Eddy current flowrate and local ultrasonic velocity measurements in liquid sodium

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Abstract. For the safe operation of sodium cooling systems a monitoring of the flow field is often desirable. We report first on the development of a new eddy current flowmeter (ECFM) and related tests in sodium. The objective of this sensor is its positioning above the fuel subassemblies and the detection of possible blockages of the sodium flow through the multitude of subassemblies. The sensor consists of a number of coils a part of which is fed by an excitation AC current. The assembly of coils is placed in a thimble and the measured flowrate is proportional to the integral flow around this thimble. In the second part we report on local ultrasonic velocity measurements. Here, the objective is to study the flow field resulting from a large electromagnetic pump installed at the PEMDYN facility of CEA. Both measuring techniques were tested at the sodium facility NATAN of HZDR.

Key Words: Eddy Current Flow Meter, Ultrasound Doppler Method, Liquid metal flow.

1 Introduction

Liquid metals have gained importance especially in the nuclear energy sector as a coolant in fast breeder reactors which represent one of the main concepts of fourth generation systems. The low melting point (98°C) as well as the wide availability makes sodium very beneficial for the application as coolant (sodium-cooled fast reactors - SFR). The application of sodium in the energy sector is not limited to the field of nuclear power but also considered for renewable energies as heat transfer and storage medium in central receiver systems of concentrated solar power plants. Future prospects consider sodium also for the application at buffer storages of electrical energy (in particular generated from renewable energies) in terms of concepts of liquid metal batteries.

A comprehensive understanding of the flow physics of liquid metals is required for these fields of application involving extensive research. Such investigations require appropriate techniques for measuring flows in hot liquid metals. We will present two advanced flow measuring techniques for liquid sodium applied for the research in the framework of the French R&Dprogram related to the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project and conducted by the CEA. The first is the Eddy Current Flow Meter (ECFM) which represents anintrusive flow measurement technique, which has already been tested in the Phenix reactor in France [1]. The second is the ultrasound Doppler Velocimetry (UDV) which is able to work in opaque fluids and to deliver spatially resolved velocity profiles along a line in real time. It is a non-intrusive, but not contactless method the operation of which becomes more and more difficult when applied to liquid metal flows at higher temperatures.

2 Test channel for measurements in sodium

The ECFM and UDV measurements were conducted in the HZDR sodium loop NATAN at sodium temperatures of 160 °C and 240 °C for velocities ranging from 0 m/s to 1.4 m/s. A special test section (FIG. 1) has been constructed to allow simultaneous measurements with both techniques. It features two slots similar to the instrumentation slots of the PEMDYN facility (see section 4.3), enabling an ultrasound velocimetry measurement in axial flow direction similar to the planned measurements at PEMDYN. Four small multi-purpose slots (HZDR design) allow for the application of various ECFM or UDV sensors. The bended path of the channel permits to measure the flow in axial direction (by UDV as well as by ECFM) with these multi-purpose slots without substantially influencing the flow. The two opposing slots provide various measuring arrangements and alternative measuring principles (as ultrasonic flowmeter method). Furthermore, the influence of the narrow channel geometry on the velocity profile can be investigated by measuring from both sides and comparing with each other. The test section has a square cross section of 62 x 62 mm^2. By using flange no. 4 higher velocities can be achieved with the same flow rate because the ECFM extends into another section of the NATAN loop which features a cross section of 44 x 44 mm².

