EXPERIMENTAL MODELLING OF THE CONTINUOUS CASTING PROCESS: THE LIMMCAST-PROGRAM

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1. Introduction

Continuous casting is the process whereby molten steel is solidified into billets, blooms or slabs for subsequent rolling in a mill. About 92% of the worldwide annual output of crude steel was produced using the continuous casting process [1]. The molten steel flow in the mould has a great influence on the obtained steel quality. In particular, an inappropriate flow regime can lead to the entrapment of oxides, slag or gas bubbles and their transport into the solidification zone. Therefore, the quest for better product quality and higher productivity makes the flow control in tundish and mould, and the initial solidification control in the mould to important issues with respect to an optimization of the continuous casting technology.

The continuous casting process is sketched in Fig. 1. From the ladle, the hot metal is poured into a holding bath called tundish. The tundish serves as a buffer vessel for regulating the metal feed to the casting machine, stabilizing the flow out, and cleaning the metal. The stopper rod regulates the flow from the tundish through the submerged entry nozzle (SEN) into the water cooled copper mould, where the initial solidification starts. The partial solidified steel strand is then withdrawn and further cooled down.

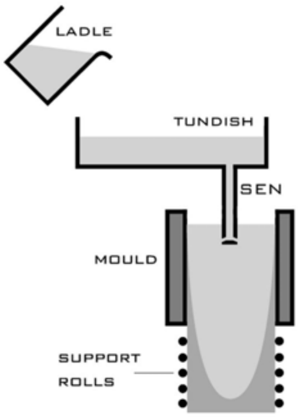


Fig. 1: Principle of the continuous casting process

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 for instance [2-5]). 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 indispensible. 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 to validate numerical calculations. A Japanese group reported some experimental studies employing simple mercury models [8, 9]. 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].

2. The LIMMCAST facility

The experimental programme of the LIMMCAST facility at FZD aims to model the essential features of the flow field occurring during the continuous casting of steel, namely the flow field in the tundish, the submerged entry nozzle (SEN) and the mould cavity as well as the solidification of the material in the strand. 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. After verification of the instrumentation, process measuring and control technology the experimental programme will start in 2010. 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. All components being in direct contact with the melt are made from stainless steel.

An overall heating power of about 200 kW is installed at the outer wall of the loop 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 loop of circular pipes. 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 modelling of the continuous casting process. The investigations will be explicitly focussed on the behaviour of the isothermal melt flow. A further test section has been installed as closed piping system and serves for material tests or verifications of various measuring techniques. A third test section will be realised in future, where a solidification of the strand will become possible.

Fig. 2: View of the LIMMCAST facility

An overall view of the LIMMCAST facility is shown in Fig. 2. An electromagnetic pump is used to pump the liquid metal into the tundish. The flow rate is measured by an electromagnetic flow meter [11]. From tundish the melt pours through a pipe with an inner diameter of 35 mm into the mould with a rectangular cross section of 400×100 mm^2. Special adapters at the lid of the mould allow for a direct access for measuring techniques to the liquid metal in the mould. Flow velocities will be measured using the UDV method. High temperature sensors with acoustic wave guides [12] 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.

3. 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. A selection of first representative results from the flow measurements will be shown within this report.

3.1. Setup

Fig. 3 shows a sketch of the experimental setup. 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 an inner diameter of 10 mm into the mould with a rectangular cross section of 140 × 35 mm^2 also made of Plexiglas. Two nozzle ports are situated about 80 mm below the free surface in the mould. From the mould the liquid metal flows through a U-bend channel into a storage vessel. The vertical position of the vessel inlet controls the free surface level in the mould. 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 distance sensor. 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 stopper rod, the SEN and the mould can be seen in Fig. 4.

