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Experimental and Numerical Modelling of the Steel Flow in a Continuous Casting Mould Under the Influence of a Transverse DC Magnetic Field

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Abstract

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. We present the new experimental facility LIMMCAST for modelling the continuous casting process of steel using the alloy SnBi at temperatures of 200-400°C. The possibilities for flow investigations in tundish, submerged entry nozzle and mould will be discussed. In addition, experimental results will be presented on the impact of a steady magnetic field on the outlet flow from the nozzle, obtained at a smaller-scale set-up working with the room-temperature alloy GaInSn. Local velocities are measured by Ultrasound Doppler Velocimetry and contactless inductive flow tomography. The magnetic field significantly changes the jet-type flow in the mould. Surprisingly, in some parameter ranges the DC field creates low-frequency oscillations of the flow structure which resulted in increased velocity fluctuations.

Introduction

The pursuit of better product quality and higher productivity of the continuous casting of steel makes the flow control in tundish and mould and the initial solidification control in the mould to important issues. Numerous sophisticated numerical simulations concerned with the metal flow during the casting process need a fundamental experimental validation. The use of water models gives the advantage to save expense 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 true 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, two-phase flows or applications of electromagnetic fields, the flow phenomena cannot be modelled correctly by means of water experiments.

The application of electromagnetic fields provides a considerable potential to control the fluid flow in the mould cavity and to influence the solidification in the strand. In principle, two categories of electromagnetic control techniques have been proposed to improve the quality of the steel in the continuous casting process: electromagnetic stirrers (EMS) and electromagnetic brakes (EMBR). First strategies for EM applications in steel casting were mainly guided from 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, e.g., [1-4]). However, the problem has to be considered as challenging because of the complexity of the geometry, the highly turbulent flow or 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 [5, 6] 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 mould. Only rough information might be achieved by visual observations of the surface velocity or by the application of imprecise mechanical metering devices. Mercury models were used for some velocity measurements by a Japanese group [7,8] as well as the group in Grenoble [9]. For instance, Okazawa et al. [7] 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 ultrasonic or electromagnetic techniques for measuring the velocity in liquid metal flows came up during the last decade allowing for a satisfying characterisation of flow quantities in the considered temperature range until 300°C [10].

1. Experimental Facility LIMMCAST

A new Liquid Metal Model for Continuous Casting of steel (LIMMCAST) is available at FZD. Fig. 1 shows a simplified scheme of the continuous casting process. The scientific program of LIMMCAST aims to model the essential features of the various flow fields that are of relevance for the continuous casting of steel, namely the flow field in the tundish, in the submerged entry nozzle (SEN), and in the mould cavity. At a later stage, the solidification of the material in the strand is also to be investigated. The facility has been designed and assembled during the last two years. The operation has been started in March 2009 with the first filling of the facility with SnBi. After verification of the instrumentation, the process measuring and control technology, the commissioning phase has been finished end of 2009.

All components to be in contact with the liquid metal are made of stainless steel. 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 400°C. An overall heating power of about 200 kW is installed at the outer wall of the piping system and the components to achieve the operating temperature. The melt inventory is stored in two vessels with a capacity of 250 l for each vessel. For operation the alloy is melted and pushed with Argon from the storage vessels into a piping system. The present situation of the facility comprises two test sections. Test section I, which contains the tundish, the SEN and the mould, will be used for physical modeling of the continuous casting process. The investigations will be explicitly focused on the behaviour of the isothermal melt flow. A further test section has been installed as a closed channel with a straight test section and serves for material tests or verifications of various measuring techniques. A third test section, at which a solidification of the strand will become possible, will be realized in future.

An overall view of the LIMMCAST facility is shown in Fig. 2. An electromagnetic pump is used to convey the liquid metal into the tundish. The flow rate is measured by an electromagnetic flow meter. From the tundish the melt pours through a pipe with an inner diameter of 35 mm into the mould which has a rectangular cross section of 400×100 mm^2. The flow rate is controlled by a stopper rod. Argon gas can be injected into the melt flow through this stopper rod. In the first instance, different kinds of magnetic fields, in particular DC fields and electromagnetic stirrers, will be installed at the mould region. However, respective studies considering the magnetic field impact are also foreseen for the flow in the tundish and the SEN.

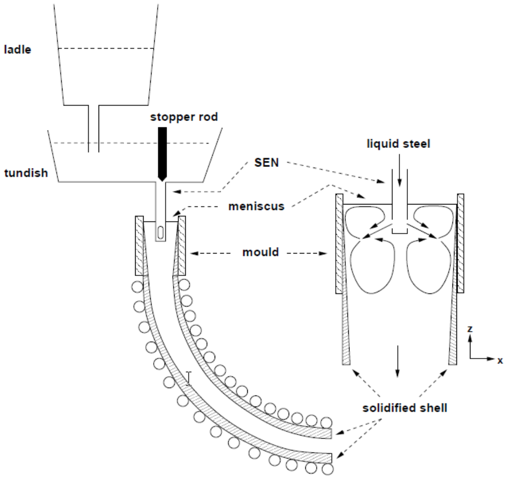


Fig.1. Scheme of the continuous steel casting process and the flow field in the mould

Fig. 2. Photo of the LIMMCAST facility

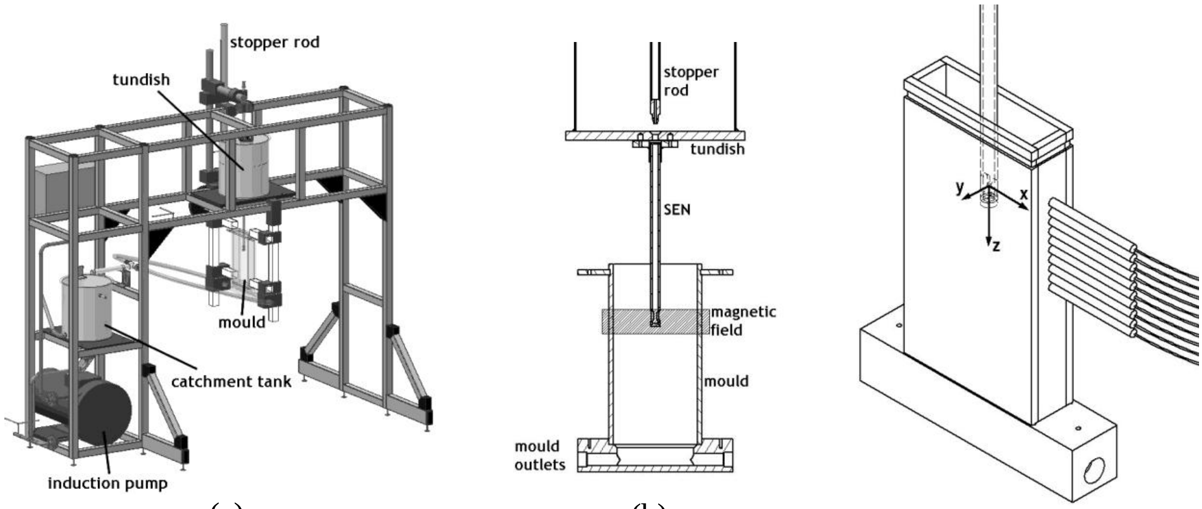
Special adapters at the lid of the mould allow for a direct access of various kinds of measuring techniques to the liquid metal in the mould. For instance, flow velocities will be determined using the Ultrasound Doppler Velocimetry (UDV). High temperature sensors equipped with acoustic wave guides will be attached to the free surface of the melt to determine the vertical component of the liquid velocity. Further adapters are available for visual inspections of the free surface. Moreover, local probes can be positioned inside the melt to measure velocity fluctuations or void fraction distributions in case of gas bubbling. Actually, the recent developments in measurement techniques for liquid metal flows [10] represent the essential basis for the construction of our "cold" liquid metal models. An almost complete measurement of the related single- or two-phase flows is the main basis for a better understanding of those flows and to serve for the validation of numerical simulations.