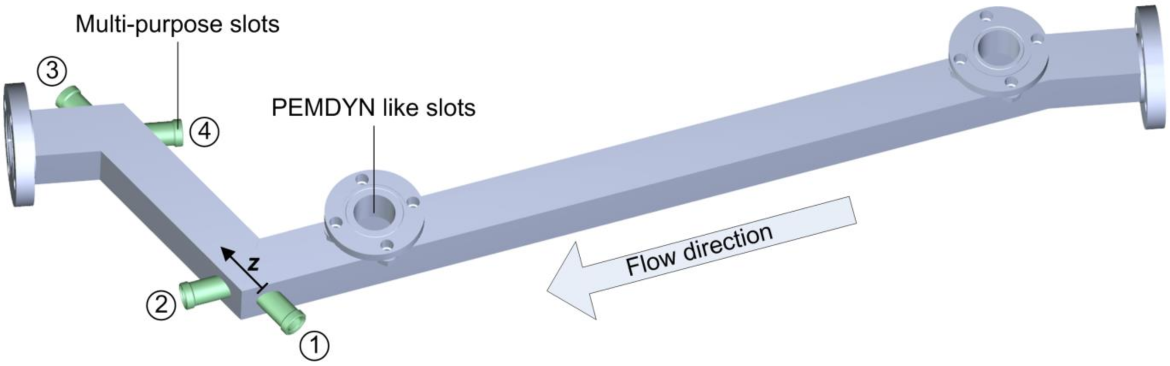


FIG. 1. ASTRID test channel for NATAN facility at HZDR.

3 Flow measurements by ECFM

The ECFM is an inductive sensor which allows a contactless measurement of the velocity of a liquid metal. A miniaturized high temperature ECFM is being developed in frame of the present project. Its purpose is to detect flow rate variations or blockages above the fuel subassemblies. The actual sensor is installed inside a cylindrical stainless steel thimble that protects the sensor coils from the liquid sodium with temperatures up to 650 °C. The local liquid metal flow around this thimble is measured by the ECFM.

3.1 Functional Principle

Usually an ECFM consists of three magnetic coils (see FIG. 2). An excitation coil induces eddy currents within the liquid metal and two detection coils measure the magnetic flux density at two positions – up- and down-stream of the excitation coil. Without any flow at the sensor, the same voltage can be measured at each detection coil as they have the same distance from the excitation coil and because the magnitude of the eddy currents in their vicinity is equal. The voltage at each detection coil is influenced by the magnetic field of the excitation coil and the oppositely directed magnetic field of the eddy currents within the liquid metal. When the liquid metal begins to flow, further eddy currents are induced due to the motion of the liquid metal through the magnetic field. Their magnitude is proportional to the flow velocity. Because the radial component of the magnetic field is opposite up- und downstream of the excitation coil, the motion induced eddy currents have opposite directions. This results in an increase of the total eddy currents at the upstream coil, because the motion induced currents have the same direction as the currents which are induced by the excitation field, causing a further reduction of the upstream detection coil voltage. The eddy currents at the downstream coil are weakened because they have opposite directions and, thus, the downstream detection coil voltage is increasing. The change of the coil voltages is linearly dependent on the flow velocity [2].

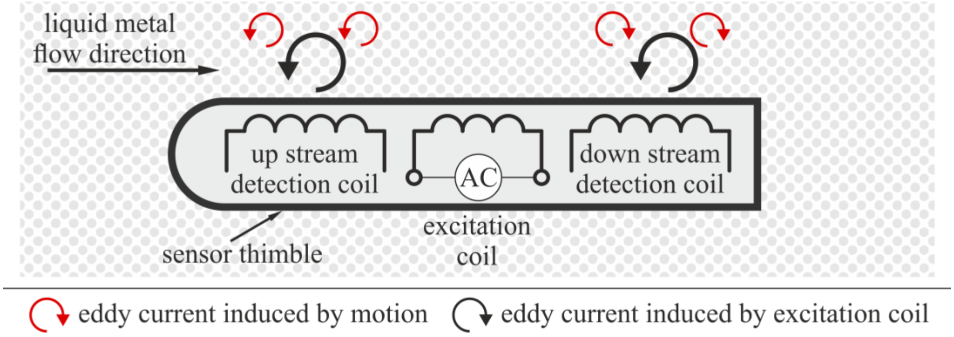


FIG. 2. Functional principle of the ECFM

The electrical conductivity of the liquid metal influences the magnitude of the eddy currents and, thus, the induced voltage within the detection coils. Therefore, a calibration of the ECFM is necessary because the electrical conductivity of the liquid metal depends on the temperature. The penetration depth of the eddy currents into the liquid metal and thereby the volume in which the velocity is measured depends on the frequency of the excitation current.

