Flow measurements in a liquid metal model of a bloom caster under the effect of rotary electromagnetic stirring

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Abstract
This paper presents an experimental study of electromagnetically stirred flow in the mold using a 1:3 scale acrylic glass model of the round bloom caster from voestalpine Stahl Donawitz GmbH. An electromagnetic stirrer was installed at the mold producing a rotating magnetic field (RMF). Flow measurements were performed by means of the ultrasound Doppler velocimetry (UDV) at room temperature in the eutectic alloy GaInSn. Up to 10 ultrasonic transducers were employed simultaneously in order to obtain a two-dimensional reconstruction of the flow structure. The experiment provides an extensive and valuable data base for validation of numerical methods.

Key words: Continuous casting, electromagnetic stirring, rotating magnetic field, flow measurements

Introduction

Electromagnetic stirring (EMS) by AC magnetic fields is a valid method for contactless flow control in billet/bloom casters since about 40 years [1-4], where the rotary stirring of the flow in the mold by means of a rotating magnetic field (RMF) can be considered as a standard application. The stirring is supposed to improve the homogeneity of the molten steel and the quality of the solidified steel strand by significantly decreasing the casting defects. In particular, it is assumed that non-metallic particles are prevented from entrapping in the solidified shell by the so-called washing effect [5]. Particles caught between columnar dendrites are washed out by the forced flow and transported into the bulk liquid. Then, the stirring shall stimulate agglomeration and the formation of larger particles which move up more easily towards the free surface. Moreover, it is expected that forcing of the melt flow in the solidification region promotes a transition from columnar to equiaxed solidification. An intense flow along the solidification front causes fragmentation of dendrites and hence a multiplication of nuclei. Su et al. [6] suggest a dendrite fragmentation criterion for low carbon and high carbon steels casted under the influence of EMS. Industrial experience has shown that the particular stirrer design, position and operating conditions have a strong influence on the metallurgical quality. First of all, a high stirring intensity should be guaranteed by a suitable coil design and appropriate magnetic field parameters. A stirrer operation at low magnetic field frequencies (typically 2 to 8 Hz) is required because the thick copper walls of the mold impede a deep penetration by an AC magnetic field at higher frequencies. The use of low frequencies limits the resulting electromagnetic Lorentz force for driving the rotary flow. On the contrary, an intensive swirling flow at the free surface poses the risk of slag or mold powder entrapment due to the depression of the melt surface at the nozzle. The resulting absorption of impurities is known to lower the quality of steel products significantly. A specific electromagnetic stirring system of two stirrers was considered to influence the meniscus stability [7]. Two independent rotating magnetic fields superimposed upon each other are applied to achieve a flexible control of the stirring motion in the meniscus zone regardless whether an intensive stirring is generated deeper in the mold. Thus, even the opposite direction of stirring of the near meniscus field can be chosen with respect to the main stirrer.
A great deal of previous research work was dedicated to the prediction of the mold flow and related heat and mass transfer under the action of EMS, mainly by numerical simulations (see for example [8-13]). Numerical calculations can provide a better understanding of the complex flow behaviour, but, experimental data are indispensable for the validation of CFD models. The motivation of our study is to provide a rather generic experiment equipped with advanced ultrasonic flow measuring technique for detailed investigations of the liquid metal flow in a cylindrical column driven by an RMF. Especially, the effect of variations of the field strength and frequency on the stirring intensity is considered. Furthermore, we compare the case of a pure RMF-driven flow with the realistic configuration of a vertically aligned submerged jet in the swirling flow. The flow measurements were conducted in a 1:3 scale Perspex model of the round bloom strand caster from voestalpine Stahl Donawitz GmbH.

Experimental set-up and procedure

The experiments were conducted at the mini-LIMMCAST facility at HZDR. A detailed description of this experimental equipment can be found in previous publications [14, 15]. About 12 litres of the ternary eutectic alloy $Ga_{68}In_{20}Sn_{12}$ were used as a model fluid.

