EXPERIMENTAL TECHNIQUES FOR HEAVY LIQUID METALS

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Abstract

This paper summarizes the most interesting measurement systems which were tested in the PbBi loops of the KALLA laboratory in Karlsruhe with the last 5 years. There are several experimental techniques which were well proven in air and water and thus could be transferred similarly to liquid metals: These techniques are split into measuring local quantities as temperature, pressure e.g. by means of pressure taps or velocities using Pitot and Prandtl tubes or the Ultra-Sound-Velocimetry (UDV) for local flow velocities, as well as global states like flow rate utilizing nozzles, orifices or turbines. Unfortunately, as liquid metals are opaque, an optical access is not given. Instead, one can take advantage of the high electric conductivity of liquid metals to measure integral and local quantities, like electromagnetic flow meters and miniaturized permanent magnetic probes for local velocity measurements.

This article describes some of the techniques used in the KALLA for different liquid metals, explains the measurement principle and shows some of the results obtained using these techniques. Additionally a few words are spent with respect to the measurement errors to be expected and some hints for a correct placement of the individual sensor in the liquid metal environment.

Introduction

The thermo-physical properties of liquid metals with low melting and high boiling temperatures, like the alkali metals with small atomic weight and heavy liquid metals like lead or its alloys, makes them attractive as coolant candidates in advanced nuclear fusion and fission systems. The fast neutron spectrum and the high neutron yield of the spallation reaction enable simple and robust flow structures with high energy densities. Thus, liquid metals are favourized for the development of neutron spallation sources, for fusion blankets, and as core coolant of fast reactors as well as for heavy ion fragmentation. However, the practical use of liquid metals still needs to be demonstrated by experiments and by numerical predictions.

The validation of numerical predictions for nuclear systems using lead or eutectic lead-bismuth alloys requires measurement technologies especially adapted to them. Besides the relatively high density, corrosivity and opaqueness of these liquids, the sensors being in contact with them are facing elevated temperatures in the range from 200°C to 550°C or even more. Although in the past decades a lot of progress has been achieved in developing liquid metal adapted measurement devices in the context of sodium operated fast breeder reactors, only part of the knowledge can be transferred to lead or lead alloy cooled systems because of its specific properties.

Fluid mechanical measurement devices are divided in principle into two classes of systems. One is the measurement of integral quantities, which are mostly scalars like the flow rate, the pressure in the system or the mean temperatures. Such devices are needed to control the nuclear facility or the experimental loop and to define inlet and outlet conditions. The other class is formed by measurement of local quantities like the velocity distribution, temperature profiles or the surface structure and shape, which is necessary to capture effects predicted by computational fluid dynamics (CFD). The detection of these particular effects in benchmark problems allows the development of new physical models and the validation of CFD simulations. Regarding the physical principles, the border between the two classes is not sharply defined. For instance by miniaturisation of pressure measurement devices, the Pitot or Prandtl tube can be scaled down to detect local flow velocities.

Many physical principles can be used to determine the flow rate of fluids in pipes, but the physical and chemical properties of lead bismuth exclude some of them right from the beginning. The opaqueness, which is common to all liquid metals, disables all optical methods. The electric conductivity, on the other hand, opens access to other measurement systems which can hardly be used for ordinary liquids. The following sections describe the physical principles of some methods tested in the KArlsruhe Liquid Metal Laboratory (KALLA) for which a detailed description may be taken from Schulenberg et al. (2007). KALLA consists of several stagnant and loop experiments using different liquid metals and enables to study flow in complex geometries, to develop measurement techniques for local and global quantities, to assess the materials compatibility in different conditions and to generate basic physico-chemical data as for instance the wetting capability of the liquid metals, oxygen solubility and others. A general overview and detailed descriptions of these and other measurement systems for heavy liquid metals have recently been summarized by Stieglitz (2007) in the liquid metal handbook.

Flow rate

In contrast to conventional fluids, for which momentum change or pressure difference based methods are usually applied in form of turbines, orifices, nozzles or gyrostatic flow meters, the liquid metals offer the capability to take advantage of the large specific electric conductivity. These electromagnetic flow meters can be operated in two modes; one using a permanent magnetic field, a so-called DC flow meter, and the other one utilizing an alternating magnetic field, which is later referred to as an AC flow meter.

DC electromagnetic flow meter

The permanent magnet flow meters (PMF) are mostly used if the installation volume is rather small, where low flow rates have to be resolved or only a small pressure drop is allowed. According to Faraday's law, an electrically conducting fluid flowing perpendicular to a magnetic field induces an electric field. The strength of this electric field is proportional to the flow velocity and can be measured with diametrically opposed electrodes on the pipe walls perpendicular to flow direction and magnetic field *B*, as sketched in figure 1.