3.2 Structure of the ECFM

The wire and coil holder of the high temperature ECFM consist of temperature resistant materials since the sensor shall be operated up to a maximum coolant temperature of 650 °C. As wire material a nickel plated copper wire with a diameter of 0.25 mm and ceramic insulation is used (note that conventional coil wire can only be used for maximum ambient temperatures of around 250 °C). The coil holder is made of the ceramic Macor which has the advantage of preventing any inductive losses within the coil holder, as it would be the case with a stainless steel coil holder, for example. The ECFM consists of three coils (see FIG. 3): there are two receiver coils with 250 turns each and one excitation coil with 125 turns. The ECFM has a diameter of 11 mm and a total length of 50 mm. The stainless steel thimble has an inner diameter of 11 mm and a wall thickness of 2 mm, hence an outer diameter of 15 mm. This wall thickness will later be adapted with regard to possible mechanical deviations or vibrations of the thimble and can likely be reduced compared to the present 2 mm. As any electrically conducting material between the coils and the liquid metal flow represents a kind of shielding, a reduction of the wall thickness will improve the accuracy and sensitivity of the ECFM measurements.

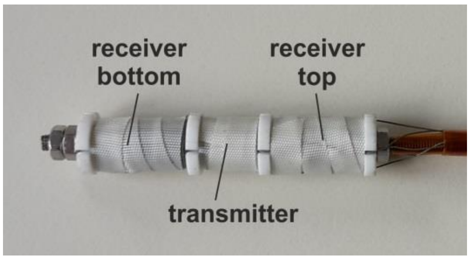


FIG. 3. Prototype of the high temperature ECFM

During the experiments, the modulus and phase of the voltage difference between both receiver coils is measured using a lock-in amplifier that allows a very accurate measurement of sinusoidal signals. The measured values are recorded automatically and used to calculate the mean value of the surrounding liquid metal velocity.

3.3 Measurement results

Numerical simulations have shown that there is a conductivity-dependent optimal excitation frequency at which the ECFM has its highest sensitivity. This frequency can also be determined by sweeping over a wide range of excitation frequencies and determining the corresponding modulus or phase of the receiver voltage difference. For the operation of the ECFM it is not strictly required to measure at the optimal frequency but it is recommended to achieve the most accurate results. For applying an ECFM in sodium a value of 500 Hz has been determined to be the optimal frequency. It can be seen in FIG. 4 that the sensor has its highest sensitivity at about 500 Hz for all velocities considered here.

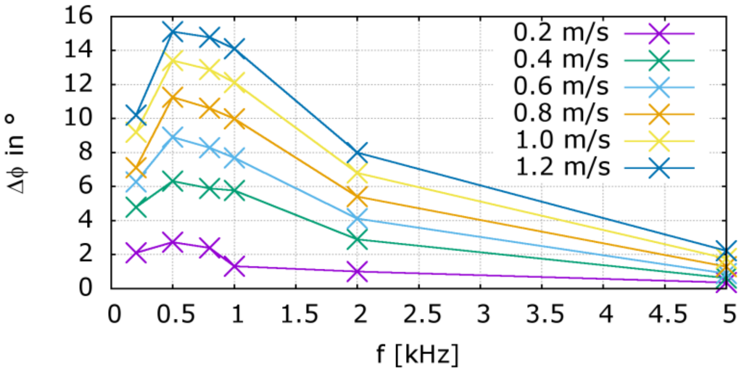


FIG. 4. Frequency sweep to determine the optimal excitation frequency of the ECFM in sodium

The following figures show how the measurement results of the modulus (FIG. 5) and phase (FIG. 6) difference of the receiver voltages depend on the flow rate, for two different sodium temperatures with an excitation frequency of 500 Hz. Each point represents the mean value of 20 separate measurements, each taken during approximately 1 second. The variation of the flow rate between 0.2 m³/h and 9 m³/h corresponds to a velocity range between 0.03 m/s to about 1.4 m/s. The straight line is a linear fit of the dataset.

