The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-xxx

CONTACTLESS FLOWRATE SENSORS FOR Na, PbBi and Pb FLOWS

D.Buchenau[1], G. Gerbeth[1] and J. