MEASUREMENTS OF THE VELOCITY FIELD IN LIQUID METALS

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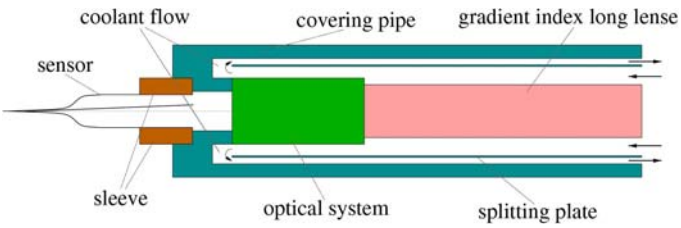
1. Introduction

Large effort is permanently directed to optimise methods and facilities for material processing technologies like melting, refining or casting of metals or alloys. The main goals are an improvement of the final product quality, an enhancement of the process efficiency and an economical consumption of resources and energy. In processes involving electrically conducting liquids, the application of an external magnetic field offers efficient opportunities for a contactless flow control and fluid handling. Further developments require a better knowledge about the details of the flow structure, the transport properties of the flow or the melting and solidification process, respectively. A better understanding and optimisation of liquid metal processes requires experimental data of the velocity field. Numerical simulations alone are often of limited value. The choice of commercially available techniques to measure the velocity structure of opaque fluid flows at high temperatures is very poor. Possibilities are known to measure the velocity at a local point by means of different invasive probes such as electromagnetic potential probes [1,2], the Mechano-Optical Probe (MOP) [3], hot-wire anemometers [4] or Karman Vortex probes [5]. New approaches are the application of the Ultrasound Doppler Velocimetry (UDV) [6-8] or the reconstruction of velocity patterns from magnetic field measurements (CIFT) [9]. However, some serious restrictions always exist to apply particular sensors, for instance, the temperature range, the type of liquid metal, the velocity range, the accuracy of the method, or the presence of electromagnetic fields.

During the last years the activities of the MHD department were focussed to develop and to qualify techniques to measure the flow rate and the local velocity of the liquid metal and two-phase flow characteristics such as void fraction, bubble velocity and bubble size, respectively. In liquid metal model experiments local sensors as well as integral methods have been tested and applied. Some promising techniques such as the MOP, the UDV or the Contactless Inductive Flow Tomography (CIFT) will be presented within this paper.

2. Mechano-optical Probe (MOP)

A new system based on a mechano-optical principle has been developed to measure local flow velocities. A sketch of the MOP is shown in Figure 1. The measuring equipment consists of a mechanical sensor, a specialized optical system, a CCD-array and a PC. The sensor is made from a quartz glass tube (∅ 2.5 mm) with a molten tip connected with a very thin rod (∅ < 0.05 mm) concentrically fixed only in the front point of the tip. To allow applications in high temperature melts a cooling system is integrated into the sensor. The interaction with the moving fluid causes a deformation of the sensor tip resulting in a displacement of the upper end of the glass rod, which is observed by the CCD-array sensor being connected via a frame grabber card with the computer. A special software has been implemented allowing the evaluation of the digitized pictures. The drag force acting on the sensor in the fluid was modelled by Eckert et al. [3]. From those estimates the rod displacement shows a parabolic dependence on the flow velocity. Such a qualitative behaviour was confirmed by the results obtained from the calibration of the sensors done at a circular rotating channel.



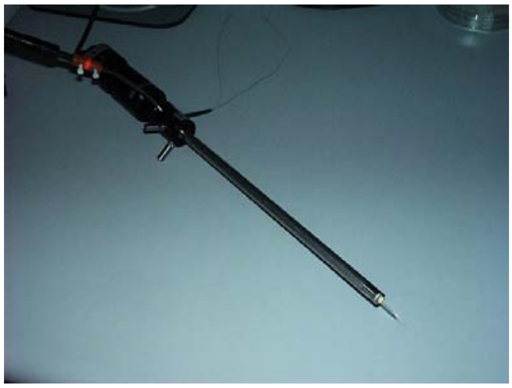


Fig. 1: Scheme and photograph of the Mechano-Optical Probe (MOP)

The suitability of the sensor was demonstrated in water and in GaInSn at room temperature as well as in SnPb and in PbBi at temperatures up to 400 °C. During the experiments the temperature of the optical system inside the sensor was measured by an internal thermocouple. The values observed were always significantly below 100°C. We can therefore expect the sensor to work reliably at higher temperatures of about 800°C. Besides the capability to work at high temperatures the mechano-optical measuring principle excludes perturbations of the signal arising from external electromagnetic fields or electric noise.