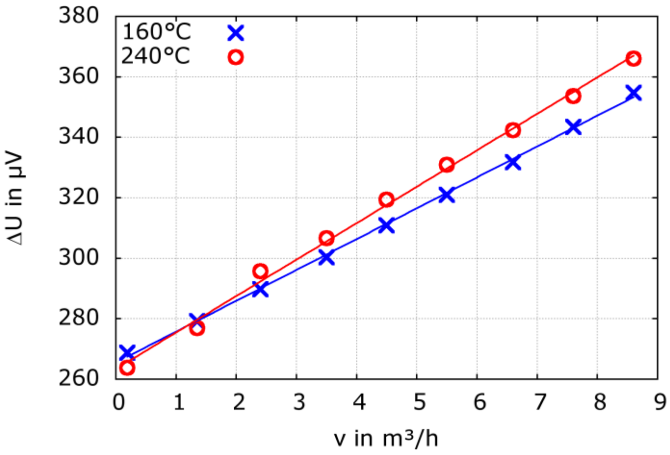


FIG. 5. Measurement results for the modulus difference at sodium temperatures of 160°C and 240°C

It can be seen that there is an offset in modulus and phase. It is caused by slight, almost unavoidable asymmetries in the structure of the ECFM and should be determined in the calibration process. Note that this offset has no impact on the accuracy of the flow rate measurements. Furthermore, it becomes obvious that the slope of the linear fit changes with the sodium temperature. This is the result of the decreasing electrical conductivity of the sodium and also of the increasing resistance of the coil wires. To take into account these changes, the EFCM has to be calibrated for different temperatures in order to achieve accurate results.

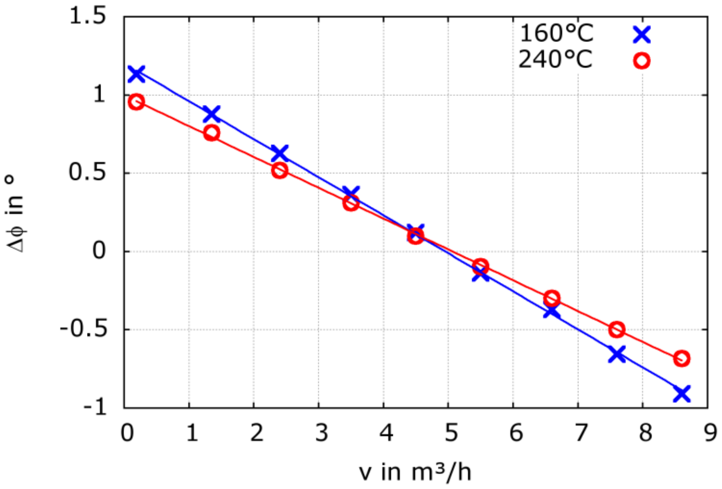


FIG. 6. Measurement results for the phase difference at sodium temperatures of 160°C and 240°C

Compared to the modulus, the phase difference is more accurate and the deviation from the linear fit is even smaller. During the measurements, the phase measurement has proven to be less influenced by disturbances and temperature fluctuations. However, there is a similar offset problem as in the case for the modulus measurement.

3.4 Conclusions ECFM

The ECFM has proven to be a robust sensor for an instant determination of the local flow rate of liquid sodium around the cylindrical thimble containing the sensor. This prototype was tested here up to temperatures of 240 °C, but is designed to work up to 650 °C. Since phase measurements yield more accurate results than the measurements of the modulus, a higher resolution of the flow rate can be achieved by using phase measurements. A very good linear dependence between modulus/phase and flow rate/velocity has been demonstrated. There is an obvious disadvantage of the ECFM arising from the need for calibration mainly due to the temperature variation of the electrical conductivity of the liquid sodium.
Further measurements and performance evaluations with the ECFM at higher temperatures and higher velocities are planned for the near future.