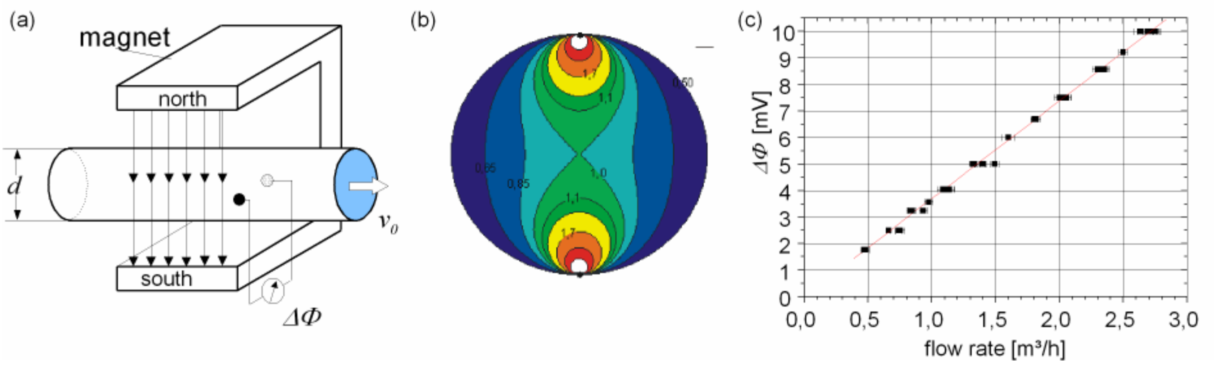


Fig. 1: (a.) Sketch of the DC electromagnetic flow meter, (b) magnetic field distribution in a PMF with a conventional permanent magnet and (c) typical PMF signal $\Delta\Phi$ in [mV] as a function of the flow rate measured in a $Pb^{45}Bi^{55}$ flow at T=300°C in the THEYS loop of KALLA.

For an axially symmetric flow profile and an infinite, homogenous magnetic field, the measured electrode voltage $\Delta\Phi$ depends on the mean velocity u_m, on the mean magnetic field strength B and the pipe diameter d as

$$\Delta\Phi = c u_m B d \tag{1}$$

where c is to the first order a constant mainly depending on the ratio of the specific electric conductivities of the wall (σ_W) compared to that of the fluid (σ_f) and thus temperature dependent. Usually, c is determined experimentally, but great care has to be taken that isothermal conditions are present during calibration, see e.g. Elrod and Fouse (1952). A general problem of the PMF is the influence of the boundary conditions changing during operation, which requires a regular re-calibration. In particular, the non-definite wetting behaviour of heavy liquid metals such as gallium or lead and lead alloys to the electrically conducting structure material can lead to incorrect readings even during a single day. Although the pressure drop in the piping may integrally indicate a mechanical contact of the fluid to the wall, an electric contact resistance may still resist at this interface. Due to this contact resistance, part of the current induced in the fluid by the magnetic field B may short-circuit within the fluid and does not enter the walls generating the potential difference $\Delta\Phi$. This effect is of crucial importance if σ_W/σ_f is of O(1) as for the *h*eavy *l*iquid *m*etals (HLM) like Pb, PbBi, Hg, Ga or the corresponding alloys using steel pipes. Usually the PMF´s utilize permanent magnets which are submerged to an aging process and which exhibit a non homogenous B-field distribution as displayed in figure 1b. Via regular re-calibration processes or appropriate computational measures a correct reading can be attained. More details may be taken from Shercliff (1987).

AC electromagnetic flow meter

An alternative method is the electromagnetic frequency flow meter (EMFM) which is independent of magnetic field effects or wetting issues. The general measurement principle of such an induction flow meter is that the motion of an electrically conducting fluid in an imposed field B produces an induced field B' which is proportional to the flow rate in the first order. The attained signal is proportional to the fluid conductivity σ_f and the mean velocity v_0. One major advantage of the EMFM flow meter is that no transducer is required which allows a large temporal resolution. Moreover, no direct contact of the sensor with the operation fluid is necessary for data acquisition, avoiding material compatibility issues.

The earliest proposal for an AC electromagnetic flow meter has been made by Lehde and Lang (1948), which is illustrated in figure 2a. The two coils A and C are supplied with alternating electric currents $j(t)$ in opposite direction, producing an AC magnetic field as illustrated in figure 2a at the bottom. In the absence of a fluid motion, the resulting magnetic field is symmetrical and in the ideal case no signal in the sensing coil B according to the induction equation is induced. As soon as flow occurs, the magnetic field lines are dragged downstream and a signal appears in coil B, which is proportional to the flow rate to the leading order. However, great care is necessary to assure that there is no output signal in case of zero flow and in practice it is hardly feasible to produce a geometrically exact symmetric arrangement. Thus, a precise fabrication is required otherwise the genuine signal, which is often quite small, will be lost among stray signals.