3. Ultrasound Doppler Velocimetry (UDV)

UDV is a non-intrusive technique to measure velocities of liquid flows based on the ultrasonic pulsed echo method [6]. The feasibility of velocity profile measurements by UDV has already been demonstrated for low temperature liquid metals as mercury [10, 11] and gallium [12]. Recently, successful measurements have been published for liquid sodium [7]. It is worth to note that the measurements have been performed through the stainless steel wall of the channel. The use of the conventional transducer made of PZT (lead-zirconium-titanate) based materials restricts the range of application of ultrasonic techniques to maximum temperatures of about 150°C (long term load) and 200°C (short term load), respectively. To overcome this problem we followed the approach to apply an acoustic wave-guide for a thermal and chemical decoupling between the active transducer and the fluid. An integrated ultrasonic probe as shown in Figure 2 was designed consisting of the piezoelectric element and the acoustic wave-guide [8]. The wave-guide is fabricated from a stainless steel foil with a thickness of 0.1 mm. The wave-guide is closed at the front end by means of laser beam welding leading to a flat stainless steel surface. This surface being in direct contact with the melt has to be prepared before the measurements to obtain a sufficient wetting with the liquid metal. The wave-guides have a diameter of 7.5 mm and a length between 200 and 1000 mm. The working frequency of the transducer is 4 MHz.

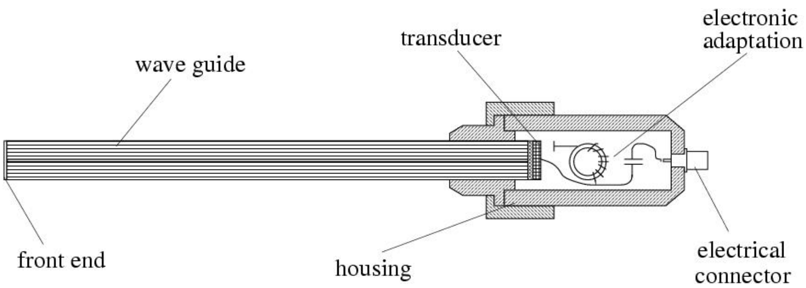


Fig. 2: Schematic view of the integrated ultrasonic transducer

As an example we consider here the motion of single argon bubbles rising in the ternary, eutectic alloy GaInSn ($T_{melt} \approx 10°C$) under the influence of a DC longitudinal magnetic field. As shown in Figure 3 the experiments were performed within an open, cylindrical container made from Perspex with a diameter of R = 100 mm. The cylinder was filled until a height of H = 220 mm. The column is positioned concentrically inside a Helmholtz configuration of two water-cooled copper coils with a vertical distance of 150 mm and an inner diameter of 210 mm. This configuration provides a homogeneous DC longitudinal magnetic field over the fluid volume. The coils were supplied with a D.C. electric current up to 1600 A corresponding to a maximum field strength of 0.3 T. The ultrasonic transducer was installed at the bottom wall outside of the cylinder directly behind the nozzle. The ultrasonic beam was directed vertically along the bubble path allowing measurements of the vertical bubble and liquid velocity component.

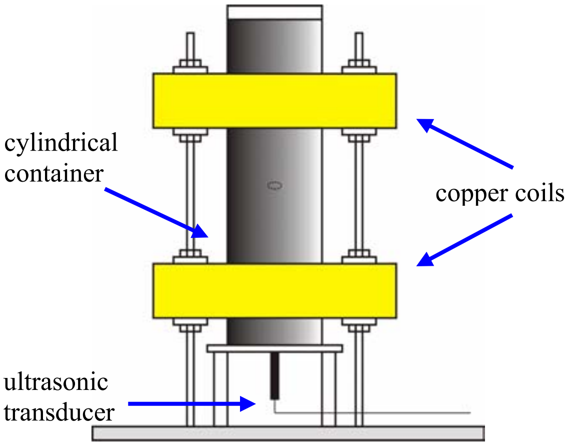


Fig. 3: Schematic scheme of the experimental configuration

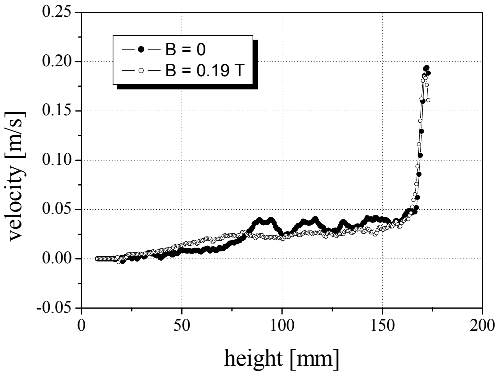


Fig. 4: Snapshots of the vertical velocity in the bubble wake when the bubble has reached a vertical height of 170 mm

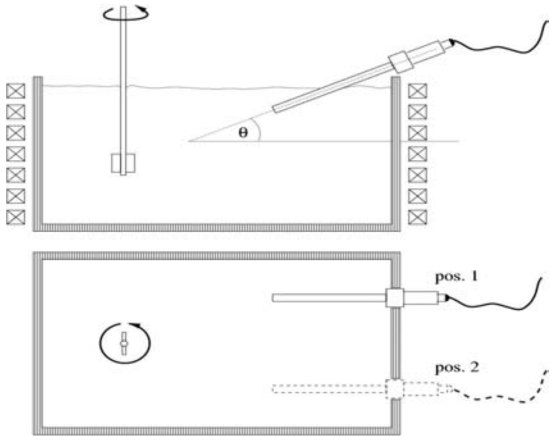


Fig. 5: Schematic view of the arrangement of the CuSn experiment

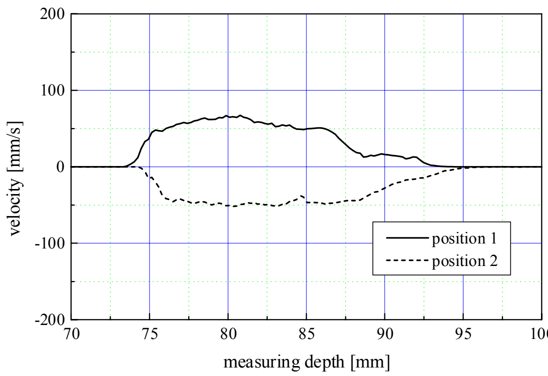


Fig. 6: Velocity profile measured in the CuSn melt at both sensor positions

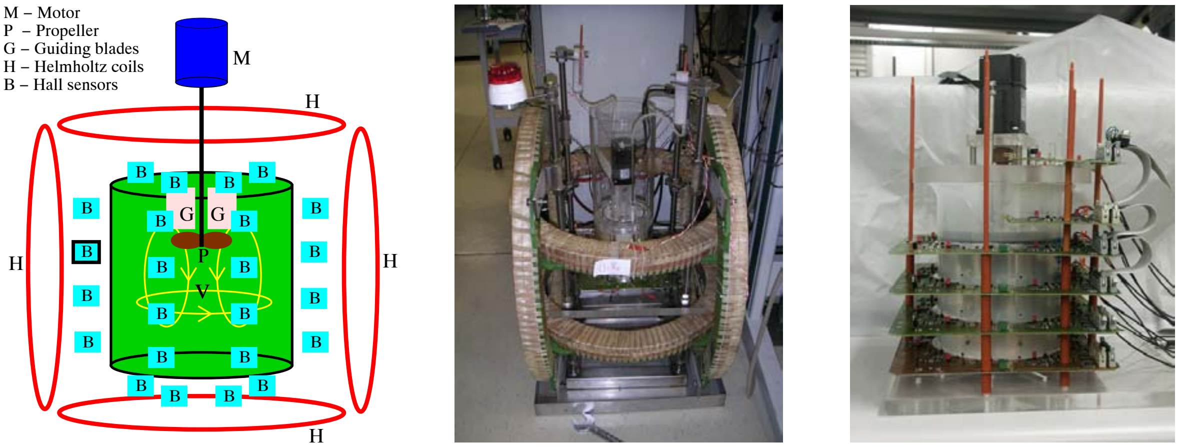
Vertical velocity measurements along the cylinder axis reveal the magnetic field influence on the bubble wake. Snapshots from these measurements shown in Figure 4 were acquired at those moments when the bubble was detected at a vertical position of 170 mm. In the case without magnetic field the vortex structure of the wake can clearly be recognized in the signal. The vertical liquid velocity behind the bubble generally becomes more uniform if the magnetic field is turned on, in other words the velocity gradient along the field lines is significantly reduced. Besides the damping of the velocity in the wake region, an elongation of the wake structure in vertical direction due to the anisotropy of the magnetic field influence can be observed. Raising of the magnetic field strength causes an enlargement of the eddies in the wake.