A schematic view of the experimental facility can be seen in Fig. 1. The tundish is a cylindrical vessel made of stainless steel connected with the submerged entry nozzle (SEN). A stopper rod controls the melt flow through the SEN. The SEN is an ordinary pipe with an inner diameter of 10 mm and a length of 300 mm. A SEN immersion depth of 35 mm below the surface level of the liquid metal was chosen. The circular mold has an inner diameter of 80 mm and a length of 800 mm. The mold and SEN consist of acrylic glass. The melt discharges from the SEN into the mold as a submerged jet. The experiments were performed in a continuous mode, i.e. after filling the tundish with the melt the stopper rod was lifted to drain the fluid into the SEN. A magnetic pump conveys the melt from the vessel back into the tundish. The liquid levels in both the tundish and the storage vessel were monitored using a laser sensor. The flow measurements have been started after achieving fully developed flow conditions. The velocity inside the SEN could be estimated to be in the range 1.2-1.5 m/s.

The electromagnetic system has a bore diameter of 200 mm and a height of 310 mm. This system of 12 coils generates a rotating magnetic field (RMF) with a maximum magnetic flux density of B_0=20 mT. Flow measurements were conducted for different values of the magnetic field strength varying in the range between 5.8 mT and 18.3 mT. A magnetic field frequency of 2.5 Hz was chosen for the flow measurements.

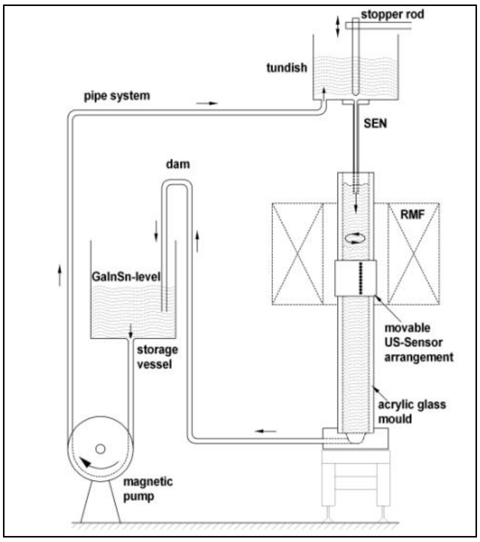


Fig. 1: Schematic view of the experimental setup showing the test section and the liquid metal loop

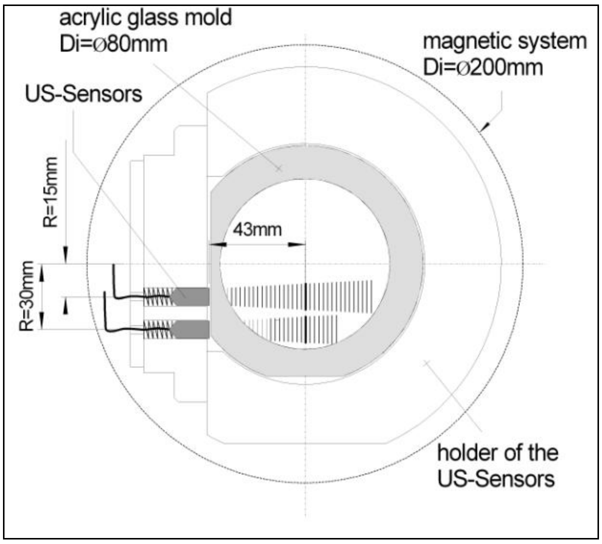


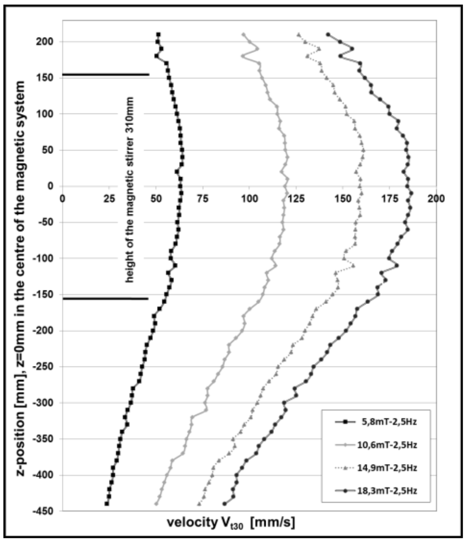
Fig. 2: Horizontal cross section of the mold showing the radial measuring positions 15 mm 30 mm

The flow velocity in the mold was measured by means of the ultrasound Doppler velocimetry (UDV). This method is based on the pulse-echo technique and delivers instantaneous profiles of the velocity component projected onto the propagation direction of the ultrasonic beam [16, 17]. The measurements in the present study were performed using the DOP2000 velocimeter (Signal Processing SA, Lausanne). A vertical line array of ten 4 MHz transducers (TR0405AS, diameter 8 mm) was assembled with a distance of 10 mm between two adjacent transducers. This vertical arrangement was installed at positions of R=15 mm and R=30 mm parallel to the mold axis to determine the tangential velocity component (see Fig. 2). The outer cylindrical wall of the mold was partly shaped to a plane surface in order to allow an exact positioning of the US sensors which were attached at the wall using a technical vaseline.

