocity for different strengths of the magnetic field and the reference case without field. The effect of increased local vertical velocity due to the static magnetic field could be observed at the big LIMMCAST just like at Mini-LIMMCAST.

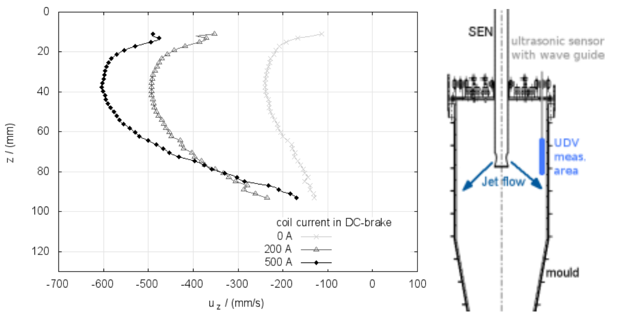

Fig. 5: Vertical velocity along the narrow mold wall (left) and sketch of measurement configuration (right).

The use of wave guides is a useful extension of the Ultrasonic Doppler Velocimetry to higher temperatures. However, it needs a careful preparation of the wave guides contact face for a good wetting to the liquid and a good acoustic coupling into it. Further, experimental conditions can have an influence on the wetting behavior even during an experimental run and therefore on the quality of the velocity measurement. So, the application of ultrasonic sensors with wave guides can be still a challenging task.

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 three experimental facilities LIMMCAST, Mini-LIMMCAST and X-LIMMCAST were built up at HZDR with slightly different scopes. This paper shortly presented two of them.

Measurement results of the liquid metal velocity by the Ultrasonic Doppler Velocimetry (UDV) were presented. The results were gained at different measurement configurations for different measurement conditions. Standard transducers were operated at the cold experimental setup, meanwhile high temperature sensors were used at the hotter LIMMCAST. The measurement was done either with a direct contact of the transducer to the liquid metal, or by pulsing through a wall, or by directing the ultrasound in an ultrasonic wave guide to the liquid metal.

The selected results from velocity measurements showed a strong influence of the static magnetic field on the vertical velocity near the face of the narrow mold. The flow intensity was locally increased, which is in contradiction to the supposed action of a static magnetic field as contactless and overall brake. 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 basic information agrees therefore very well.

The measurement results of the liquid metal experiments represent a valuable data base for the validation of numerical models, e.g. [15-18].

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