MEASUREMENT TECHNIQUES TO DETERMINE LOCAL QUANTITIES IN LIQUID METAL FLOWS

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1. Introduction

In the last few decades magnetohydrodynamic (MHD) effects have attracted growing interest because of its potential impact on numerous industrial technologies such as metallurgy, crystal growth, electron or laser beam melting/evaporation of surfaces, etc.. In processes involving electrically conducting liquids, the application of an external magnetic field offers efficient opportunities for a contactless flow control and fluid handling.

However, for a well-aimed optimisation of the flow structure local information about flow quantities like velocity, pressure, temperature, concentration or void fraction are necessary. The techniques of local and instantaneous measurements in liquid metals are known to be much more difficult than in classical fluids like water or air. Whatever diagnostic method is used, two categories of problems have to be solved: those due to the nature of the fluid (opaque, hot, chemical aggressive) and, in addition, due to the presence of electromagnetic fields. Almost all conventional measuring techniques used for ordinary flows, for instance LDA or hot-wire anemometry, totally fail in liquid metal MHD flows or their applicability is strongly limited. As a consequence, no commercial measuring systems are available.

During the last years activities of the MHD department are focussed to develop and to qualify techniques to measure the 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.

2. Measurements of the liquid metal velocity

2.1 Potential-difference Probe

The potential-difference probe (sometimes also called conductance anemometer) can already be considered as standard technique in MHD experiments (see Branover [1]). The problem to be solved here was the development of special sensors being capable of working reliably in liquid sodium.

If a flow is exposed to a sufficiently strong magnetic field the measured electric potential drop \( \Delta \phi \) between the electrodes is essentially determined by the \( \mathbf{u} \times \mathbf{B} \) term [2] (see figure 1), resulting in a linear dependence on the flow velocity. The following advantages promote the use of such kind of probes:

- The geometry of the probe is very simple (two isolated electrodes). Therefore, a good minimisation of the sensor size is possible to reduce the flow disturbances caused by the probe itself.
• The sensor is reliable and robust in liquid sodium at temperatures up to 320°C.
• The relation between the voltage signal and the fluid velocity is linear for a wide parameter range.
• The sensor responds promptly and guarantees the suitability to measure the turbulent velocity fluctuations.

Fig. 1: Principle of the potential probe

However, the use of the potential probe is combined with some serious limitations and difficulties. The measuring principle requires the application of a steady magnetic field, whereas the velocity component parallel to magnetic field lines cannot be determined. To measure the velocity fluctuations one has to deal with very small signals (some μV), which can be disturbed by a significant level of electric noise arising from components of the experimental facility (electromagnetic pump, heating elements). Moreover, the linear relation between output signal and velocity is not valid if the flows is bounded by highly conducting walls or influenced by changes of the magnetic field, the cross sectional area or the wall conductance [2].

Fig. 2: Turbulence intensity as a function of Stuart number N

Fig. 3: Slope of the spectral energy versus Stuart number N
Potential probes have been employed to characterise the local, turbulent properties of liquid sodium channel flows by the determination of the turbulence intensities and the power spectra [2]. Some interesting effects have been revealed, for instance, the increase of the turbulence intensity with increasing Stuart number $N = \frac{\sigma B^2 L}{\rho u}$ (see Figure 2) or the steeper slope of the spectral energy in the inertial range with increasing Stuart number starting from a $k^{-5/3}$-behaviour for $N \leq 1$ and reaching a $k^{-4}$-scaling at $N \approx 100$, which becomes obvious in Fig. 3.

### 2.2 Mechano-optical probe

A new measuring system based on a mechano-optical principle has been developed to determine local flow velocities. Our intention was to meet the following requirements:

- The sensor should be able to work in opaque fluids at high temperatures.
- The resolution should be sufficient to measure also velocities below 0.1 m/s.
- The system should be characterised by good spatial resolution.
- Flow disturbances caused by the sensor should be negligible.
- An influence of external electromagnetic fields or electric noise on the signal should be avoided.

