Comparison of Flow Measurements in a Cold Liquid Metal Model for Continuous Casting of Steel Carried Out by an Arrangement of Individual US Transducers and a Linear US Array

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Flow measurements by means of the Ultrasound Doppler Velocimetry (UDV) have been carried out in a cold liquid metal mockup experiment to model the continuous casting process of steel. The setup was realized in the mini-LIMMCAST facility and represents a 1:3 scale model of a typical industrial bloom caster. An arrangement of ten individual ultrasonic sensors attached to a commercial system and an academic UDV system with linear ultrasound array was mounted along the mold to capture the velocity distribution near the meniscus and the submerged entry nozzle (SEN). The results obtained by the two measurement systems are compared and show the superiority of the academic system due to its higher spatial resolution.

Keywords: Model Experiments in Liquid Metal, Continuous Casting, UDV

1. Introduction

1.1 Continuous casting and the need for model experiments

The Continuous Casting process is currently responsible for 96% of the steel production in the world and the annual amount of steel produced doubled in the last 20 years [1]. Due to its high energy and resource consumption and the customers increased demand for high quality steel products it is a process that needs to be investigated and optimized.

In the continuous casting process liquid steel is located inside the tundish and flows, driven by gravity, through the submerged entry nozzle (SEN) into a water-cooled mold, which has the shape of the desired end product, e.g. a slab, bloom or billet. The steel solidifies at the walls of the mold but the core stays liquid until after several meters of length, the whole cross-section has solidified completely. The cast product is continuously pulled through the mold, so that it’s length is much greater than the cross-section.

Flow control by means of electromagnetic fields is widely employed in industry to improve the casting process. In bloom and billet casting electromagnetic stirring (EMS) is applied. EMS uses alternating magnetic fields to induce a rotational motion near the solidification zone to improve the grain structure of the cast product.

Unfortunately, the real casting process is not accessible to complex flow measurement techniques due to the harsh conditions and high temperatures (around 1500 °C). Only few limited measurements are available, mainly approximations of the free surface velocity obtained by so called “nail-board tests”. The main experimental data that can be obtained from the real process is related to the properties of the final cast product, like grain structure, number of casting failures, inclusions and so on. To obtain a deeper understanding of the dominating flow phenomena in continuous casting and to provide data to validate numerical simulation codes, it is therefore necessary to perform model experiments.

The LIMMCAST experimental facilities at HZDR are used to model the continuous casting process in low temperature liquid metal experiments [2], [3]. The facilities allow investigations of several aspects of the continuous casting process and focus mainly on the determination of the flow structures that develop in the continuous casting mold. The high versatility of the facilities allow measurements in different casting geometries, also under the influence of magnetic fields.

2. Experimental Setup

2.1 Mechanical Setup

The study presented in this work is performed at the mini-LIMMCAST facility, which is composed of a liquid metal loop, operated at room temperature with GaInSn. Some physical properties of the model fluid are compared to those of liquid steel and water in Table 1. From the low electrical conductivity of water compared to that of steel it can be concluded that the use of a liquid metal as a model fluid is compulsory when the influence of magnetic fields has to be investigated.

The PMMA model of a round mold and strand for continuous casting of round blooms (see Figure 1) represents an industrial configuration in a scale of 1:3. It is located in the mini-LIMMCAST, has an inner diameter of 80 mm and a length of 800 mm. The submerged entry

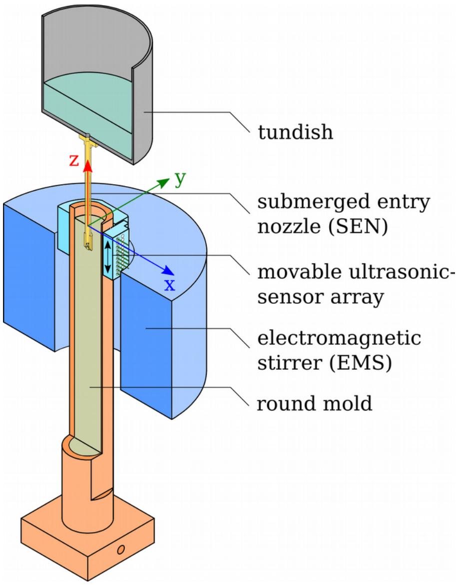

Figure 1: Schematic representation of the continuous casting model. The positioning of individual ultrasonic sensors is shown.

nozzle is of a swirl-type and induces a rotational flow inside the mold by four jets exiting the four twisted ports of the nozzle. Optionally the mould electromagnetic stirrer can be used to apply a rotating magnetic field to the set up. The coordinate system for the measurements is located in the center of the cylindrical model with the z-axis pointing to the top and z = 0 located on the free surface in the model mold.