4 Flow measurements by UDV

4.1 Measurement principle

The measuring principle is based on the pulse-wave echo technique. Narrow ultrasonic pulses of a few cycles emitted from an acoustic transducer propagate into the fluid along a measuring line which is identical to the axis of the ultrasonic beam. A part of the ultrasonic pulse is scattered by micro particles suspended in the liquid. Their echo signal is received by the same transducer within the time period between two pulse emissions. A short sequence of such echo signals contains the entire information of the velocity profile along the ultrasonic beam. Knowing the sound velocity of the liquid, the axial position of the scattering particles along the beam axis is determined from the measured time span between the pulse emission and the reception of the respective echo signals. The movement of the scattering particles inside the measuring volume between two consecutive bursts results in a small time shift of the echo signal. A correlation analysis between the echo signals of consecutive bursts reveals the velocity component of the velocity vector in direction of the beam axis for all positions along the beam. Owing to the Nyquist theorem, the product of measurable maximum velocity and penetration depth is limited by the sound velocity and the ultrasonic frequency. Ultrasonic methods are non-invasive, but not contactless since a continuous acoustic path from the ultrasonic transducer to the fluid under investigation is required. For a more detailed description of the basics of the measuring principle the reader is referred to Takeda [3].

4.2 Application in hot liquid metals

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 into the fluid has to be guaranteed. Here, the acoustic coupling between transducer and wall, the acoustic transmittance of the wall (due to safety reasons the sensors are typically not in direct contact to the fluid) and the wetting conditions have to be considered as important issues. Moreover, a balanced concentration of scattering particles has to be provided to obtain reliable velocity information from the fluid. On the one hand, a very high concentration attenuates the signal in the front region to such an extent that the acoustic waves cannot propagate into larger measurement depths. On the other hand, a lack of scattering particles in certain measurement depths impedes to determine the flow velocity correspondingly.

First successful velocity profile measurements at higher temperatures were published by Eckert [4]. The flow profile of liquid sodium in a square channel cross section was measured at temperatures up to 150°C, whereby this maximum temperature described the limitation of the commercial ultrasonic probe. A specific sensor development for overcoming this limitation focuses on the use of acoustic wave guides [5]. 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, however, the measurement depth of waveguides is fairly limited due to strong reflections from the waveguide-liquid interface, which prevents profile measurements beyond these strong reflections.

Due to this drawback of waveguide sensors we have adapted the sensor concept with standard transducers given in [4] to measure instantaneous flow velocities of liquid metals at an enlarged temperature range up to 230°C. Thereby, the main focus is to obtain large measurement depths. Below this approach is presented in detail and its reliability is demonstrated by measurements at a channel flow of sodium at the NATAN facility at HZDR.

4.3 Measurement objective for the PEMDYN facility

The PEMDYN facility of CEA comprises a small hermetically closed loop with the focus on the electromagnetic pump to be studied and specified. This pump is accomplished as a bidirectional Annular Linear Induction Pump (ALIP) driving a flow in an annular channel between an inner and outer tube (FIG. 7). An inductor with a ferromagnetic core beyond the outer tube and a secondary inductor or a passive core inside the inner tube generate a traveling magnetic field with a perpendicular component induced by a three-phase current in the coils. The ALIP is projected to perform a pumping discharge up to 1500 m^3/h and a pressure up to 2.5 bar. However, principle issues of ALIPs are MHD instabilities predicted for higher magnetic Reynolds numbers [6]. The study of these instabilities requires information about the axial flow velocities inside the annular channel of the inductor section. For this purpose 24 instrumentation slots are provided for the application of UDV at both the in- and outlet of the pump. The instrumentation is very challenging since (i) the distance between slots and inductor is at minimum 600 mm, (ii) the radial extent of the annular channel is 47.5 mm and (iii) the expected maximum flow velocities are up to 20 m/s (the product of measurement depth and maximum velocity represents a physical limitation of the operation principle of UDV). Furthermore, the necessary axial alignment of the transducer involves a sophisticated sensor mounting (perpendicular to the slot alignment) due to the finite slot diameter. Additionally, this sensor adapter obviously disturbs the flow. The main objectives of our study comprise general issues related to velocity measurements in sodium (wetting, particle concentration,…), the evaluation of the maximum measurement depth, the investigation of the ultrasound beam divergence in the small channel, and the optimization of the transducer mounting in axial direction.