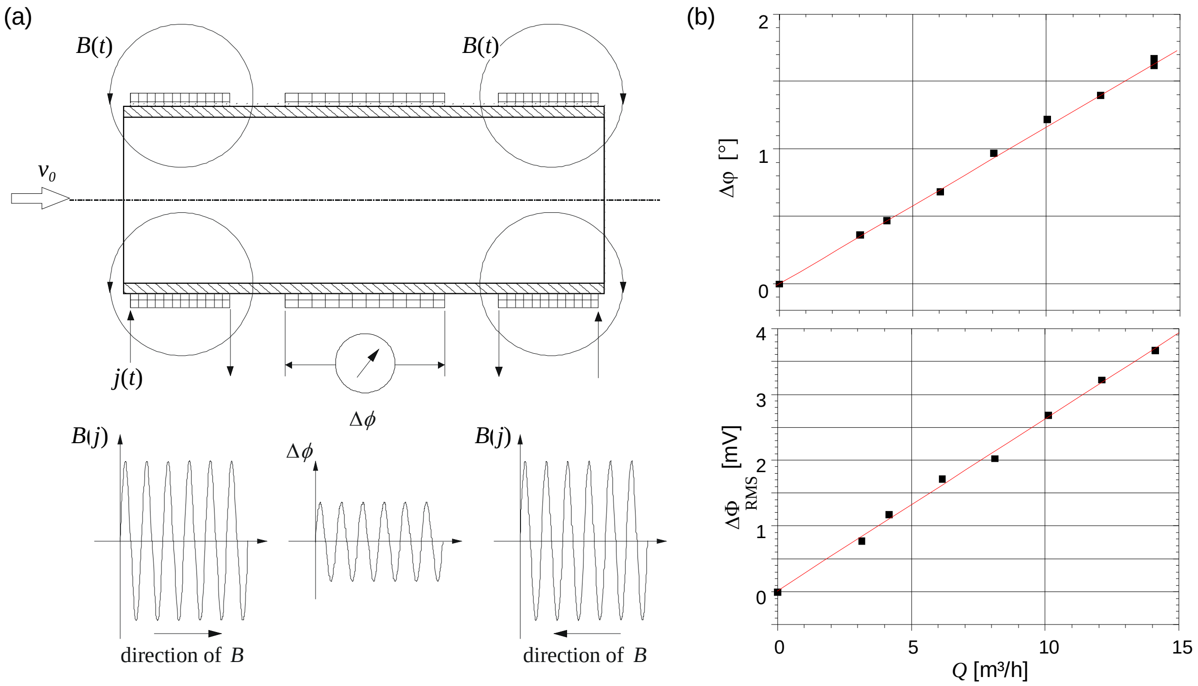


Fig. 2: (a) Measurement principle of the AC electromagnetic flow meter. (b) typical acquired RMS values ($\Delta\Phi_{RMS}$) and phase angles ($\Delta\varphi$) of the EMFM flow meter as a function of the flow rate Q in a tube (d=60mm) for a $Pb^{45}Bi^{55}$ flow at 300°C and an excitation frequency of 500Hz.

The flow direction can be detected by the sign of the RMS value of the sensing coil *B*. The magnitude of the RMS value in the sensing coil is proportional to the magnetic Reynolds number of the fluid flow Re_m, where Re_m is calculated according to

$$Re_m = \mu_0 \; \sigma_f(T) \, u_0 \, d \; . \tag{2}$$

Here, μ_0 is the magnetic permeability of vacuum, given as $4\pi \; 10^{-7}\; As/(Vm)$, σ_f the specific electric conductivity of the fluid as a function of the temperature T, u_0 the mean flow velocity within the duct and d its diameter. If the temperature remains constant, the measured *RMS* value of $\Delta\Phi$ is proportional to the mean fluid velocity u_0.

A typical complication is caused by phase shifts due to eddy currents in nearby solid and fluid conductors, because of the generation of harmonics through the non-linearity of the material or because of capacitive pick-up. Another source of trouble can be resonance or beats when the flow contains slight periodic fluctuations due, for instance, the use of electromagnetic or mechanical pumps running at or near synchronous speed. A technically feasible solution to minimise pick-up effects is a complete enclosure of the AC electromagnetic flow meter device by means of a ferromagnetic foil. This foil has to be grounded through the liquid flow far away from any eddy currents.

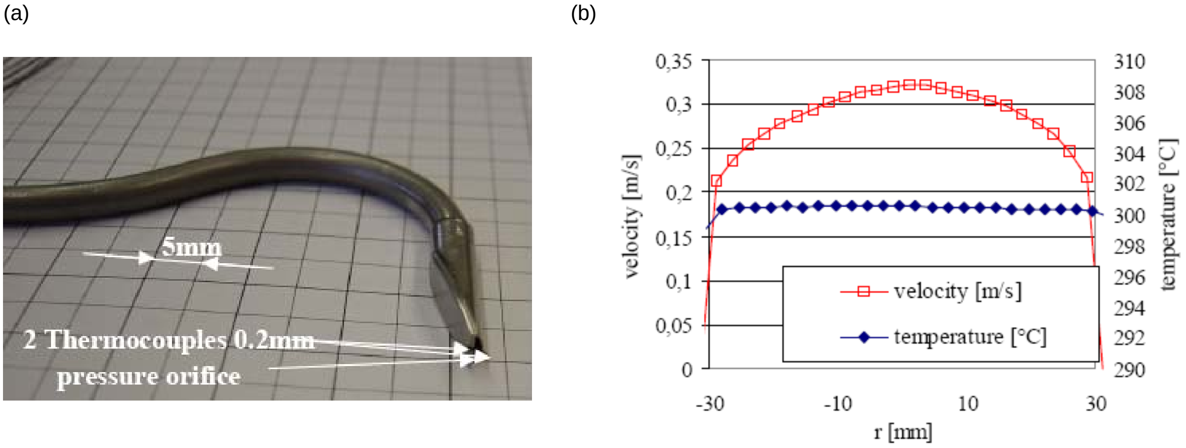
Nevertheless, the capacity and thus the future prospects of the EMFM are significantly larger than those of the PMF, since it has three gross output signals, one for the direction and two for the flow rate, because not only the RMS value ($\Delta\Phi_{RMS}$) but also the phase shift angle $\Delta\varphi$ is proportional to the flow rate *Q*. This is illustrated in figure 2b and allows an in situ self-calibration of the device and also the calibration using a different liquid metal.