![Fig. 4: Measuring principle of the mechano-optical sensor](image)

The sensitive part of the probe is a glass tube formed to a thin conical tip which is in direct contact to the fluid (see figure 4). A small glass rod, the so-called pointer, is positioned inside this glass tube and connected with the sensor tip only at the front point. The interaction with the flow causes a deformation of the sensor tip resulting in a displacement of the pointer. The flow velocity can be derived from this observed displacement. A detailed description of the measuring principle and the equipment is given by Eckert et al. [3]. The authors also modelled the drag force acting on the sensor in the fluid. From those estimates the rod displacement shows a parabolic dependence on the flow velocity. Such a qualitative behaviour has been confirmed by first experimental investigations, where the sensors have been calibrated in a circular rotating channel.

The sensors have been tested in water and InGaSn at room temperature as well as in SnPb and PbBi at temperatures up to 300 °C. The suitability of the sensor in this temperature range was
demonstrated. A further increase of the temperature can be questionable, because the elastic module of the borosilicate glass becomes then a function of the temperature. The transformation temperature of this type of glass is approximately 650 °C. To use the measuring system at higher temperatures, for instance in aluminium at about 700 °C, the probe tip has to be manufactured from different material. A possible alternative is quartz glass with a transformation temperature above 1200 °C. The adaptation of the existing technology for the sensor production to quartz glass is the present subject of investigation.

The measuring system has already been used to determine the local flow structures in real experimental flows. In our lab swirling flows of InGaSn alloy in a circular box created by the application of time-variable (travelling and/or rotating) magnetic fields have been investigated. The interest is focussed on geometry and parameters relevant for crystal growth technologies. Measured profiles of the azimuthal velocity obtained at different frequencies and field amplitudes are displayed in Figure 5. In case of low frequency the increase of the velocity starting from the centre to the boundary seems to be linear. This indicates that the flow structure of the melt can be associated with a solid body rotation. The application of a magnetic field rotating with a significantly higher frequency results in an evident variation of the profiles. The enhancement of the velocity maximum near the boundary corresponds to the above-mentioned skin effect of the concentration of the field action in the boundary region.

Fig. 5: Radial profiles of the azimuthal velocity in a cylindrical flow driven by a rotating magnetic field

Another application will be the channel flow of liquid sodium at the experimental sodium loop of FZR. It is planned to measure the velocity profiles in the channel cross section with and without transverse magnetic field. The obtained results shall be compared with the existing data of the potential probe. Moreover, first measurements have been confirmed in co-operation with industrial partners.

2.3 Ultrasound-Doppler method

The instantaneous velocity profile which is one of the most fundamental quantities in fluid flow phenomena can be obtained by the Ultrasound-Doppler technique [4]. Main advantages are the ability to investigate flows of opaque liquids in a non-intrusive way and to deliver complete velocity profiles in real-time. The principle of this method is to utilise the pulsed
echo technique of ultrasound and to detect the Doppler shift of the ultrasound wave reflected from moving particles suspended in the fluid.

The general feasibility of velocity profile measurements has already be shown in low temperature liquid metals like mercury [5] and gallium [6]. However, the technology reveals severe limitations regarding the practicability of measurements at high temperatures and the useable velocity range. Therefore, activities have been started to develop this technique for high temperature liquid metal applications. First tests have already been performed at the sodium facility of FZR. At the present status the following main problems have been identified:

- Limitation of the temperature range of the ultrasonic transducer: The transducer can be used up to a maximum working temperature of 150°C. Moreover, the efficiency at temperatures close to this maximum is low.
- Coupling of the ultrasound into the fluid: Due to the high temperatures and the chemical properties of liquid sodium the transducer was installed at the outer channel wall. Therefore, an excellent wetting of the liquid metal at the inner surface of the wall is required to get a small acoustic impedance at the interface steel - liquid metal.
- Availability of tracers in the flow: The sensitivity and accuracy of the method depends on the occurrence of flow tracers reflecting the ultrasonic beam. If the amount of naturally existing impurities is not high enough, additional scattering particles have to be added to the flow.

