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Velocity measurements in liquid sodium by means of ultrasound Doppler velocimetry

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Abstract A successful application of ultrasound Doppler velocimetry in liquid sodium flows is described. To obtain sufficient Doppler signals, different problems had 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. A sodium flow in a square duct exposed to a transverse magnetic field is investigated. In accordance with the existing knowledge about MHD channel flows, we found that the velocity profiles modified to a M-shape owing to the effect of an inhomogeneous magnetic field.

1

Introduction

Because of the pioneering work of Takeda (1991, 1995), ultrasound Doppler velocimetry (UDV) (but also called UVP in the literature) has been established for measuring velocity profiles of fluid flows in physics and engineering. The principle of the UDV 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. Spatial resolution is possible by measuring simultaneously the time after emission of the ultrasound pulse. Hence, a full velocity profile along the US beam can instantaneously be obtained by UDV. The measured velocity represents the projection of the three-dimensional velocity vector onto the ultrasonic (US) beam line. The US transducer might be in direct contact with the fluid or applied to the melt wall. The ability to deliver complete velocity profiles in real time, to obtain spatio-temporal information (i.e. the velocity field as a function of space and time, see, for example, Takeda et al. (1993) or Peschard et al. (1999)) as well as to work also in opaque fluids in a non-intrusive way are considered to be the main advantages compared to other measuring techniques.

The aim of this paper is to extend the range of applicability of the UDV technique to flows of liquid sodium at temperatures up to 200 °C. Because of the properties of the fluid (opaque, hot, chemically aggressive) the choice of suitable measuring techniques to determine local velocities of a sodium flow is strongly limited. Velocity information was obtained from liquid metal flows by means of different types of local probes. Hot-wire and hot-film sensors were used by Hill and Sleicher (1971) in mercury and by Platnieks and Uhlmann (1984) in sodium. Permanent magnet probes were developed by Ricou and Vives (1982) and Von Weissenfluh (1985). Eckert et al. (2000) suggested a new mechano-optical probe to measure local velocities in a metallic melt. However, the use of local intrusive probes is always connected with serious shortcomings with respect to the accuracy of the measurements or the lifetime of the sensors (see Eckert et al. (2000) for a critical discussion).

The feasibility of velocity profile measurements by UDV has already been demonstrated for low temperature liquid metals by Takeda (1987) and Takeda et al. (1998) in mercury and by Cardin et al. (1996) and Brito et al. (2001) in gallium. However, the present technology reveals serious limitations regarding the measurements at higher temperatures. Successful measurements by means of UDV in other liquid metals at higher temperatures, for instance in sodium at about 200 °C, have not been published until now. Besides the thermal limitations of the US transducers, the acoustic coupling between the transducer and the fluid via the channel wall, and the allocation of suitable tracer particles, are considered to be relevant problems.

A crucial point of the UDV application in the considered case is the transmission of the US beam through the channel wall. This problem is discussed in Sect. 2. The measurements were performed at the sodium loop of the Forschungszentrum Rossendorf (FZR). Main features of the experimental facility and the measuring system can be found in Sect. 3. The presentation of the results considering the influence of a transverse magnetic field on the velocity profiles will follow in Sect. 4.

2

Transmission of a US beam through a perpendicular, plane interface

To prevent the chemical attack of the liquid sodium on the sensor surface a direct contact between transducer and

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liquid metal has to be avoided. Therefore, the US transducer has been coupled with the outer channel wall inside a special measuring adapter made of stainless steel (see Fig. 1). To optimise the transmission of the US wave through the adapter wall into the fluid, a suitable configuration has to be chosen

- to allow an incidence of the US wave perpendicular to the interfaces
- to fulfil the well-known $\lambda/4$ adaptation.