Local flow velocity

Pitot and Prandtl tubes

The measurement principle of Pitot and Prandtl tubes is well known from ordinary liquids or gases. Thus only some remarks on the operational experience with liquid metals are made here. These devices can be used either to measure the integral flow rate through an experimental loop or, via miniaturisation of the sensors, local velocities and pressures can be resolved. Moreover, if thermocouples are embedded, local temperatures can be measured simultaneously. The resolution is given by the resolution of the used pressure gauges.

In the $Pb^{45}Bi^{55}$ operated THESYS loop of KALLA, a velocity distribution measurement within a tube has been conducted using a miniaturized Pitot tube, see cf. fig 3a. The achieved accuracy was about 5 mm/s, corresponding to a pressure resolution of the pressure transducer of approximately 12.5 Pascal. Higher resolutions may be obtained by more sensitive sensors. A typical turbulent velocity profile and the corresponding temperature profile which has been measured by means of a combined Pitot tube with two thermocouples in a circular tube at a temperature of 300°C with a Pitot tube is depicted in figure 3b.


(a)

(b)

Fig. 3: a.) Miniaturized Pitot tube combined with thermo-couples. b.) Measured velocity and temperature distribution in a duct (d=60mm) in $Pb^{45}Bi^{55}$ utilizing the Pitot tube from a).

The smallest spatial dimension over which the velocity is integrated is given by the size of the orifice of the Pitot tube. As the surface tension of heavy liquid metals like lead or lead-bismuth is quite large (in the order of some 100mN/m), the pressure difference required to fill the tubes orifices increases significantly with the degree of miniaturisation. A reliably operating Pitot tube system is only obtained for a gas free tube. Thus, drain tubs are required to ensure a complete filling of the sensor. Due to the large Reynolds numbers (*Re*) appearing in heavy liquid metal flows, the boundary layers appearing there are relatively thin. Thus, they are only resolvable with Pitot tubes near their outer region towards the main flow. An experimental example of the flow field measurement using a Pitot tube near a heated rod in an annular cavity is shown in figure 4. In order to acquire the flow distribution within the boundary layer, non-intrusive methods shall be preferred as the ultrasound Doppler velocimetry (UDV).

In order to obtain accurate mean velocity profiles using a Pitot tube, many corrections are needed to account for the effects of viscosity, turbulence, velocity gradients and the presence of a wall. Recent measurements by Zagarola and Smits (1998) in a turbulent pipe flow in a Reynolds number regime from $3.1 \cdot 10^3 < Re < 3.5 \cdot 10^7$ have raised questions regarding the accuracy and applicability of the current correction methods, which are summarised in the work of Perry *et al.* (2001). In pipe flows with Reynolds numbers around 10^5 to 10^6, which easily appear in heavy liquid metal applications, there is a difference of greater than 5% in the slope of the logarithmic region between data with and without wall correction (McKeon *et al.*, 2003). A detailed summary of wall corrections is given by Stieglitz (2007).

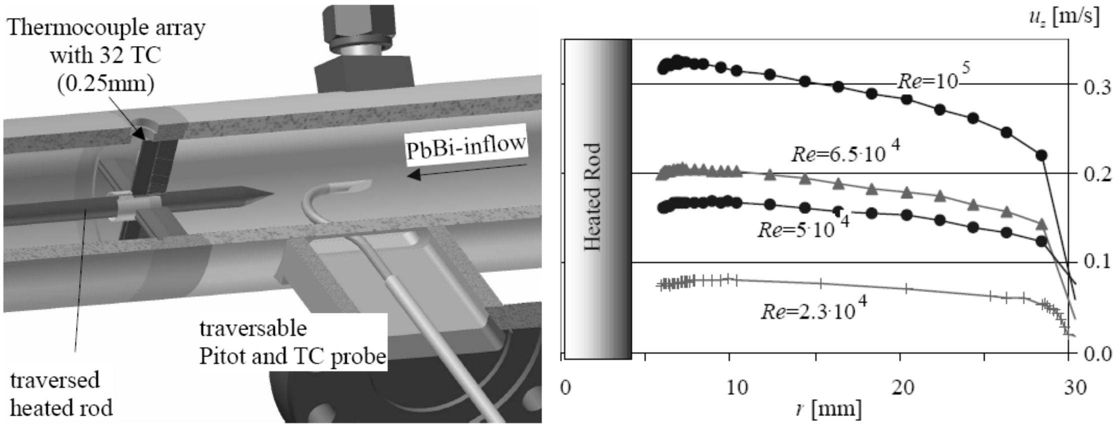


Fig. 4: Set-up of the Pitot tube in an annular cavity near a heated rod (left). Measured velocity distributions in an annular cavity of a PbBi-flow as a function of the radius r for different Re (right).