3. Measurements of two-phase flow parameters

3.1 Resistance probes

The single-wire resistance probes are local sensors to measure the local void fraction well-known from the applications in ordinary two-phase flows (see Jones & Delhaye [7], Prasser [8]). There is an electrically conducting tip (Cr/Ni wire, 0.1 mm) in direct contact with the liquid metal. The probe is supplied with an alternating current (1-10 kHz), which results in an electric current flowing from the probe tip to the cladding pipe acting as the other electrode. The gas contact at the sensitive wire is detected by an interruption of the current. Due to the huge differences in the electrical conductivity between the gas and the liquid metal we obtain very sharp signals easy to evaluate by a threshold method.

An extensive survey about a number of two-phase flow measurements carried out by several kinds of local sensors characterised by different tip sizes and probe shapes is provided by Cartellier & Achard [9]. As a rough estimation it may be generalised, that bubbles with a minimal size being about 10 times higher as compared to the probe wire can be detected by the sensor. In our experiments single-wire conductance probes with wire diameters of 25 μm and 100 μm have been used.

Double-wire resistance probes have been used to measure gas velocity and bubble size by detecting the time delay of the bubble contact between two wires arranged closely together in flow direction. But, such a sensor configuration enhances seriously the tip size of the probe. In fact, reliable measurements of bubble diameters less than 1 mm by means of local conductance probes have to be considered as doubtful. Despite of measuring errors of bubble
velocities and chord lengths up to about 20 % for bubble diameters of a few mm also
measurements by means of double-wire probes provide useful information about the structure
of the two-phase flow.

Fig. 6: Local distributions of the void fraction $\alpha$ [%] in a turbulent sodium channel flow
exposed to a transverse magnetic field (Re = 9300)

Figure 6 shows some representative isoplots of the void fraction distribution in the cross
sectional area of a MHD channel flow obtained at different Reynolds numbers and different
values of the magnetic field by Eckert et al. [10]. In the case of a transverse field direction an anisotropic distribution is observed indicating the existence of quasi-two-dimensional vortices as typical for turbulent MHD flows.

3.2 X-ray measurements

A direct observation of gas bubbles in non-transparent liquid metals is impossible by optical means. Despite of the substantial technical effort, the use of high energy radiation allows also investigations of liquid metal two-phase flows. X-ray measurements can be used to directly observe gas bubbles rising in liquid metals. However, due to the high attenuation in the liquid the experiment is restricted to narrow flow domains. The thickness of the fluid, which can be screened by X-ray, depends of the atomic number of the liquid metal.

Experiments with mercury and InGaSn, respectively, have been performed at the X-ray facility of the FZ Jülich. A 450kV industrial X-ray tube was employed for the inspection of liquid metal contained in rectangular cell made from Perspex. A sketch of the experimental configuration is depicted in Figure 7. For a detailed description of the experimental technique the reader is referred to Stechemesser et al. [11]. Flow sequences were recorded in mercury layers with a depth of 6 mm at 450 kV and 10 mm for InGaSn at 147 kV. Experiments with InGaSn would allow an enlargement of the fluid domain, whereas for mercury the limit has been reached. The resolution of the X-ray screening technique is restricted to a bubble diameter of about 1 mm. The decrease of the X-ray absorption inside the liquid volume due to smaller gas bubbles is not sufficient to produce a corresponding image with a reliable contrast.

Fig. 7: Experimental configuration of the X-ray screening technique

Fig. 8: Gas injection through a nonwetted sintered metal tube into mercury (observed by X-ray technique)

The features of a gas injection into mercury by means of miscellaneous gas injectors for the case, if the surface of the injector is not wetted by the liquid metal, has been demonstrated [12]. Among other types of gas injectors a bent stainless steel tube has been used completed with a sintered metal body at the end having a mean pore diameter of 4 μm. The gas flow can escape from the injector only at the upper surface. Nevertheless, it becomes obvious in Figure
that instead of a bubble formation directly at the end of the pores, a gas layer is growing around the injector until the buoyancy force will be high enough to promote the release of particular, large bubbles. However, in this situation the size of the generated bubbles does not depend on the typical diameter of the injection pores.

References


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