Table 1: Physical properties of liquid steel at 1500 °C and GaInSn and water at 20 °C. The values for liquid steel are exemplary values from [4], [5], GaInSn values are from measurements [6] and water from [7].

		Liquid Steel	GaInSn	Water
density	kg / m³	~ 7 000	6 353	988
speed of sound	m / s		2 740	1 500
dyn. viscosity	mPa s	~ 2 ... 18	2.1	1
el. conductivity	1 / Ω m	~ 0.833 × 10^6	3.29 × 10^6	<50

2.2 Measurement Setup

For the application of Ultrasound Doppler Velocimetry (UDV) the walls of the model are milled even to enable measurements through the wall. The transducers measure the velocity component in x-direction (u) inside the model and are placed at several z-positions, at y = 15 mm. The diffraction of the ultrasonic beam due to the curvature of the inside wall of the round model mold can be neglected since the ultrasound velocity of PMMA (2700 ... 2800 m/s, according to [8]) is similar to that of GaInSn (c.f. Table 1). Sequential polling of neighboring transducers returns a two dimensional representation of the velocity component u in the xz-plane.

2.3 Description of the UDV devices

Ultrasound Doppler Velocimetry (UDV) is employed by a commercial system, the DOP 3010 by Signal Processing (Savigny, Switzerland) [9] and an academic UDV system by Franke [10].

The commercial DOP 3010 system can be used to measure the velocity profiles of up to ten individual transducers sequentially and returns the processed velocity profiles. The individual transducers are connected to the device, which is connected to the measurement PC via a USB connection. To apply measurement settings and record data a proprietary software for Microsoft Windows is supplied by the manufacturer of the DOP.

The multiplexing of the sensors is conducted by mechanical relays, which limits the switching time from sensor to sensor. The device's intended operational mode is to evaluate several profiles at one sensor before the velocities at the next sensor are evaluated. This operational scheme results in a good temporal resolution for each sensor but limits its use when a velocity information in two dimensions is required since the velocities at the sensors are not measured at the same time.

The academic UDV system can be used to obtain velocities with up to two linear ultrasonic arrays (Figure 2, [11]). Each linear array consist of 25 rectangular transducers, with piezo dimensions of 5 x 2.5 mm^2, which can be polled in user defined patterns, allowing parallel measurements by multiple transducers at the same time and therefore an increased measurement frequency. Also in sequential operation the switching time between the transducers is shorter and therefore results in a higher measurement frequency compared to the commercial system. The system consists of an electronic measuring system that handles the multiplexing and delivers the raw time-dependent echo for each transducer. The data is recorded by a PC which is

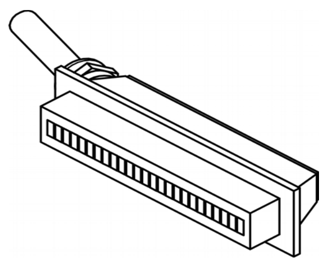

Figure 2: Representation of the linear ultrasound array.