Permanent magnetic probes (PMP)

Another method to measure local fluid velocities within an electrically conducting fluid is given by permanent magnetic probes (PMP). The PMP contains a miniaturised permanent magnet arranged perpendicularly to the main flow. The magnet is encapsulated within a steel tube. This probe allows to measure simultaneously velocities and the temperatures similar to the combined Pitot tube. The turbulent heat fluxes can be determined from the cross-correlation of both signals, i.e. from temperature and velocity fluctuations. The principle set-up is shown in figure 5.

The PMP probe signal is obtained as a low ohmic electric potential $\Delta\Phi$ arising from the interaction of the flow field u with the magnetic field B. The simplified Ohm's law for moving electric conductors and temporal steady magnetic fields reads to

$$j = \sigma_f \left(E_e + E_{th} + u \times B \right) \tag{3}$$

where j is the current density, σ_f the specific electric conductivity of the fluid, E_e the electro-static field, E_{th} the thermo-electric field, u the integrated velocity of the probe dimension and B the magnetic induction. Generally, there are two main disturbances affecting the induced electric potential.

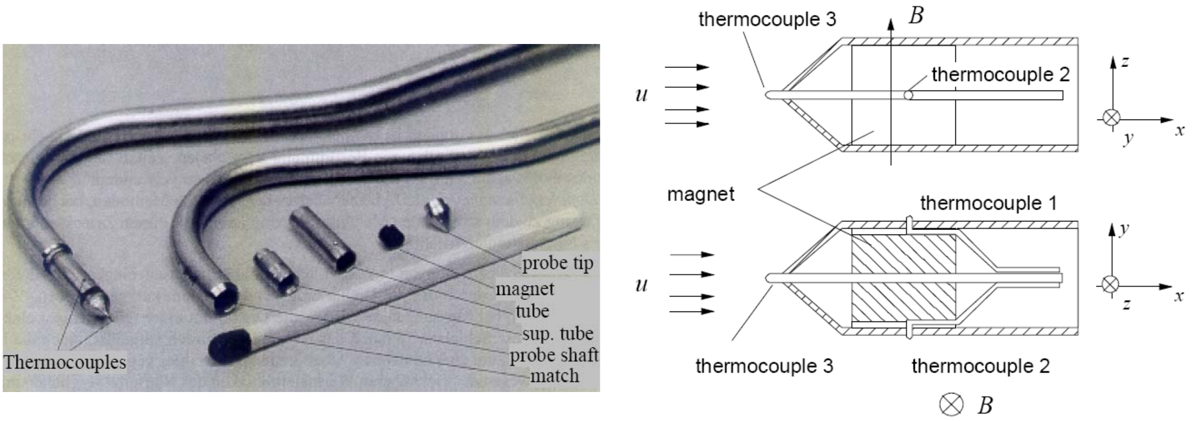


Fig. 5.: Photograph of a Permanent magnetic probe PMP from Kapulla (2000), left, and location of the different thermo-couples in the permanent magnetic probe PMP, right.

Using the Maxwell equations and the simplified Ohm's law, one obtains

$$E_{th} = -S\nabla T - Q(\nabla T \times B) \tag{4}$$

in which S is the thermo-electric coefficient in V/°K and Q the Nernst-Ettinghausen coefficient in V/(°K.Tesla). Thus, in order to calibrate the probe, isothermal measurements are required in a flow with a defined velocity field. A detailed description of this procedure may be taken from Ricou and Vives (1982), Weissenfluh (1986) and Kapulla (2000). The calibration yields the specific Seebeck coefficient of the individual probe. Additional care has to be taken if external magnetic fields are present in the domain of interest as, e.g. near to electromagnetic pumps or close to DC electro-magnetic flow meters. Then, an even more complicated effort has to be spent in order to determine the coefficients of the probe. The methodology necessary in this case is exhaustively elaborated in the work of Ricou & Vives (1982) and more precisely by Müller *et al.* (2006).

In the absence of external magnetic fields, the PMP probe allows to detect liquid metal velocities in the range from 0-10m/s with an extremely high sensitivity of about 1mm/s as the experimental works of Horanyi and Krebs (1988), Knebel and Krebs (1994), Ricou and Vives (1982) and Weissenfluh and Sigg (1988) document. The sensitivity and the velocity range are not restricted and scope several decades, which is not possible with other techniques. Generally, this technique is applicable up to temperatures of 720°C as the paper by Ricou and Vives (1982) shows with measurements in mercury, aluminium, tin, zinc and some alkali metals. The upper limit of the temperature is given by the Curie temperature of the magnet, which is e.g. for nickel-based permanent magnets about 860°C, see e.g. Eringen (1980).

Due to responses that are fast and proportional to the velocity of the liquid metal flow, high temporal resolutions can be obtained which is necessary for the study of turbulent flows. Although it is an intrusive method, modern fabrication technologies allow to miniaturise the PMP probe down to diameters less than 2 to 3 millimetres, and thus to minimise the impact of the probe on the flow.