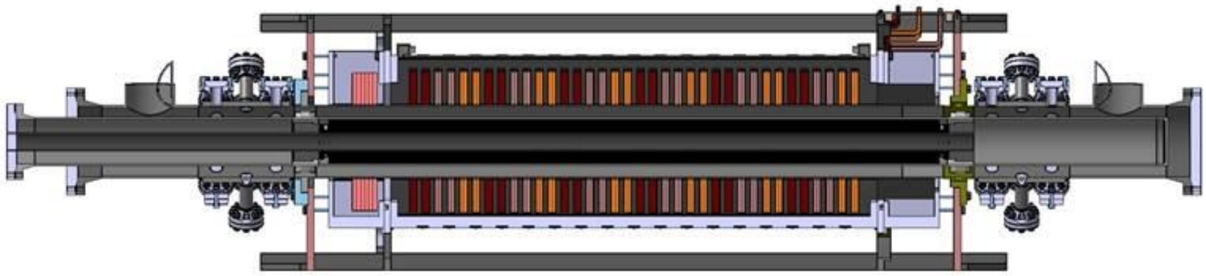


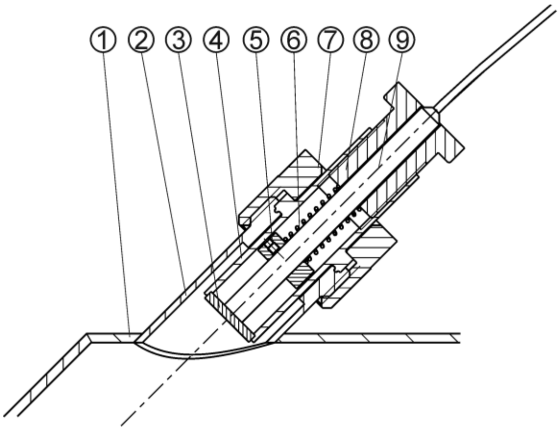
FIG. 7. PEMDYN ALIP, sectional view.

4.4 Experimental setup

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. 8) is designed for the multi-purpose slots of the NATAN test section (FIG. 1) to protect the sensor and to provide reliable measuring conditions. The socket consists of an open stainless steel cylinder (4) with a thin plate at the cylinder front (3) serving as acoustic transmission window. The sensitive face of the transducer (9) is directly attached to this window through which the measurement is conducted.

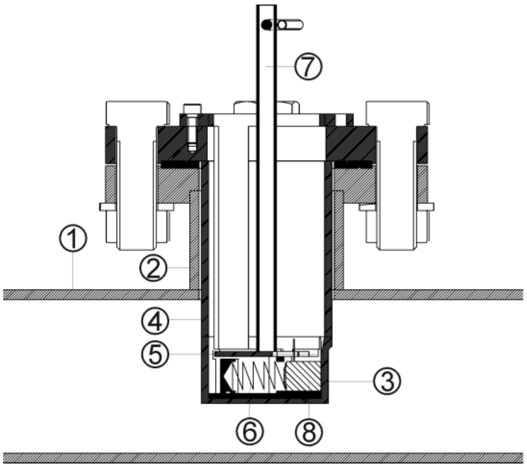
The proper centring and alignment of the probe is guaranteed by a duct (5) attached to the probe. It is also intended as counterpart for a spring mechanism (6) pressing the probe at the polished inner wall of the transmission window. The spring pressure can be adjusted by a knurled nut (8) during operation to ensure a stable acoustic coupling despite thermal expansion.