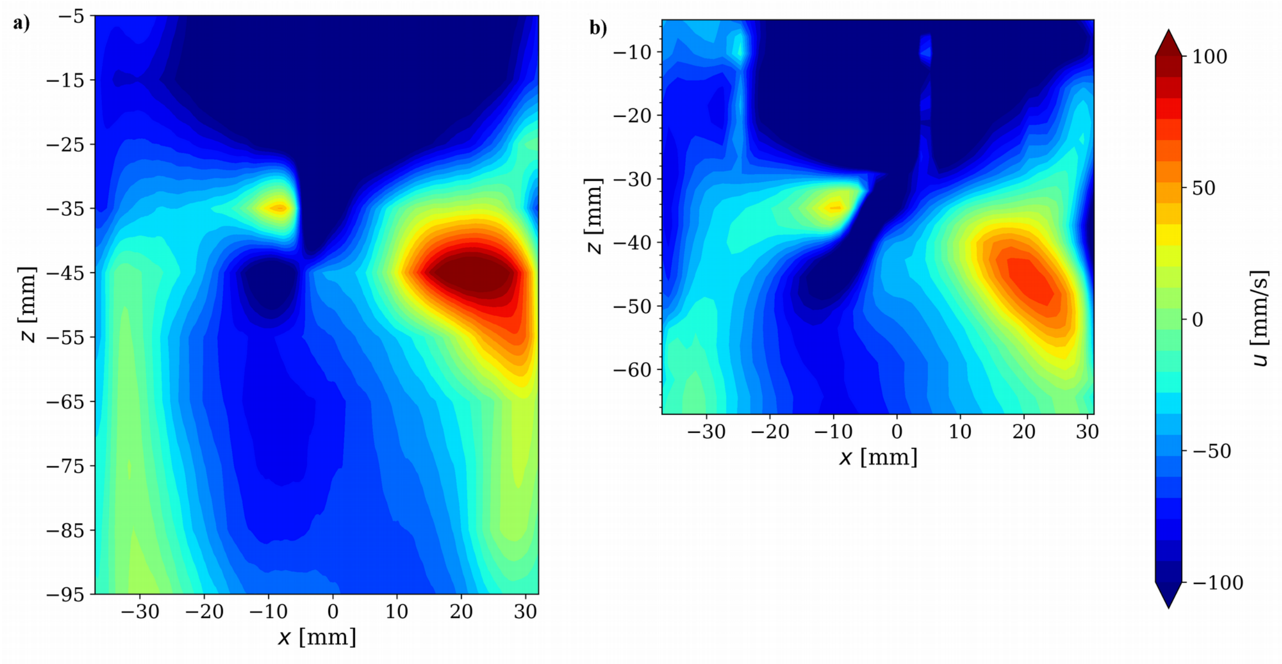

Figure 3: Time average contour plots of the measured horizontal velocity u at y = 15 mm. Measured with a) a DOP 3010 and ten individual transducers with a spacing of Δz = 10 mm, and b) the academic system and a linear ultrasound array of 24 measurement lines (Δz = 2.7 mm).

connected to the measurement system via a PCIexpress connection. Once the data is recorded the velocity estimation algorithm is applied to the raw data and returns the velocity data.

In this study both instrument are operated with a ultrasonic frequency of 4 MHz and achieve a frame rate of approx. 5 fps.

3. Results

Time average contour plots of the horizontal velocity u at y = 15 mm are shown in Figure 3 for the measurement with the commercial and academic system. In the DOP 3010 measurement (Figure 3a), the ten individual ultrasound transducers with a piezo diameter of 5 mm cover a vertical range of 90 mm with a spacing between the measurement lines of Δz = 10 mm. The main flow structures inside the mold can be identified by this measurement: The highest negative velocities appear under the free surface, while also at z = -35 mm and -45 mm two areas of high negative velocities can be seen. These two areas of negative velocities are caused by the twisted jet, that exists one port of the SEN. Positive velocities occur at z = -45 mm and correspond to a second jet, which exists the SEN from a second port perpendicular to the measurement plane. A high gradient of the velocity can be seen at z = -35 mm where positive and negative velocities occur in direct vicinity between x = -15 mm and x = 0.

Figure 3b) depicts the results obtained by the linear ultrasound array, which consists of 24 measurement lines with a spacing of Δz = 2.7 mm and covers a measurement range of 62 mm in z-direction. The higher z-resolution results in a much better representation of the flow structures inside the mold: The elliptic shape of the jet from the second port (at z = -45 mm, x = 20 mm) can be clearly identified. The lower maximum velocity compared to that in the DOP measurement might be caused by slightly different operating conditions since the two measurements were not conducted at the same time. Also the shape of the jet from the first port can be seen only in the array measurement. The interpolation in the contour plot together with the lower z-resolution of the measurement with individual transducers, is responsible for the misleading shape appearance. The contour plot of the array system shows two areas (x > -30 mm, y = 5 mm and y = 27 mm), where a standing echo caused by the SEN interferes and disturbs the velocity measurement. This could possibly be overcome by the application of a special filter to the recorded raw data in the velocity estimation algorithm.