Therefore, the adapter wall is a plain steel plate that is in direct contact with the liquid sodium on one side and coupled with the US transducer by silicon grease on the other side. The thickness d of this parallel plate is determined by the requirement to maximise the coefficient of transmission D_{plate} according to the following equation given in Krautkrämer (1990):

$$D_{\mathrm{plate}} = \frac{1}{\sqrt{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 \frac{2\pi d}{\lambda}}} \tag{1}$$

where m denotes the ratio of the acoustic impedances $m = Z_{\mathrm{so}}/Z_{\mathrm{st}}$ between liquid sodium and steel, d is the thickness of the plate and λ is the wavelength in the plate material. The acoustic impedance is given by $Z = \rho\ c_s (c_s$ – sound velocity ρ density). Compared to the acoustic impedance of stainless steel ($Z_{\mathrm{st}} = 45 \times 10^6$ Ns/m^3), we can assume the acoustic impedances of sodium ($Z_{\mathrm{so}} = 2 \times 10^6$ Ns/m^3) and grease ($Z_{\mathrm{gr}} = 1 \times 10^6$ Ns/m^3) as identical.

The coefficient of transmission D_{plate} in liquid sodium as a function of the thickness d at an ultrasound frequency of 4 MHz is depicted for different plate materials such as stainless steel, aluminium and Teflon (DuPont Deutschland GmbH, Bad Homburg) in Fig. 2. Because of its large acoustic impedance, the resonance peak for steel is very strong and narrow. Outside the region of resonance only 10% of the sound pressure of the incident wave is transmitted into the fluid. The same situation occurs if the velocity of a water flow confined by metallic walls should be measured by UDV as discussed by Mori et al. (1999). The transmission of US energy into the liquid can be improved if it is possible to decrease the ratio of the acoustic impedances as becomes obvious in Fig. 2 for aluminium ($Z_{\mathrm{al}} = 17.3 \times 10^6$ Ns/m^3) and Teflon ($Z_{\mathrm{so}} = 3 \times 10^6$ Ns/m^3) – see Fig. 2. The acoustic properties of Teflon match very well with those of liquid sodium resulting in transmission coefficients always above 90%. However, in this case the transmission of the US wave is prevented by the poor wetting between Teflon and liquid sodium. The wetting problem of solid surfaces in liquid sodium will also be discussed in the following section.

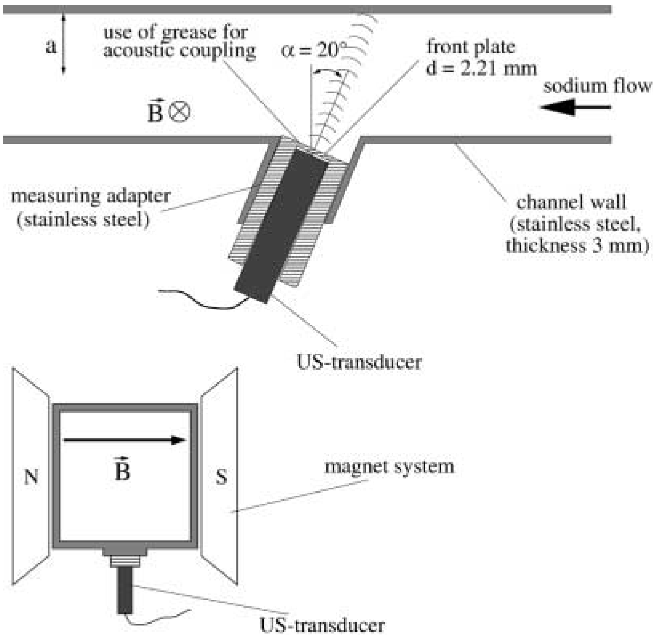

Fig. 1. Schematic view of the experimental arrangement: square test section with installed US transducer

