Channel flow profile measurements at hot liquid metal loops by the Ultrasound Doppler method

Sven Franke, Sven Eckert, Thomas Gundrum and Gunter Gerbeth
Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01314 Dresden, Germany

The successful application of the ultrasound Doppler method at hot channel flows by means of commercial high temperature probes is presented. To obtain sufficient Doppler signals, different problems have to be solved: the transmission of the ultrasonic beam through the channel wall made of stainless steel, the acoustic coupling between the transducer and the channel wall, and the wetting of the inner surface of the wall by the liquid metal, respectively. An integrated sensor concept and method are figured out to meet these requirements. The feasibility of this sensor concept is demonstrated in experiments in metallic melts at temperatures up to 230°C. Measurements are performed at a circular channel flow at the LIMMCAST facility at HZDR applying an eutectic bismuth-tin alloy. In addition, a lead-bismuth flow in a rectangular channel profile measured at the METAL:LIC loop at the Institute of Physics Riga (IPUL) is presented in this report.

Keywords: Flow measurements, ultrasound Doppler method, liquid metal, channel flow, high temperature measurements

1 INTRODUCTION

Liquid metal technologies gain in importance for the metal industry, for example, the production of cast parts, the continuous casting of steel and the crystal growth at the semiconductor industry. As well the role of liquid metal technologies grows steadily for the branch of energy industry. Present and future examples may be found at the nuclear power industry, more precisely at fast breeder power plants and fusion reactors. However, also renewable energies may benefit from liquid metal technologies, for example with respect to the application of liquid metal coolants at concentrated solar power plants. Applications in the energy sector typically utilize liquid metals as coolant, however, future prospects consider liquid metals also for energy storage systems.

For the last two decades the ultrasound Doppler method has developed to a very powerful tool to investigate the velocity structure of liquid metal flows as reported, for example, by Takeda [1] for mercury and by Brito [2] for liquid gallium. However, in case of hot metallic melts the user is confronted with a number of specific problems: First of all, the application of the ultrasonic transducers is usually restricted by temperature. Furthermore, the transmission of a sufficient amount of ultrasonic energy from the transducer to the fluid has to be guaranteed. Here, the acoustic coupling and the wetting conditions have to be considered as important issues. Moreover, a sufficient high concentration of scattering particles has to be provided to obtain reliable Doppler signals from the fluid.

First successful velocity profile measurements at higher temperatures were published by Eckert [3]. The flow profile of liquid sodium in a square channel cross section was measured at temperatures up to 150°C by means of commercial ultrasonic probes. A specific sensor development for high temperature applications focuses on the use of acoustic wave guides [4]. In this concept the acoustic energy propagates inside a construction comprising a coiled, thin foil of stainless steel. The temperature gradient along the wave guide impedes that the temperature of piezo ceramic of the probe exceeds its Curie point. The reliability of the waveguide probe has been demonstrated by successful measurements in lead-bismuth at 300°C and copper-tin at 650°C.

Despite the advantages of the waveguides, there are still shortcomings of this technology. Apart from high costs of the waveguide probes an inconvenient limitation is the measuring depth since the transition from the waveguide into the fluid generates a strong reflection signal in the ultrasonic echo. This interface reflection may be mirrored into the range where the velocity profile is measured disturbing the reconstruction of the velocity profile. Due to technical limitations it causes difficulties to filter these interface reflections. The best approach for compensation is to delay the interface reflection by extending the length of the waveguide. However, the sound velocity of steel is very high, much higher than the sound velocities of typically applied liquid melts implying that the waveguide must be much longer than the measuring depth.

Hence, in this report our sensor concept given in [3] will be extended to measure instantaneous flow velocities at liquid metals up to temperatures of 230°C without the application of waveguide sensors. The feasibility of the concept is demonstrated by measurements of channel flows at the LIMMCAST and the METAL:LIC facility, which are operated at temperatures around 200°C with Sn-Bi alloys and Pb-Bi alloys, respectively.