Figure 4 shows velocity profiles over z at x = 15 mm, y = 15 mm for the commercial and academic system. The component u at this point was measured directly. Under the assumption of flow symmetry to the xz- and yz-plane, it is possible to introduce virtual measurements by rotating the measurement plane by 90° and therefore obtain the v-component of the velocity as $v_{x15,y15}$ =

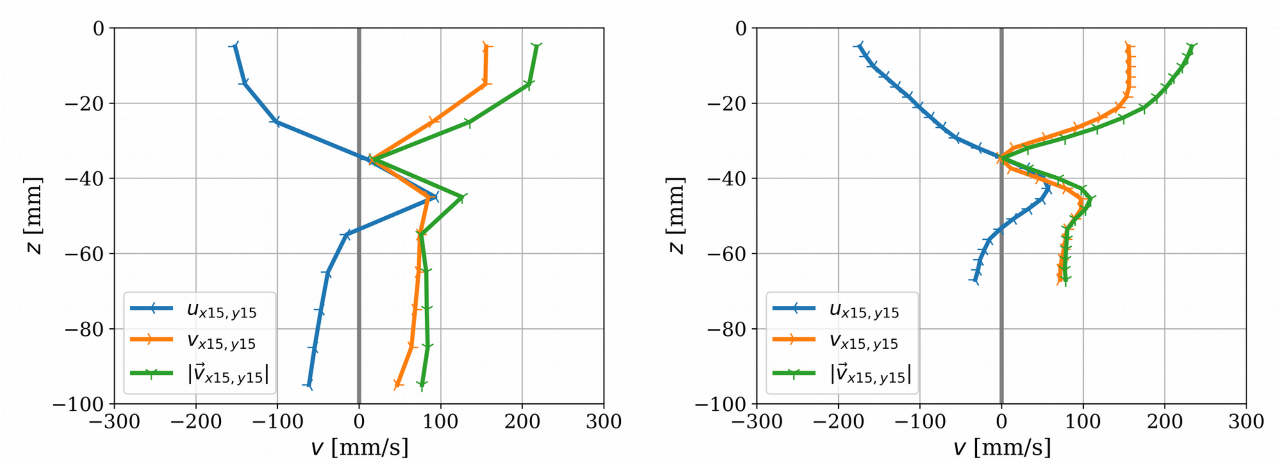

Figure 4: Time average velocity components and absolute velocity at x = 15 mm, y = 15 mm obtained from the measurements. $u_{x15,y15}$ measured directly, $v_{x15,y15}$ from symmetry assumption. Measured with a) a DOP 3010 and ten individual transducers, and b) the academic system and a linear ultrasound array.

$-u_{x-15,y15}$. The absolute velocity at x15, y15 is then calculated and shown in the figure.

The overall trend can be seen in both diagrams: The highest velocities occur under the free surface, above the nozzle ports, which are located between z = -35 mm and -25 mm. At the lower edge of the nozzle (z = -35 mm) the time average velocity is zero and rises again until z = -45 mm where a local maximum can be seen. At this depth the jet from the nozzle port crosses the measurement line. At depths below z < -52 mm the velocity stays quite constant until the end of the measurement area at z = -67 mm.

The higher resolution in z-direction by the academic linear array (Figure 4b) enables a better identification of the local velocity maxima around z = -45 mm. In contrast to the measurement with individual transducers it is possible to see that the maxima for u and v occur at a slightly different z-position.

4. Conclusions

Measurements with Ultrasound Doppler Velocimetry by a commercial system with individual transducers and an academic system with a linear transducer array in a liquid metal model for continuous casting of round blooms have been presented and compared. It was shown that the overall representation of the flow structures could be elaborated by both systems. While the commercial system is less complicated to use, the academic UDV system showed its superiority due to its higher number of channels, the much finer resolution of the linear array and the possibility to adjust all parameters and apply different data processing since the source code of the software is fully available.

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