Though the EM stirring in the mould seems promising for future applications in steel casting [11], our measuring program will start with systematic investigations of the influence of a horizontal DC magnetic field on the flow inside the mould.

2. Mini-LIMMCAST: a Small-scale GaInSn Facility

During the construction and commissioning period of the large scale LIMMCAST facility, the small-scale set-up Mini-LIMMCAST was employed which uses the eutectic alloy GaInSn that is liquid at room temperatures. At this set-up we started a preliminary experimental program which is focused on quantitative flow measurements in the mould and in the submerged entry nozzle (SEN). This way we expected to gain valuable experiences for the detailed design and the operation of the larger LIMMCAST facility.

Fig. 3a shows a schematic drawing of the Mini-LIMMCAST facility. A stainless steel cylinder serves as the tundish which contains about 3.5 l of the GaInSn alloy. The melt is discharged through a Plexiglas tube with inner diameter of 10 mm into the mould with a rectangular cross section of 140×35 mm^2 (also made from Plexiglas). Two nozzle ports with an oval cross section (vertical dimension 18 mm) are situated approximately 80 mm below the free surface in the mould. From the mould the liquid metal flows over a dam into a storage vessel. The vertical position of the dam controls the free surface level in the mould. An electromagnetic pump conveys the melt from the vessel back into the tundish.



(a) (b) (c)

Fig. 3. Sketch of Mini-LIMMCAST (a), Details of Mini-LIMMCAST (b), and linear arrangement of 10 US transducers for flow measurements along the vertical midsection (c)

The experiments presented here were performed in a discontinuous mode, i.e. after filling the tundish with the melt the stopper rod was lifted to drain the fluid into the mould. During this process the liquid level of both the tundish and the mould were monitored using a laser and an ultrasonic distance sensor, respectively. The liquid flow rate has been derived from the descent of the surface level in the tundish. A schematic view of the section comprising the outlet of the tundish with the stopper rod, the SEN and the mould can be seen in Fig. 3b. 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. Measurements of the field strength showed that the field is homogenous between the pole faces within a tolerance of about 5%. The pole faces of the magnet cover the wide side of the mould completely. The vertical extension of the pole shoes is 40 mm, whereas the position of the upper edge of the pole faces coincides with the nozzle outlet (see Fig. 3b).

UDV was used for measuring the fluid velocity in the mould. This method is based on the pulse-echo technique and delivers instantaneous profiles of the local velocity along the ultrasonic beam and can be applied to attain experimental data from a bulk flow in opaque liquids. The measuring volume consists of a series of disks lined up concentrically along the propagation direction of the ultrasound. In the present study we have applied the DOP2000 velocimeter (model 2125, Signal Processing SA, Lausanne) equipped with up to ten 4 MHz transducers (TR0405LS, acoustic active diameter 5 mm). The internal multiplexer of the DOP2000 has been used for a sequential acquisition of data from all sensors with an overall scan rate of 5 Hz. Ten transducers were arranged within a vertical line array which was attached at the outer wall of the mould and located at the midsection of the narrow side, see Fig. 3c. The distance between two adjacent transducers was 10 mm.

3. Results at Mini-LIMMCAST

Fig. 4 contains time-averaged plots showing the UDV measurements of the horizontal velocity field for the cases without magnetic field and with a transverse field of 0.31 T, respectively. Profiles of the horizontal velocity were recorded at the midsection along the wide side of the mould between the side wall (left side) and the submerged entry nozzle (right side). The application of the magnetic field provokes a recirculating flow at the upper part of the nozzle outlet. With magnetic field the jet became more horizontal. The impingement point at the opposite side wall is shifted upwards by about 20 mm. The intensity of the velocity within the jet is only slightly reduced.