One of the most crucial problems of the PMP is the wetting behaviour in the sense of an electro-chemical wetting without any contact resistance between fluid and probe. Regarding the alkali metals, this is not a problem. However, lead and its alloys show a poor electro-chemical wetting behaviour of steel surfaces. Therefore, the PMP has been plated with nickel or silver as a sacrificial layer, which is dissolved immediately by the lead bismuth in order to ensure a proper wetting of the sensor. Nevertheless, after two weeks exposure of the probe to lead bismuth at 400°C, the wetting got lost even in an oxygen controlled atmosphere. Also within a reducing atmosphere by adding hydrogen to the loop, the wetting of the probe could not be recovered again, see Knebel *et al*. (2001). This wetting problem is an issue not yet fully understood. It requires a detailed investigation in order to develop HLM adapted sensors.

Ultrasound Doppler velocimetry

A non-intrusive method to measure instantaneously entire velocity profiles is offered by the ultrasound Doppler velocimetry (UDV). The UDV technique is based on sending ultrasound pulses into the liquid with seed particles. The echoes from particles immersed in the fluid are sampled. The position of particles is derived from the time delay of this echo, whereas the related velocity information is obtained from the shift in position of scatters between ultrasound pulses. Hence, the velocity information is yielded from a time correlation function. One of the major advantages of UDV is that it is a non-intrusive method, with which the velocity is scanned not only at a single position like in a laser Doppler anemometer. It rather samples velocity information instantaneously at several positions along the ultrasound wave path. The operation principle is shortly explained and sketched in figure 6.

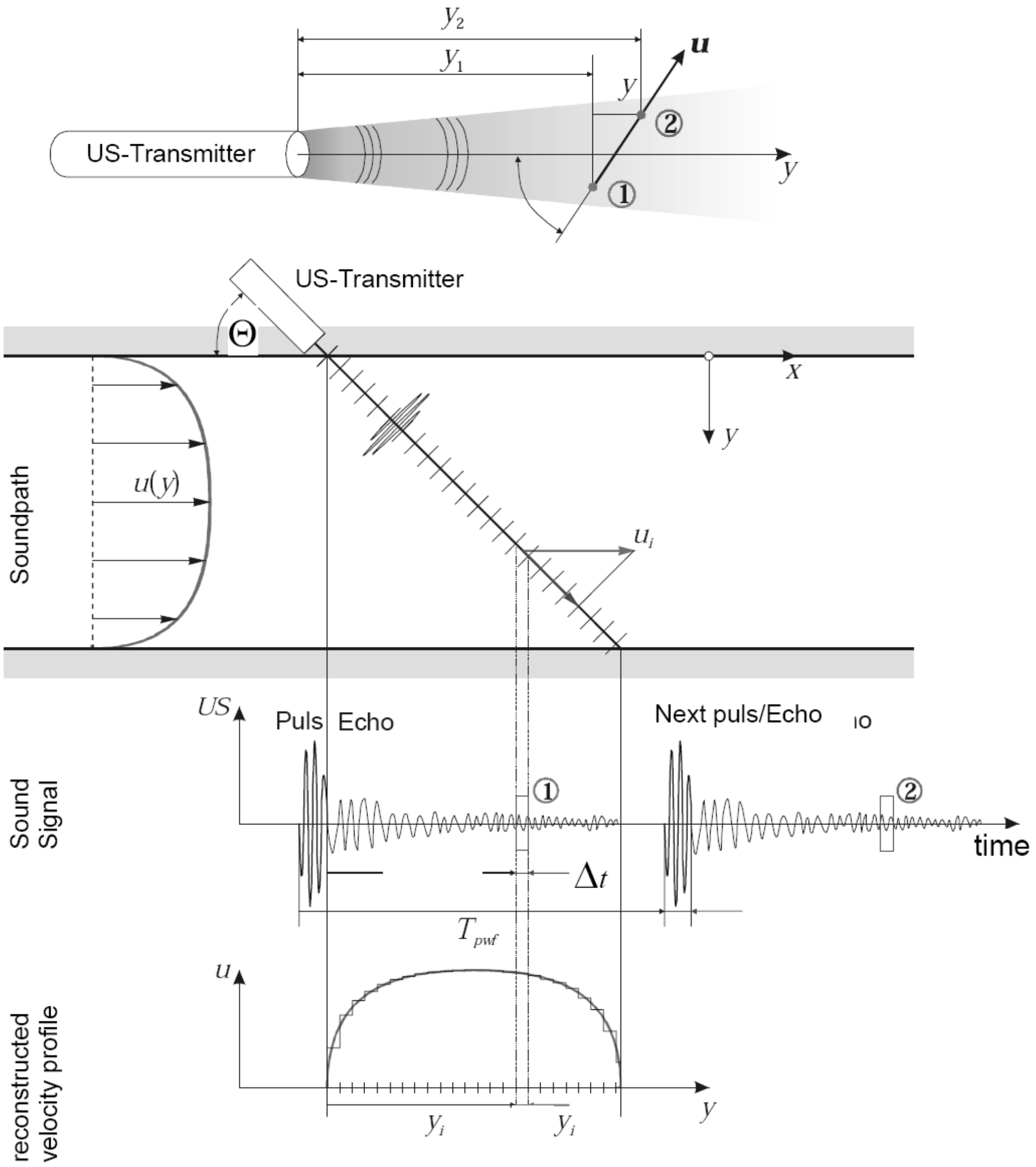


Fig. 6: Measurement principle of the Ultrasound Doppler velocimeter (top) and acquisition path (below). Reconstruction of the velocity profiles from the recorded echoes (lower two graphs).