Results

A first set of velocity measurements was carried out for the situation of a rotating flow driven by the magnetic field without submerged jet. Tangential velocities are measured at a radius of R=15 mm and R=30 mm. On both measuring lines at a distance of a=43 mm from the sensor the measured velocity equals the tangential velocity. At this position there is no disturbance of the measurement due to projections of the radial velocity. Vertical profiles of the mean tangential velocity obtained at R=30 mm for four different magnetic field intensities and a stirring frequency of f=2.5 Hz are shown in Fig. 3(a). The time-averaged values are calculated from 100 to 300 flow profiles recorded over a period of ca. 30 s to 60 s. The magnetic stirrer was installed in the domain highlighted by the two red lines in the diagram. The largest values of the mean tangential velocity were detected at a height which approximately coincides with the geometric centre of the stirrer. The flow is directly driven by the Lorentz force within the stirrer region whereas the magnetic field intensity decreases rapidly outside the stirrer. Internal friction and secondary flows are responsible for the rotating motion of the fluid above and below the magnetic stirrer. The volume of liquid in the model is distributed asymmetrically with respect to the stirring system. The free surface of the liquid metal is 60 mm above the stirrer. Measurements in the lower area of the mold reveal that the tangential velocities is about 50 % of the maximum detected within the stirrer zone.

Fig. 3(b) shows corresponding measurements of the mean tangential velocities for the radius R=15 mm. As it was expected for the lower radial position the velocities are smaller compared to the data obtained at R=30 mm. However, the respective rotation frequencies are almost the same indicating a solid body rotation in a wide domain of the liquid metal column. A fluid rotation frequency of about 1 s^{-1} as found here corresponds to 40 % of the magnetic field frequency. A remarkable difference is the fact that the vertical velocity profiles do not show the highest velocities in the region of the magnetic stirrer. The maximum of the mean tangential velocity of V_{t15}=120 mm/s was detected at a position of approx. 200 mm below the stirrer. This velocity distribution can be explained by the conservation of angular momentum. Besides the primary rotating motion a secondary flow exists in the meridional plane of the liquid which is directed from the sidewalls towards the cylinder axis in the regions outside the stirrer. That means that rotating fluid is transported inwards and increases its angular velocity along this way. This mechanism results in an almost uniform vertical profile of the mean tangential velocity at R=15 mm. It is interesting to note that at a position far below the stirrer (z =-440 mm) higher velocities can be observed close to the axis than at radius R=30 mm.

(a)


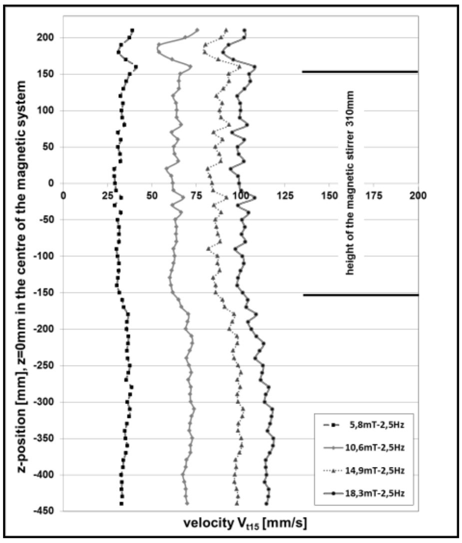
(b)


Fig. 3: Vertical profiles of the time-averaged, tangential velocity at radial positions of (a) 30 mm and (b) 15 mm

Fig. 4 shows the time-averaged tangential velocities for four magnetic flux densities with additional jet flow at a radial position of R=15 mm. The SEN outlet is located centrically within the mold at a vertical position of z=185 mm. The liquid metal flow inside the SEN has an average speed of V_{SEN}=1.4 m/s. The horizontal alignment of the ultrasonic sensors does not allow determining the almost vertically directed outflow from the nozzle.