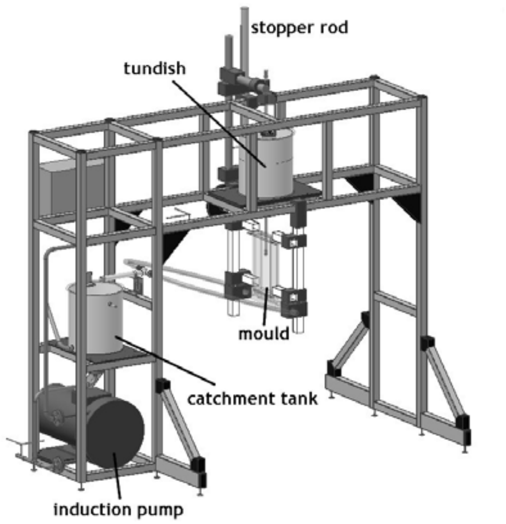


Fig. 3: Schematic view of the Mini-LIMMCAST facility

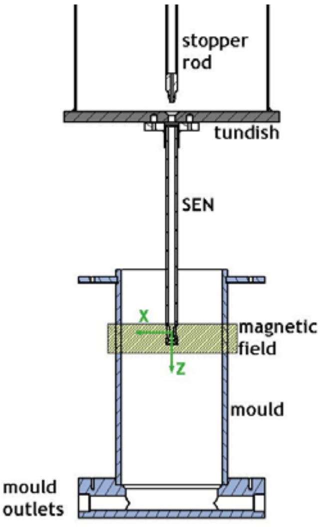


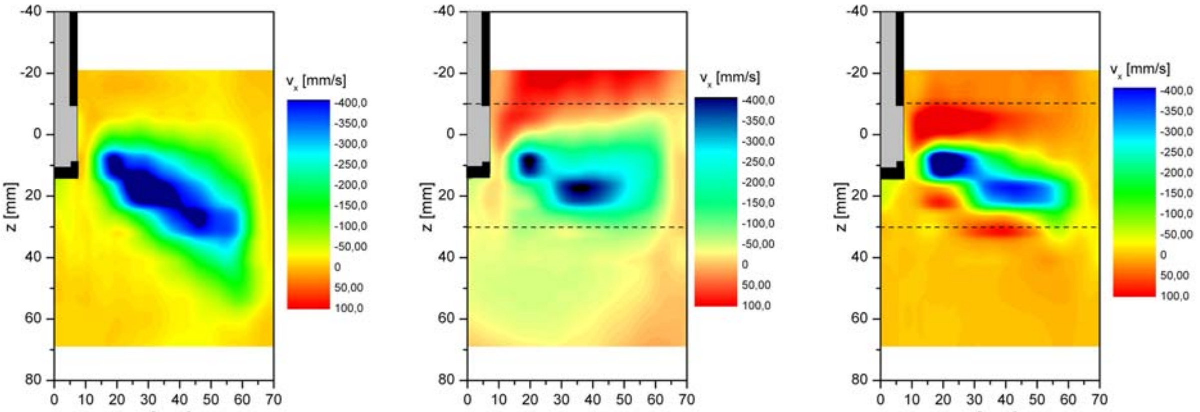
Fig. 4: Detailed view on tundish with stopper rod, SEN and mould

A DC magnet supplies a transverse magnetic field. Measurements of the field strength have shown 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. For the simulation of the solidified shell in the real casting process, brass plates were placed on the wide side walls of the mould. The induced currents in the liquid metal are now able to close through the rigid, electrical conducting walls.

The ultrasound Doppler velocimetry (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 [13]. In the last twenty years the UDV technique became an accepted method for flow investigations in various liquid metals (see [10] and references therein). In the previous experiments we have applied the DOP2000 velocimeter (model 2125, Signal Processing SA, Lausanne) equipped with up to ten 4MHz transducers (TR0405LS, acoustic active diameter 5 mm). The transducers were arranged within a vertical line array which was attached at the outer wall and located at the midsection of the narrow mould side. The distance between two adjacent transducers was 10 mm. Profiles of the horizontal velocity were recorded along the wide side of the mould between the narrow side wall and the submerged entry nozzle 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.

3.2. Some results from the flow measurements

The influence of a transverse DC magnetic field on the jet flow discharging from a submerged nozzle into a rectangular cavity has been investigated. The pole faces of the magnetic field span the entire wide side of the mould below the SEN ports. In the measurements considered here the position of the magnetic field was chosen that the upper edge of the pole faces coincide with the vertical location of the nozzle ports. Linear profiles of the vertical flow velocity were acquired in a domain between 20 mm above and 70 mm below the midpoint of the SEN between the nozzle ports which is taken as point of origin for the coordinate system in all measurements which will be presented below.