The distance P of the measurement volume from the pulse emitter is given by relation (5)

$$P = \frac{c t_d}{2} \quad , \tag{5}$$

in which c is the sound speed and t_d the time delay of the pulse. The spatial shift ΔP of the position between two pulses applying a pulse repetition time t_{prf} is given by equation (6):

$$\Delta P = u(z) t_{prf} \cos\theta = \frac{c(t_2 - t_1)}{2} \quad , \tag{6}$$

where θ is the angle between the wave path and the velocity component of interest. The time difference (t_2-t_1) is recorded by means of the phase shift of the echoed signals.

From this, the velocity $u(z)$ at a discrete co-ordinate z can be evaluated by relation (7)

$$u(z) = \frac{c\, f_d}{2\, f_e \cos\theta} \tag{7}$$

in which f_d represents the Doppler shift and f_e the frequency of the emitted signal. One can determine easily from these equations that an upper limit of the maximum measurable velocity and the maximum measurement depth exists. This constraint is expressed by the relations 8a and 8b, which read to:

$$u_{Max} = \frac{c}{4 t_{prf} f_e \cos\theta} \;\; ; \;\; y_{Max} = \frac{c\, t_{prf}}{2} \tag{8a, b}$$

Another feature of the UDV technique is the capability to record even deep within the boundary layer velocities. Utilizing an adapted form of the UDV, Lefhalm (2004) has been able to measure velocities only a few μm away from the wall. For this purpose, wall correction functions have to be applied which account for the fact that part of the measurement volume is located within the wall. In order to get the correct velocity contribution from the fluid domain, only echoes from the fluid region shall be sensed. Therefore, the mass centre of the fluid/wall volume is calculated. The distance of the mass centre of the fluid/wall volume from the mass centre of the pure fluid volume yields a displacement of the measured point. A detailed description of this procedure may be taken from Wunderlich *et al.* (2000), Nowak (2002) or Lefhalm (2004).

The measurements of the velocity profiles within the turbulent boundary layer of an annular duct conducted by Lefhalm (2004) are shown in figure 7. They illustrate that the velocity can be acquired by means of such correction functions. The measured velocities coincide almost perfectly with the literature data of Reichhardt (1951). The deviations found are less than 5%. Moreover, it was possible to measure even inside the viscous sub-layer up to values of y^+=3, which corresponds to a wall distance of 46 μm in the experimental set-up of Lefhalm (2004). Also, measurements of the turbulent fluctuations could be performed within the boundary layer down to y^+>10 using this wall correction procedure as figure 7 (right) illustrates. They almost coincide within literature data.

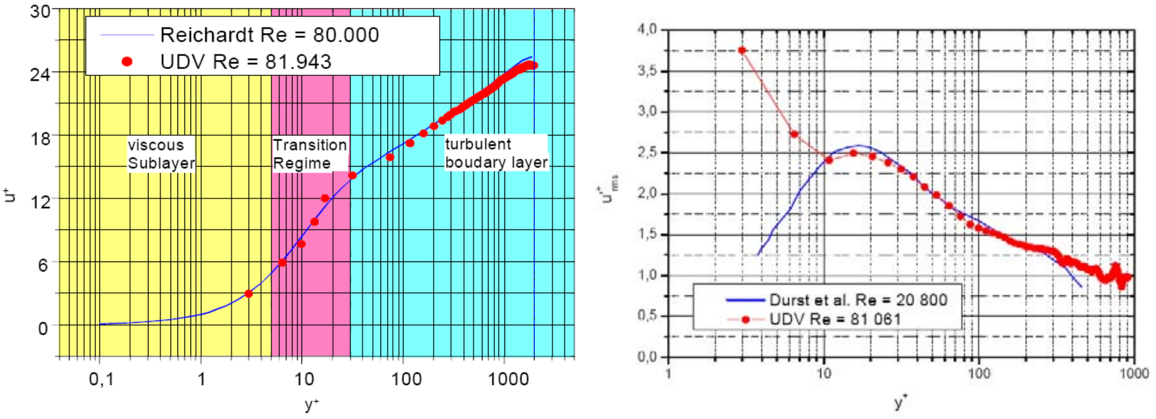


Fig. 7: Measured dimensionless boundary layer velocity distribution as a function of the dimensionless wall distance y^+ in comparison with literature data using an Ultrasound Doppler velocimeter in a turbulent PbBi flow at 300°C (left); measured dimensionless velocity fluctuations as a function of y^+ in the set-up of Lefhalm (2004), right.

From the procedure explained above it is clear that numerous effects contribute to the acquisition of a proper signal and in fact about 100 parameters are necessary to define the measurement process.