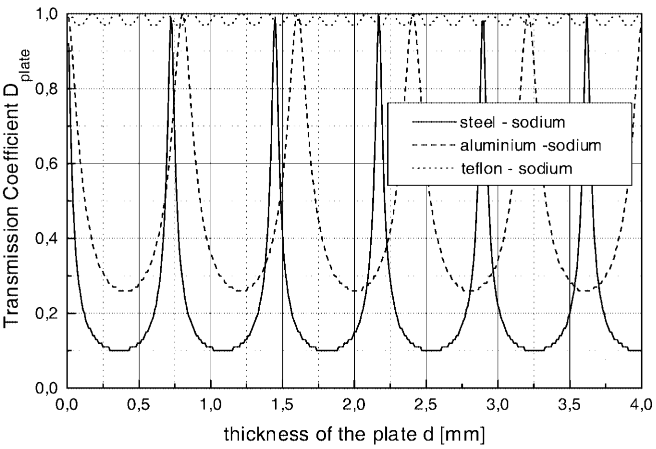

Fig. 2. Transmission coefficient D_{plate} of a plane-parallel plate plotted against the plate thickness d (frequency of the emitting ultrasound: 4 MHz)

Equation (1) has been derived for infinitely long waves, i.e. continuous waves. However, the UDV method uses short wave trains, i.e. pulses of a few oscillations. If the wave train is too short, no interferences are produced. In our experiments we have used a stainless steel adapter with a parallel front plate that was machined to have a thickness of 2.21 mm giving a ratio between d and λ of 1.5. The measurements were performed with ultrasound pulses of 4 and 8 cycles, respectively, leading to interferences inside the plate.

3
Experimental set-up

3.1
FZR sodium loop

The velocity measurements were performed at the experimental sodium loop, NATAN, of FZR. The facility operates with a sodium flow in the temperature range between 120 °C and 350 °C. The mean flow is generated by an electromagnetic pump and passes a transverse magnetic field ($B_{\max} = 0.8$ T). The magnetic field can be considered as homogeneous over the channel cross-section along a length of 1100 mm ($\Delta B/B_0 < 2\%$) and shows an exponential decrease in the end regions. The horizontal test section is made of stainless steel and has a square cross-sectional area of 44×44 mm^2. An electromagnetic flow meter was used to determine the sodium flow rate. The velocity profiles were determined by UDV in the direction perpendicular to the magnetic field lines. For all variations of the magnetic field intensity the sodium flow rate was kept constant.

The US transducer is installed inside a cylindrical measuring adapter under an angle of 70° with respect to the mean flow direction (see Fig. 1). The acoustic coupling between the US transducer and the adapter wall was achieved by means of silicon grease. A mounting support with a spring is located at the rear end of the transducer to fix it and to push it against the inner wall of the adapter.

As already discussed in the previous section the front plate of the adapter is machined stainless steel with a thickness of 2.21 mm. To guarantee a sufficient transmission of US energy from the adapter into the flow, the adapter surface must be well wetted with liquid sodium. Therefore, it is essential to remove the oxide layer from the steel surface. In principle, this can be realized by mechanical, chemical or thermal treatments. The thermal method described by Gailitis (1993) is laborious, but well proved. Here, the filled test section must be heated up to temperatures above 300 °C for at least 10 h. We used a combination of mechanical and chemical preparation. First, both sides of the front plate of the adapter were polished. Before the measuring adapter was installed at the facility, the outer surface that would be in direct contact with the liquid was cleaned using phosphoric acid.

Reflecting particles in the liquid are required in order to receive Doppler echoes. In water, good results can be achieved by adding hollow glass spheres to the liquid. In view of the problems involving the removal of the tracers from the sodium loop after the experiment, we decided to start the measurements without an additional seeding of the sodium. As will be shown in Sect. 4 below it is possible to obtain signals with sufficient quality. The sodium used in the experiments can be designated as clean only in a technical sense. Therefore, it is likely that oxide particles act as reflecting inhomogeneities.