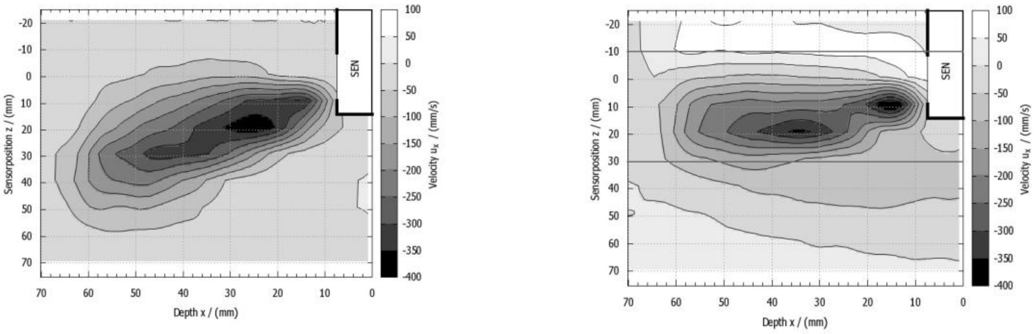


Fig. 4. UDV measurements of the horizontal flow at the nozzle outlet (vertical arrangement of 10 transducers): (left) without magnetic field, (right) B = 0.31 T

Besides the time-averaged velocity fields, it is interesting to consider the transient velocity signals at a fixed position. Fig. 5 displays time series of the velocity recorded at a position inside the jet close to the nozzle outlet. The expected reduction of the velocity fluctuations due to the magnetic field influence cannot be observed. Instead, the measurements show large scale oscillations of the local velocity which probably arise from an alternating up-and down of the jet flow. In other words: The electromagnetic “brake” causes a significant enhancement of the turbulent fluctuations of the melt velocity, at least in the region of the jet close to the nozzle outlet.

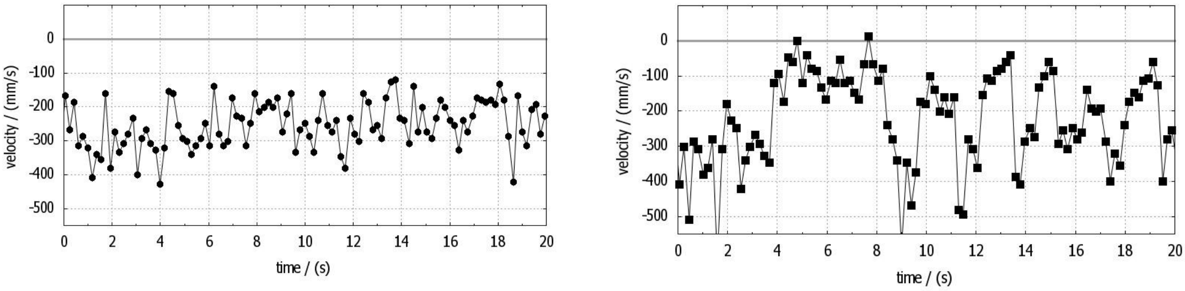


Fig. 5. Time series of the local velocity at x = 33 mm, z = 19 mm: (left) without magnetic field, (right) B = 0.31 T

4. Summary and Concluding Remarks

Cold liquid metal models appear as an important tool for the experimental investigation of many open questions in steel casting. Moreover, these model experiments can provide valuable experimental data for the validation of numerical flow simulations. The LIMMCAST facility at FZD is now available for respective investigations at scales being comparable to the realistic continuous casting process. The consideration of various possibilities of electromagnetic flow control comprising both DC and AC magnetic fields will be a main issue in the experimental program. Besides the investigation of fluid flow and transport processes the facility will be used to develop and test measuring techniques and components for the real industrial process.

First preliminary experiments have been carried out at the Mini-LIMMCAST facility focusing on the mould flow and its modification by an applied transverse magnetic field. The impact of a DC magnetic field on the outlet flow from the submerged entry nozzle (SEN) has been studied. A striking outcome was the feature that a static magnetic field may give rise to non-steady, non-isotropic large-scale flow perturbations. The flow measurements presented here did not confirm the expectation of a smooth reduction of the velocity fluctuations at the nozzle outlet due to the magnetic field. Further details of LIMMCAST and the preliminary results at Mini-LIMMCAST may be found in the recent publications [12, 13].

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