The enormous sound speed of HLM´s requires extremely fast acquisition and data processing systems to obtain reliable velocity information. Besides these quite sophisticated demands on the data transmission recording and processing units, which are depicted in figure 8, left, several constraints regarding the environmental conditions have to be matched. One of the most crucial problems is the elevated temperature of more than 200°C, which cannot be sustained by commercially available Bariumtitanat sensors ($BaTiO_3$). Thus, wave guides have been developed to decouple the temperature from the sensor. Such an integrated probe consisting of a wave guide and a sensor is shown in photograph figure 8 (right). It has been developed by the Forschungszentrum Rossendorf and is applicable to operate in liquid metal temperatures up to 620°C, see Eckert *et al*. (2003). Secondly, an acoustic coupling of the sensor and the fluid has to be ensured which means that the probe has to be physically wetted. This is partially achieved by applying a sacrificial nickel layer on the probe surface before inserting it into the fluid. Within the lead-bismuth, this nickel layer is dissolved and ensures the wetting of the surface for a certain time. However, the wetting of the sensor surface gets lost after a few days of operation. The study of the wetting behaviour of lead bismuth on steel surfaces is a task which has to be solved not only for this application.

Another problem is the long term stability of the probe and the flow seeding. By means of conditioning the oxygen content within fluid, a certain long term stability of the probe was achieved and a sampling of velocity profiles was successfully performed without any additional artificial flow seeding. Artificial flow seeding with particles of a density like the lead-bismuth is hardly available and stable within the operational conditions typically used. If temperature gradients are present in the flow being studied, travelling time corrections have to be applied, because the sound speed depends on the square root of the temperature. Thus, either the temperature field of the studied flow has to be known or temperature correlations have to be used. Besides the numerous difficulties using UDV within the THESYS loop in KALLA, velocity measurements have been successfully performed in a turbulent lead bismuth pipe flow at temperatures up to 400°C and velocity fluctuations of frequencies up to 15 Hz were recorded.

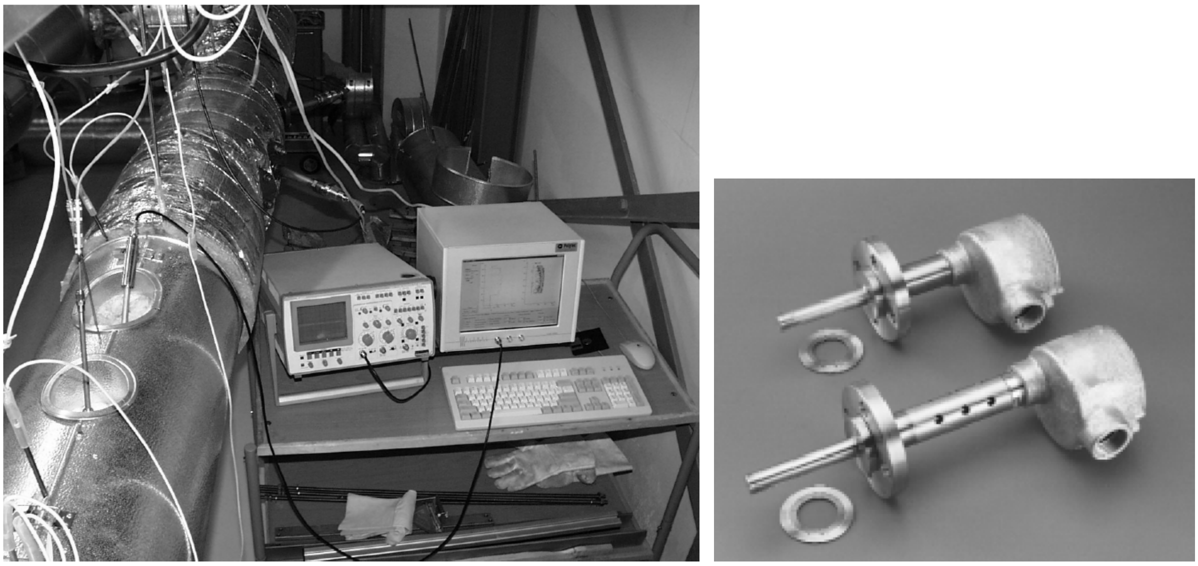


Fig. 8: Data acquisition system of the Ultrasound Doppler velocimeter (left); Sensors with wave guides of an Ultrasound Doppler velocimeter (right).

Summary

The hot and corrosive environment especially of heavy liquid metals requires dedicated systems to measure temperatures, pressures and velocities. On the other hand, the high electric conductivity permits to use electro-magnetic systems which are not applicable with ordinary liquids, giving access to a further class of measuring devices. All systems shown here have been tested successfully in the KALLA laboratory within the last 5 years. We could resolve local velocities with probes and with non-invasive systems in the bulk as well as in the boundary layers of the flow down to a dimensionless wall distance of $y^+=3$. Turbulent velocity fluctuations could be resolved up to a frequency of 15 Hz and with a smallest wall distance of $y^+=10$. The Ultrasound Doppler velocimeter gave the highest resolution of boundary layers after suitable wall corrections. Combined turbulent velocity and temperature fluctuations as appearing in the turbulent heat flux could be measured with a permanent magnetic probe with thermocouples which can be miniaturized down to about 2 or 3mm. Proper wetting of these probes, however, is still an open issue. The most robust local velocity, pressure and temperature measurement device is the Pitot tube. It may be combined with thermo-couples to optimize its features.

Integral flow meters, on the other hand, are more reliable today, reaching an accuracy of around 1% after calibration. Especially the electro-magnetic frequency flow meter shows a quite large potential for electrically conducting fluids since it owns two gross output signals and does not require a direct contact of the sensor with the liquid.

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