3.2
UDV measuring technique

The DOP2000 US velocimeter manufactured by Signal-Processing SA (Lausanne, Switzerland) was used to carry out the velocity measurements. The US transducers are 4 MHz probes of a high temperature series (TR40405). The range of application for this transducer is limited to maximum temperatures of 150 °C (long term load) and 200 °C (short term load), respectively. The measurements were performed at a sodium temperature of about 145 °C. Some important material properties of sodium at this temperature are given in Table 1. The temperature was carefully controlled by a thermocouple in the vicinity of the measuring domain. The input parameter sound velocity was corrected according to the actual value of the temperature. Instantaneous temperature fluctuations of about ±1 K were observed inside the sodium flow. Taking into account the temperature dependence of the sound velocity, this effect results in maximum uncertainties in the determination of the measuring depth of about 0.1 mm.

The measurement of a velocity profile by means of UDV has to be controlled adjusting a set of parameters. The parameter configuration used in the experiments is shown in Table 2. The mean velocity profiles were determined by averaging 256 single profiles corresponding to a measuring time of about 5.6 s.

Table 1. Material properties of liquid sodium at 145 °C

Density ρ	917 kg/m^3
Kinematic viscosity ν	0.62×10^{-6} m^2/s
Electrical conductivity σ	8.92×10^6 1/Ω m
Sound velocity υ_s	2500 m/s

Table 2. Set of system parameters adjusted in the experiment

US frequency	4 MHz
Doppler angle	70°
Pulse repetition rate	6700 Hz
Measurable depth	175 mm
Bursts per profile	128
Velocity resolution	9 mm/s
Time resolution (single profile)	22 ms
Number of gates	140
Number of profiles	256
Spatial resolution in sodium	1.25 mm
Minimum US beam diameter	5 mm
Divergence of the US beam	10.4°

4
Results and discussion

To demonstrate the capabilities of the UDV technique with respect to the applicability for sodium flows, we determined the velocity profiles of a MHD channel flow exposed to a homogeneous, transverse magnetic field. In this context, we can also show the following interesting aspects:

- a distinct change of the velocity profile well known in MHD as M-shaping (see Moreau 1990)
- the robustness of the UDV technique in a complicated electromagnetic environment.

In Fig. 3, two examples of the measured velocity profiles are displayed for the case with and without magnetic field

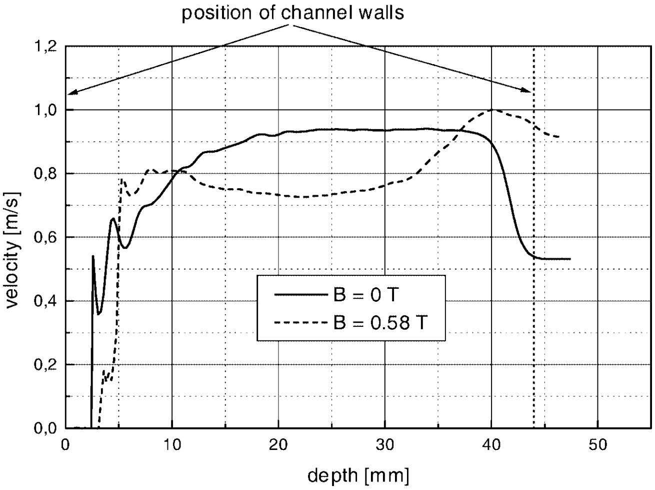

Fig. 3. Measured raw profiles of the velocity of the sodium duct flow with and without an applied transverse magnetic field