The acoustic transmission among transducer and transmission window of the socket is accomplished by an acoustic couplant withstanding temperatures up to 250°C. For an optimal acoustic signal transmission the thickness of the transmission window has to meet a multiple of the half ultrasonic wave length in the wall material in order to maximize the acoustic transmittance [4]. Accordingly, the optimal thickness of a stainless steel wall amounts to 2.9 mm for an ultrasonic frequency of 1 MHz and its multiples (2 MHz, 4 MHz, …). Variances of the optimal wall thickness arising from temperature changes or an imperfect fabrication can be compensated by a fine tuning of the emitting frequency. The wetting behaviour of sodium at the outer wall of the acoustic window is promoted by a polished surface electroplated with a nickel layer.



1	Channel wall
2	Slot for sensor probes
3	Acoustic transmission window
4	Probe socket
5	Probe duct / fixing
6	Spring
7	Sleeve nut
8	Knurled nut
9	Ultrasonic transducer probe

FIG. 8. *Probe socket for multi-purpose slots in a channel bending*



1	Channel wall
2	Slot for sensor probes
3	Acoustic transmission window
4	Probe socket
5	Probe duct / fixing
6	Spring
7	Clamping lever
8	Ultrasonic transducer probe

FIG. 9. *Probe socket for PEMDYN slots*

FIG. 9 shows the adaption of probe socket concept for the PEMDYN like slots of the ASTRID test channel (FIG. 2) enabling a flow measurement along the pipe axis. Due to the measurement principle of the ultrasonic velocimetry the transducer has to be installed inside the flow channel in direction of the pipe axis. Thus, a remarkable disturbance of the flow cannot be avoided. Owing to the limitation of the slot diameter the transducer installation perpendicular to the slot axis requires a very short transducer customized for this setup. Furthermore, due to the perpendicular installation of spring (6) and transducer (8) the pressure to the transducer cannot be varied (only slacked and spanned) by the clamping mechanism (7) impeding to optimize the acoustic transmission in contrast to the multi-purpose socket.

The measurements are carried out using the pulsed ultrasound velocimeter DOP3010 from Signal Processing SA, Switzerland. The same company also provides specific high-temperature transducer probes (LTH series) specified up to a maximum temperature of 230°C. For the selection of the probe parameters various aspects with respect to the spatial and temporal resolution, the velocity limitation, multiple reflection characteristic as well as constructional issues have to be considered. As a result probes with an ultrasonic frequency of 2 MHz or 4 MHz and a piezo diameter of 5 mm (models TR0205LTH and TR0405LTH) were selected.

4.5 Measurement results

First results from ultrasonic flow measurements carried out at the multi-purpose slots are presented here. Measurements at the sensor sockets constructed for PEMDYN revealed that at frequencies of 1 MHz and 2 MHz the echo signal is saturated by very strong reflections inhibiting the reliable acquisition of velocity profiles. It may be assumed that this echo saturation is caused by standing waves traveling inside the probe socket and loop pipe. The application of 4 MHz transducers may solve this issue and will be prospectively examined.
FIG. 10 shows time-averaged velocity profiles (mean flow) measured at the multi-purpose slot 1 (in *z*-direction, see FIG. 1) for different coil currents of the MHD pump at NATAN. The elevations of flow velocity at the beginning and the end of the profile arise from the bendings in the pipe. Additionally, the persistent slope of velocity profile after the first elevation is a result of the flow which centralizes again after being squeezed at the wall in the first bending. The profiles for $I_{pump} = 5$ A and $I_{pump} = 10$ A are reliable but the profile for $I_{pump} = 15$ A decreases significantly in the last third of the measurement depth. Furthermore, the shape of the profile of $I_{pump} = 20$ A corresponds to the other profiles only in the first segment.