2 MEASUREMENT METHOD

2.1 Instrumentation

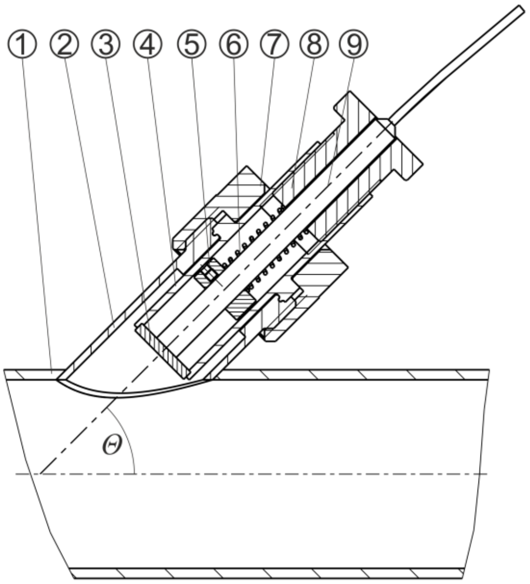
The measurements are carried out using the Doppler device DOP3010 from *Signal Processing SA* equipped with specific high-temperature transducer probes (model *TR0405LTH* from *Signal Processing SA*) specified up to a maximum temperature of 230°C. The selection of an ultrasonic frequency of 4 MHz with a piezo diameter of 5 mm considers various aspects with respect to the spatial and temporal resolution, the velocity limitation, the multiple reflection characteristic as well as constructional issues.

2.2 Probe socket

Owing to the high temperature, the abrasive character of the metal melt, wetting issues and safety reasons the ultrasonic transducer probe cannot be brought in direct contact to the fluid. Therefore, a special probe socket (fig. 1) is designed to protect the sensor and to provide reliable measuring conditions. The socket consists of an open stainless steel cylinder with a thin plate at the cylinder front. The transducer face is directly attached to this acoustically transmitting front plate through which the measurement is conducted. Because of cleaning and constructional issues the inner diameter of the socket cylinder is distinctly larger than die probe diameter. The proper alignment of the probe is guaranteed by a duct attached to the probe. The duct is also intended as counterpart for a spring mechanism pressing the probe at the polished inner wall of the front plate. This mechanism ensures a stable acoustic coupling despite thermal expansion.

A sleeve at the channel wall incorporates the probe socket and aligns it in a specific angle Θ with respect to the channel axis (fig. 1). The axial flow component in a rectilinear channel can be derived by taking into account the correction factor cos Θ.

The acoustic transmission among transducer face and front plate of the socket is supplied by an acoustic couplant known from non-destructive testing technique which can withstand temperatures of about 230°C. Further aspects of acoustic transmission have to be considered to guarantee a sufficient amount of ultrasonic energy along the acoustic path in the fluid: The thickness of the front plate has to meet a multiple of the half wave length of the ultrasonic wave in the wall material in order to maximize the acoustic transmittance [3]. According to this, for the front plate (also made of stainless steel) a wall thickness of 2.9 mm is selected to match for ultrasonic frequencies of 1, 2 and 4 MHz. Tolerances of the resonant wall thickness arising from temperature changes or an imperfect fabrication can be compensated by a fine tuning of the emitter frequency. In addition, a sufficient wetting of the outer wall of the front plate with liquid metal has to be guaranteed by a specific preparation: After mechanical polishing the surface is electroplated with nickel. Afterwards this nickel layer is coated with bismuth-tin eutectic to act as a protection layer against oxidation. The nickel layer promotes the wetting of the stainless steel socket with the liquid metal.



1	channel wall
2	sleeve at channel
3	front plate for acoustic transmission
4	probe socket
5	probe duct
6	spring
7	sleeve nut
8	knurled nut
9	transducer probe

Figure 1: Probe socket design

2.3 Further measurement issues

An appropriate density of scattering particles is essential for reliable velocity profiles. However, it is very difficult to add artificial scattering particles to the metal melt. Instead, natural scatterer are available for that purpose supposed to be oxides or local segregations of the eutectic alloy. These particles apparently deposit at the channel wall after a while. Here, it is necessary to occasionally stir up the particles into the fluid volume by high flow rates.

3 MEASUREMENT RESULTS

3.1 LIMMCAST Facility

The LIMMCAST (Liquid Metal Model for Continuous Casting) facility at HZDR aims to model the essential features of the flow field in the continuous casting process. The low melting point alloy Sn60Bi40 ($c_s \approx 2000$ m/s) is applied as model liquid whose liquidus temperature of 170°C allows for an operation in the temperature range between 200 and 400°C. The facility contains about 250 l of SnBi. An electromagnetic pump is used to convey the liquid metal trough the loop.