Other demonstrations at high temperatures were done in a CuSn alloy (Cu35Sn65, T_{melt} = 550°C) at a temperature of about 620°C and liquid aluminium at 750°C, respectively. The metal was melted inside a rectangular alumina crucible (130 × 80 mm^2) by means of an inductive heating system. The depth of the melt was about 40 mm. A mechanical stirrer was used to generate a flow. The integrated sensor was dipped into the metallic alloy through the free surface with an angle of 35° with respect to the horizontal line (Figure 5). Results obtained from this experiment are shown in Figure 6. The velocity profiles determined at both measuring positions are similar with respect to the shape and the amplitude and show different signs in accordance with the chosen rotation direction of the mechanical stirrer. Several repetitions of the measurements showed the reproducibility of the results.

4. Contactless Inductive Flow Tomography (CIFT)

The three-dimensional distribution of the velocity field is of crucial interest for a number of metallurgical applications. A contactless determination of the full flow field is highly desirable, even under the restriction that it provided only a rough picture of the velocity structure. Three-dimensional inductive velocity reconstruction was the topic of some recent papers [9, 13-15]. In [13,14] we had addressed the inverse problem of velocity reconstruction in conducting fluids from combined magnetic field and electric potential measurements. Basically, the electromotive force, which is proportional to the cross-product of the desired flow velocity and the externally applied magnetic field, gives rise to an additional induced magnetic field, which is measurable outside the fluid volume, and to an induced electric potential which can be measured at the fluid boundary. A particular result of [14] was that the main velocity structure of the flow can be reconstructed from such a combined magnetic/electric field measurement, apart from an uncertainty in the radial distribution of the flow. Later, in [9,15], we considered the case of using two sets of measured induced magnetic fields instead of a single set together with one set of electric potentials. Such a contactless method is especially interesting for those applications in which the electric potential measurement at the fluid boundary is hard to manage. This seems particularly important for hot and aggressive fluids or for facilities where the fluid boundary is not accessible for technological reasons.

In order to demonstrate the feasibility of the contactless inductive velocity reconstruction method in real applications an experiment has been set up in which the propeller driven flow of a liquid metal has to be reconstructed solely from externally measured magnetic field data (Figure 7). We use 4.4 liters of the eutectic alloy GaInSn. The flow is produced by a motor driven propeller with a diameter of 6 cm inside a polypropylene vessel with 18.0 cm diameter. The height of the liquid metal is 17.2 cm, giving an aspect ratio close to 1. The propeller can rotate in both directions, resulting either in upward or downward pumping. The rotation rate can reach 2000 rpm producing a mean velocity of 1 m/s, which corresponds to a magnetic Reynolds number of $Rm \approx 0.4$. The flow structure for the two directions is not symmetric. The downward pumping produces, in addition to the main poloidal roll, a considerable toroidal motion, too. For the upward pumping, this toroidal motion is, to a large extend, inhibited by guiding blades installed above the propeller. It was one of the tasks of the experiment to discriminate between those different flow structures.



(a) (b) (c)

Fig. 7: The CIFT experiment. Schematic view (a), total view (b), and details of the vessel with the circuit boards for the Hall sensors and AD transformer (c).