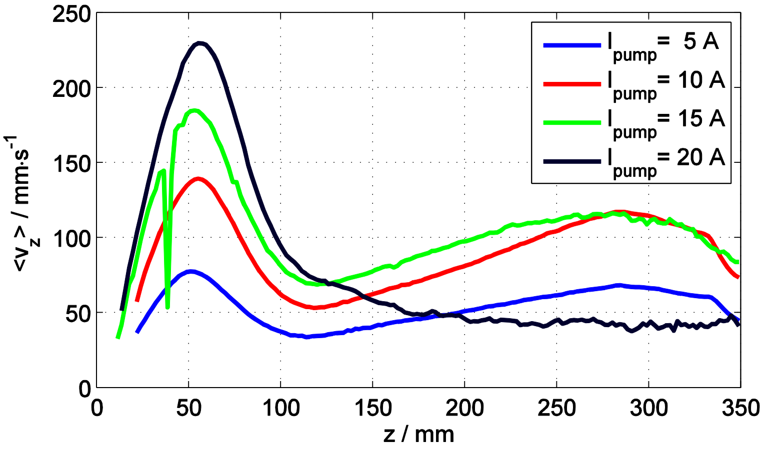


FIG. 10. Velocity profiles measured at slot 1 for different pump currents

At higher flow rates probably more scattering particles are stirred into the bulk flow causing an increased attenuation of the ultrasonic pulse in larger depths resulting in a low signal-to-noise ratio and underestimated velocity values. This assumption is supported by the energy profile of the scatterers provided by the measurement device revealing a slow decreasing energy level with *z* for low flow rates and an intense energy level at the beginning with almost no energy at the end for high flow rates. In this case the required balanced concentration of scatterers is not guaranteed anymore. The peak at the beginning of the velocity profile for $I_{pump} = 15$ A is an artifact caused by a strong stationary echo. The effect of the narrow channel geometry associated with the significant beam divergence for such high measurement depths is presented in FIG. 11 where the velocity profile was measured from one side (from slot 1, see FIG. 1) and from the other side (from slot 3). By mirroring the profile obtained from slot 3 the profiles can be directly compared to each other. It should be noted that the profiles additionally were shifted a little bit to compensate the spatial filtering by the measurement device. Furthermore, an artifact occurs at the end of the profile of slot 1. FIG. 11 reveals that strong velocity gradients are smoothened and sharp velocity elevations are spread with increasing measurement depth.

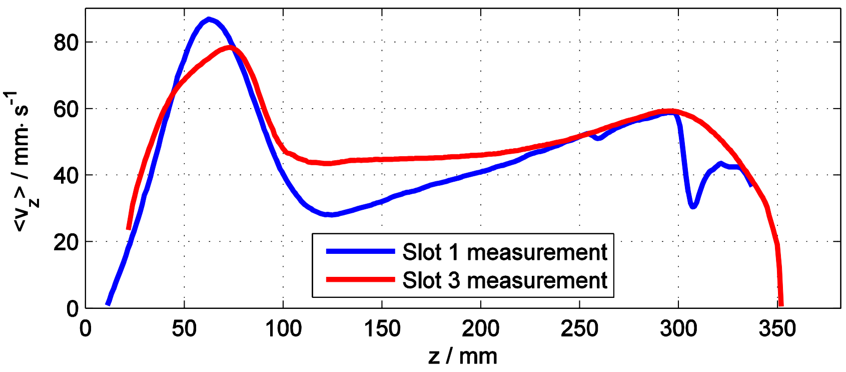


FIG. 11. Velocity profiles (I_{pump} = 5A) measured from opposite sides (slot 1 and slot 3)

4.6 Conclusions UDV

It was proved that measurement depths of at least 350 mm can be achieved with the ultrasonic velocimetry in sodium; however, an unbalanced particle concentration may be a major issue for such measurements depending on the flow conditions at different flow rates since the concentration of these natural scatterers is difficult to adjust. In our case the sodium in the loop exhibits a too high concentration impeding reliable measurements at higher flow rates.

Furthermore, the measured flow velocity may suffer from an increasing systematic measurement error with increasing measurement depth in narrow geometries. This has to be considered in the measurement analysis.

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