(a) (b) (c)

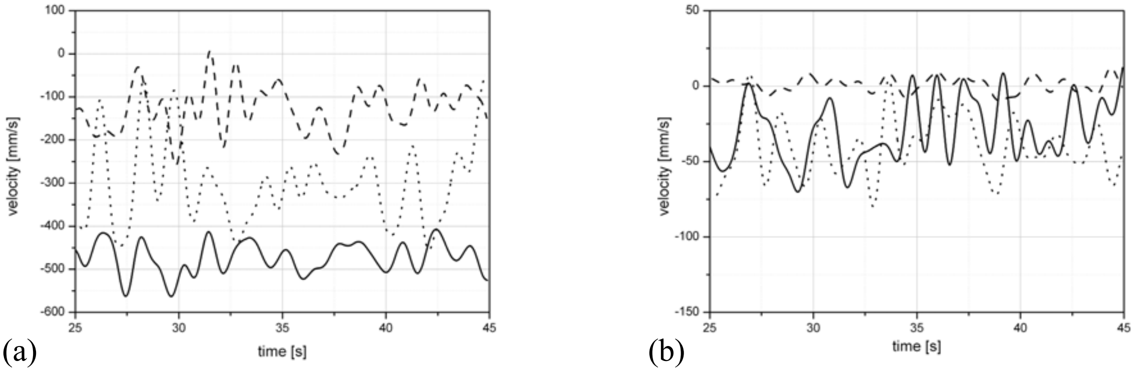
Fig. 5: Time-averaged, horizontal flow at the nozzle outlet (a) without magnetic field, (b) B = 310 mT, non-conducting channel (c) B = 310 mT, conducting channel

Fig. 5 contains time-averaged plots showing the UDV measurements of the horizontal velocity field. The liquid metal jet emerging from the nozzle port can be clearly identified in all displayed flow structures (blue regions represent a flow from the SEN towards the narrow wall). Nevertheless there are remarkable differences in the flow fields. The application of the magnetic field in a non-conducting mould as displayed in Fig. 5(b) provokes a recirculating flow at the upper part of the nozzle outlet (horizontal green lines indicate the position of the magnet pole faces). The inclination angle of the jet becomes flat. 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. The addition of a conducting wall creates another flow structure. A further recirculation zone is established below the liquid metal jet and the horizontal flow below the pole shoes becomes uniform.

Fig. 6 shows time series of the local velocity recorded in the inner jet region and a measuring position below the discharging jet, respectively. The ultrasonic sensor detects a turbulent flow with strong irregular velocity oscillations if no magnetic field is applied. The highest velocities within the jet region (see Fig. 6(a)) were found in the case B = 0. Although, the mean velocity is lowered for both imposed magnetic fields, the velocity fluctuations were not reduced, but, even increased by the magnetic field in the non-conducting vessel. An effective damping of turbulent velocity fluctuations can only be observed at a position below the jet (see Fig. 6(b)) in a conducting mould.

4. Conclusion

We investigated the impact of a steady magnetic field on the liquid metal flow in the continuous casting mould. The imposition of the magnetic field causes regions of reverse flow on both sides of the central jet. Furthermore, the exit angle of the jet becomes more flat. Thus, the penetration depth of the discharging flow into the lower part of the mould is reduced. 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.



(a) (b)

Fig. 6: Time series of the local velocity for B= 0 (solid lines), B= 310 mT in the non-conducting mould (dotted lines) and B = 310 mT in the conducting channel (dashed lines): (a) inside the jet; (b) below the jet

The application of tailored magnetic fields is the key issue for an effective optimisation of the continuous casting process, but it requires further investigations of the interplay between the mould flow and the magnetic field, in particular experimental data are needed to verify the electromagnetic braking effect.

The availability of liquid metal cold models appears as an important tool for an experimental investigation of complex flows structures and transport processes being relevant for the continuous casting process. Moreover, the model experiments at LIMMCAST and Mini-LIMMCAST will provide valuable experimental data for the validation of numerical flow simulations.

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