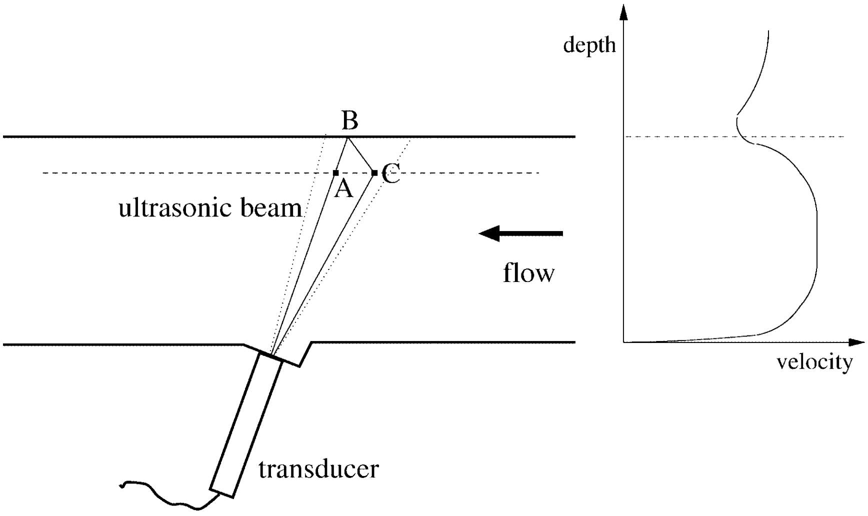

Fig. 4. Multiple reflections of the US wave may result in imaginary velocity values outside the region of the flowing liquid

exposition. The effect of the magnetic field on the flow structure can be clearly detected. However, it becomes obvious from the graphs that problems still exist to determine the velocity data along the entire channel width with a sufficient accuracy. An inherent shortcoming of the UDV is the ringing effect of the US transducer that follows immediately after the emission of the pulse. The ringing effect results in a saturation of the transducer preventing measurements at depths located just a few mm behind the surface of the transducer. In the present case additional perturbations are created by the influence of the adapter wall. Reflections of the US wave travelling inside the adapter plate are also registered by the transducer. The depicted curves demonstrate that the measurements are disturbed up to depths of about 12 mm.

The existence of reflecting interfaces may modify the acoustic field (J.-C. Willemetz, Personal communication, 2001; http://www.signal-processing.com). In general, this problem is typical for UDV applications. As shown in Fig. 4, a US beam reflected by the opposite channel wall in point B transforms this interface in a transmitter. Consequently, a particle contained in the liquid moving along the dashed line may backscatter Doppler energy more than once in the direction of the transducer (at points A and C). The depth associated with the reflection at point C is located outside the flow region. Imaginary velocity components are added to the real velocity profile. The significance of this artefact is determined by the lateral size of the US beam. The divergence of the US beam generated by the transducers used in our experiments is 10.4 °C, leading to a measuring volume of about 20 mm in the vicinity of the opposite wall. Therefore, the occurrence of such multiple reflections are considered to be the reason why we do not find the velocity going to zero at the opposite channel wall at a depth of 44 mm. Because of this bias, the velocity profiles presented in Fig. 5 have been truncated. The maximum negative velocity gradient measured in the boundary layer was chosen as a criterion for truncation.

Figure 5 shows mean velocity profiles of the sodium duct flow obtained at a Reynolds number of about 56700 and if the Hartmann number (the definition of which is given below), i.e. the magnetic field strength, is varied.

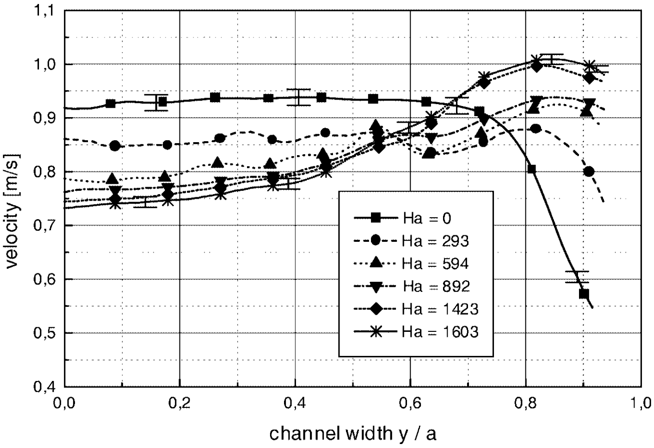

Fig. 5. Effect of a transverse magnetic field on the mean velocity profiles: development of M-shaped profiles with growing magnetic field intensity