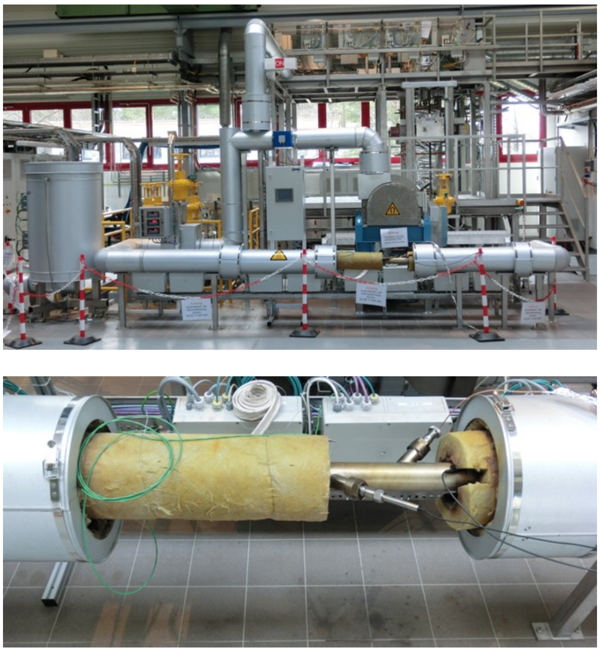


Figure 2: LIMMCAST facility with test section

Moreover, the facility offers an additional test section with a horizontal, straight tube (diameter $d_0 = 54.5$ mm) installed for material tests or verification of various measuring techniques. A segment of this test section shown in figure 2 features two measurement sleeves for the probe sockets aligned in an angle $\Theta = 45°$ with respect to the channel axis. The measurements presented here are obtained from these test points.

Figure 3 shows an instantaneous flow velocity profile versus the pipe diameter *d*. The edges of the diagram conform to the boundaries of the channel. The profile reveals a high signal-to-noise ratio at a high temporal resolution of about 60 ms and a fluid temperature of 210°C. The wall regions of the profile are truncated since the flow velocity cannot be determined correctly there. Saturation effects of the transducer probe and flow perturbations created by the probe socket impede a velocity measurement at the front wall [3]. Multiple reflection paths owing to the divergence of the ultrasonic beam prevent the drop of the velocity profile to zero at the opposite channel wall [3].

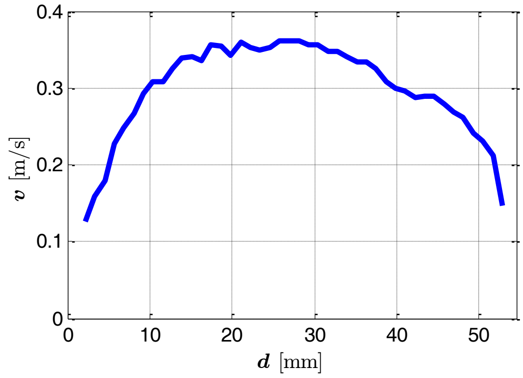


Figure 3: Exemplary velocity profile vs. pipe diameter of SnBi flow at 205°C (speed of rotation of pump: 50 rpm)

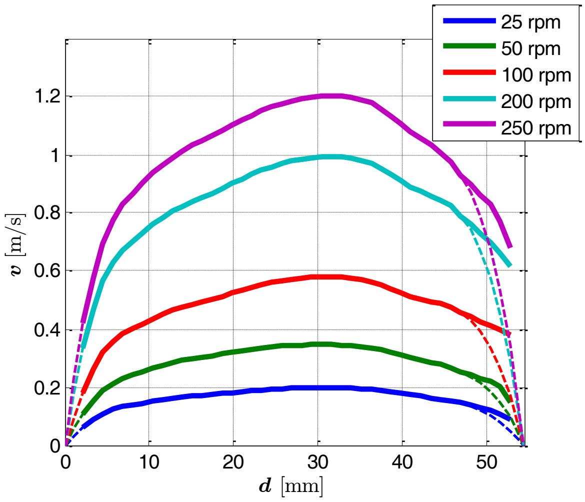


Figure 4: Mean flow velocity for various speed of rotation of the EM pump (velocity values are corrected with respect to the Doppler angle)

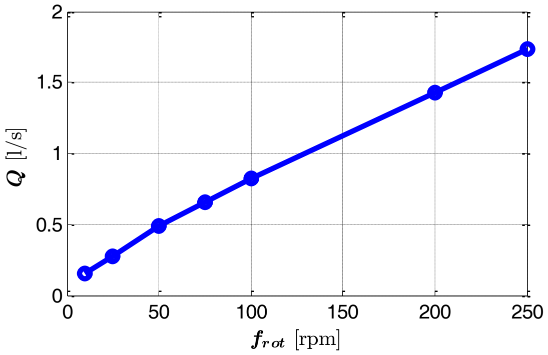


Figure 5: Volume flow rate Q vs. speed of rotation f_{rot} of the EM pump

Using the mean flow profiles (fig. 4) the volume flow rate Q versus the speed of rotation (in rpm) of the EM pump (fig. 5) is calculated assuming an almost axisymmetric flow profile. For this purpose the distorted velocity data at the channel walls are interpolated by using a cubic spline with the velocity directly at the walls set to zero. The interpolated curves are denoted as dashed line in figure 4. The maximum negative velocity gradients measured at the wall regions were selected as a criterion for truncation.