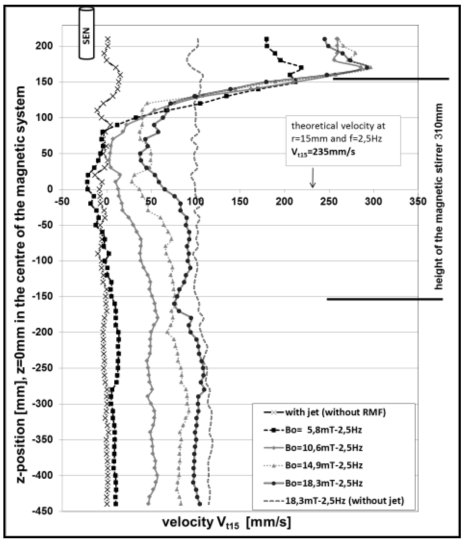


Fig. 4: Vertical profiles of the time-averaged, tangential velocity measured at a radial position of 15 mm showing the influence of the submerged jet

Our analysis in this study focuses on the effect of the jet flow on the rotating motion in the mold. For comparison, Fig. 4 includes a curve (dashed line) showing the tangential velocity at B_0=18.3 mT for the case without jet as presented beforehand in Fig. 3(b). A striking feature of the velocity profiles under the influence of the jet becomes apparent for vertical positions near the free surface. Rather large tangential velocities up to 300 mm/s can be measured here. These high rotational speeds can be seen on the free surface where a strong vortex is formed around the SEN associated with a significant deflection of the meniscus. Rotating fluid is conveyed from the side walls towards the SEN. The radially inward transport of angular momentum is the reason for the distinct acceleration of the fluid near the SEN. This secondary flow which exists in every finite rotating flow is significantly amplified by the impinging jet. The secondary flows driven by rotation and the jet have the same direction, with the jet flow being approximately two orders of magnitude stronger. Therefore, the acceleration of the rotation near the SEN and the deflection of the free surface are much more pronounced with the jet flow as for the case of the pure RMF-driven flow discussed in the previous section. It is interesting to note that the fluid above the stirrer rotates much faster than inside the magnetically forced region, the angular velocity even exceeds the magnetic field frequency f=2.5 Hz.

On the other hand, the submerged causes lower tangential velocities at R=15 mm in the upper stirring zone (between z=120 mm and z=-40 mm) in comparison to the situation without jet. The conservation of angular momentum is the reason for this phenomenon. The jet widens after leaving the SEN and pushes the rotating fluid from the core towards the side wall. This effect is not significant for positions farther down the strand (z   -40 mm).

Conclusions

This paper describes laboratory experiments in a 1:3 scale model for continuous casting of round blooms at voestalpine Stahl Donawitz GmbH. Fluid velocities inside the cylindrical mold were measured non-invasively by means of the ultrasound Doppler velocimetry (UDV). The measuring setup enables the detection of the horizontal flow being a combination of tangential and radial velocity component.

Flow measurements of time-averaged velocity profiles can be summarized by the following conclusions:

1. The tangential velocity resulting from the application of a rotating magnetic field (RMF) without jet flow shows different dependencies on the radius with respect to the vertical positions of the measurements.
2. The mold flow is composed of a primary, swirling flow and a meridional secondary flow which consists of two toroidal vortices lying on top of each other. This secondary flow is responsible for a redistribution of angular momentum within the mold.
3. Measurements of the tangential velocity for the situation of a pure RMF-driven flow at R=30 mm show a maximum rotation speed in the stirrer region and a continuous decrease of the tangential velocity with growing distance to the stirrer. On contrary, the tangential velocity does not vary significantly over the height at R=15 mm. In fact, the tangential speed outside the stirrer is even slightly higher as in the magnetic field region which can be attributed to the angular momentum transfer by the secondary flow.
4. A discharging jet through the SEN intensifies the meridional flow near the free surface. The superposition with the RMF-driven flow leads to a drastic acceleration of the rotating flow and a vortex formation near the SEN. This is accompanied by a strong deflection of the shape of the free surface of the liquid metal.

Acknowledgment

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