Typical error bars shown are calculated from the corresponding values of the standard deviation. In the case without a magnetic field we find a velocity profile as usual for turbulent channel flows. The application of the magnetic field causes a significant modification of the flow structure. In the end regions where the flow enters the magnetic field the resulting electromagnetic force is not homogeneous in the cross-sectional area leading to M-shaped profiles of the velocity (see Moreau 1990). The change of the velocity profiles with increasing magnetic field can be clearly observed in Fig. 5. An enhancement of the field intensity results in a stronger braking effect in the core of the flow whereas the flow in the side layers is accelerated. A relation that can be used to estimate the ratio between the velocity rise in the side layers compared to the core of the flow, δu, and the mean velocity, u, is given by Moreau (1990):

$$\frac{\delta u}{u} \approx \frac{l}{aHa}\beta\frac{\sigma B^2 a}{\rho u} \approx 10\beta\frac{Ha}{Re} \tag{2}$$

The non-dimensional parameter Hartmann number is defined as follows

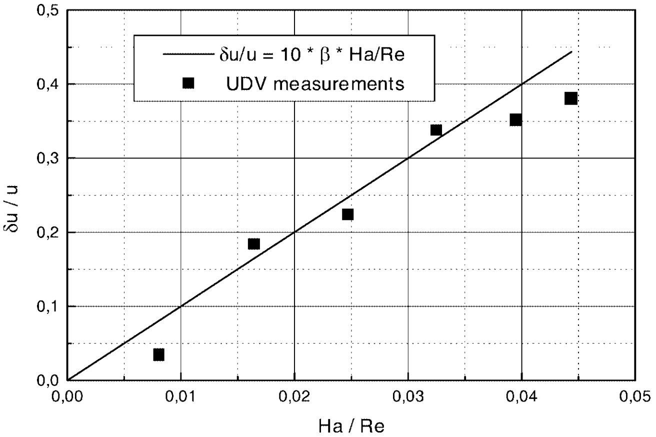

Fig. 6. Difference between the maximum velocity in the side layers and the core velocity: comparison between theoretical estimation and experimental data

$$Ha = Ba\sqrt{\frac{\sigma}{\rho v}} \tag{3}$$

The notations ρ, v and σ stand for the density of the material, kinematic viscosity and electrical conductivity, respectively. The aspect ratio of the duct is designated as β ($\beta = 1$ in our case, a is a channel half-width) and l is a measure for the typical length of the electric current loops at the entry of the magnet. An experimental work carried out by Tananaev (1979) confirmed this estimate. The author used electrical potential probes to measure the local velocities.

A comparison between relation (3) and corresponding data extracted from the measured velocity profiles is displayed in Fig. 6. Obviously, the agreement between our experimental results and the theoretical estimation can be considered as reasonable.

5
Conclusions

UDV has been successfully used to determine velocity profiles in liquid sodium at temperatures of about 150 °C. The effect of a transverse magnetic field on the flow in a square duct has been measured. Values of the velocity rise in the side layers compared to the core of the flow extracted from the measuring data show a reasonable coincidence with theoretical estimations and already existing experimental results demonstrating the reliability of our measurements.

For temperatures up to 200 °C a sufficient solution was found to realise the coupling between the US transducer and the adapter front wall by means of silicon grease. The measurements have shown that a sufficient wetting at the inner surface of the adapter was achieved. We were able to receive Doppler signals from the flow without an additional seeding using natural impurities like oxides as reflecting particles. Significant perturbations of the measurements arise from the transmission of the US beam through the stainless steel wall. An improvement of the situation would require matching the acoustic properties of the liquid sodium. Therefore, further activities must check whether the stainless steel can be substituted as the adapter material by other candidates (aluminium, graphite, etc.) characterised by lower acoustic impedance.

In view of the application of UDV to liquid metal flows, the limitation of US transducers to temperatures lower than 200 °C is a severe restriction. A way to overcome this limit could be the use of an acoustic wave guide.

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