For upward and downward pumping, Figs. 8 and 9 show the induced magnetic fields measured at the 49 positions, and the inferred velocity field at 52 discretization points. In Fig. 8c we see the upward flow in the center of the cylinder and the downward flow at the rim, but nearly no rotation of the flow. In Fig. 9c we can identify the downward flow in the center and the upward flow at the rim, together with a rotation of the flow. This absence and presence of the swirl is an important feature which can evidently be discriminated by our method. It is worth to note that not only the structure of the flow, but also the range of the velocity scale is correctly reproduced by the inversion.

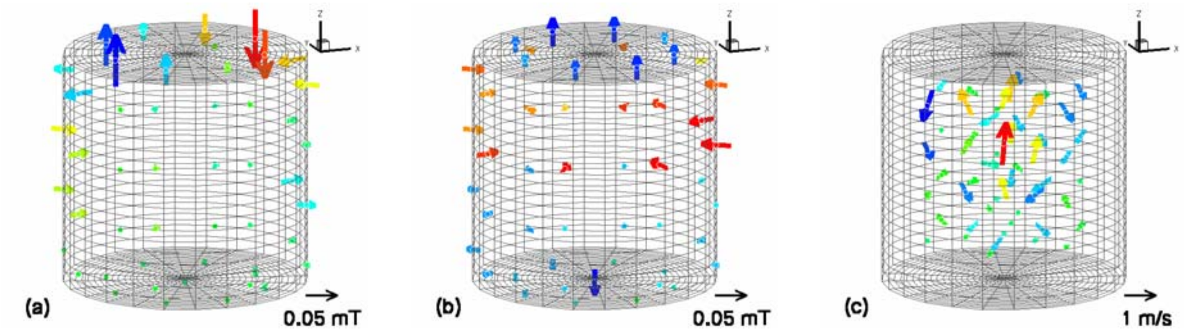


Fig. 8: The measured magnetic fields and the reconstructed velocity field for the case that the propeller pumps upward with 1200 rpm. Measured induced field for transversal applied field (a); measured induced field for applied axial field (b); and reconstructed velocity (c). For (a) and (b) the color coding discriminates between ingoing and outgoing magnetic field lines, for (c) the color coding mirrors the axial component of the velocity.

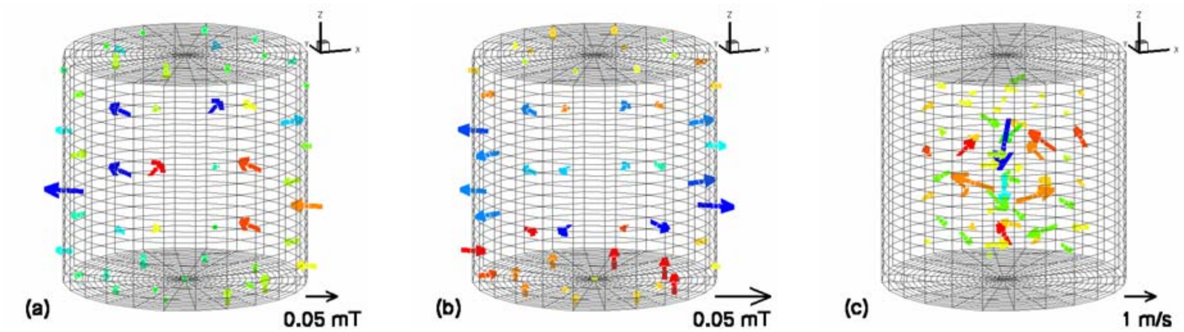


Fig. 9: The same as Figure 8, but for the propeller pumping downward with 1200 rpm.

5. Conclusions

Each measuring technique is marked by a list of advantages and drawbacks, the choice of an optimal method has to be done considering the actual experimental configuration and parameters. Moreover, it is important to identify the kind of information that should be obtained from the experiment (flow rate, local velocities, turbulence intensities,...) as well as the spatial and temporal resolution and accuracy which should be achieved. Nevertheless, we can conclude that for liquid metal model experiments at a range of moderate temperatures (< 300°C) a sufficient number of measuring techniques are available to investigate the flow structure. Moreover, we have presented here some measuring techniques showing the capability to be extended to an application range of high temperatures (700-1000°C) being attractive for industrial applications.

Acknowledgement

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