3.2 METAL:LIC loop

The METAL:LIC loop is a model experiment at the Institute of Physics of University of Latvia (IPUL) for studying a liquid metal target within the *European Spallation Source* project. The loop deploys a total mass of 1100 kg of lead-bismuth eutectic (LBE; chem. Pb45Bi55; $c_S \approx 1750$ m/s) which is driven by an electromagnetic permanent magnets pump. The flow rate is determined by a difference pressure measurement at a Venturi tube.

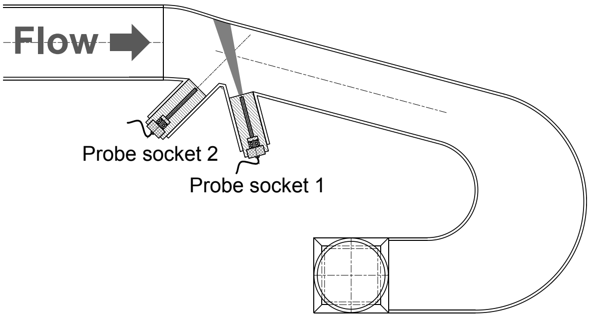


Figure 5: Curved liquid metal target section with probe socket assembly

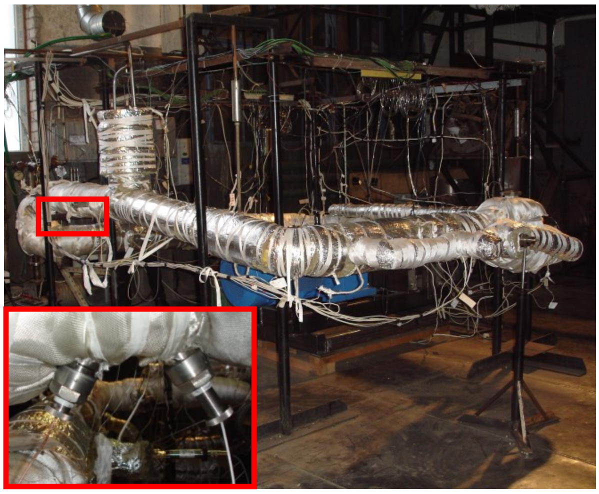


Figure 6: METAL:LIC loop with measurement points

The target test section shown in figure 5 comprises a channel segment with a rectangular cross section of height × width = 80 × 100 mm². The measuring points are mounted directly after the channel slightly bends. The probe sockets are aligned in an angle of $\Theta = 60°$ with respect to the channel axis of this pipe segment. Mean velocity profiles are shown in figure 7 for four different flow rates *Q* measured by the Venturi sensor. Owing to the pipe bending, neither the velocity information nor the measuring depth *p* is corrected by the Doppler angle. The edges of the diagram conform to the channel boundaries. The measurements were performed at a melt temperature of about 210°C. The velocity profile for the flow rate $Q = 6.67$ l/s exposes distinct noise probably induced by a low tracer particle concentration.

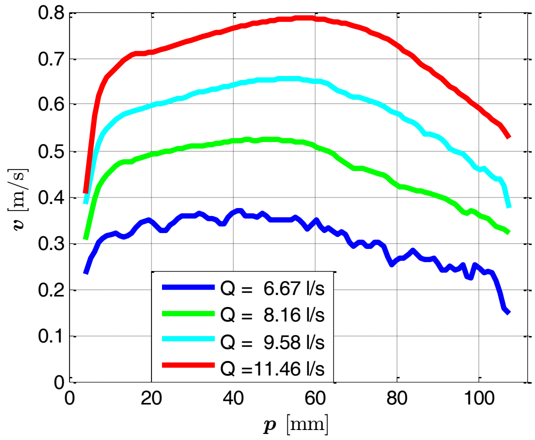


Figure 7: Mean velocity profiles of various flow rates measured at probe socket 1

4 CONCLUSIONS AND SUMMARY

A technology is presented to perform flow velocity measurements at metal melts with temperatures up to 230°C using the ultrasound Doppler method. Commercial high temperature probes are deployed which do not suffer from the limitation of the measuring depth as in the case of acoustic waveguides. Our approach includes a specific design of a probe socket considering thermal and chemical aspects as well as issues of wetting and acoustic coupling. Our method is demonstrated at two eutectic alloys, the lead-bismuth and the tin-bismuth eutectic which may gain in interest for future technologies. The results of our investigations prove that not only the mean flow is gathered with an adequate performance but also instantaneous velocity profiles can be measured with high reliability assuming a sufficiently high concentration of scattering particles in the fluid.

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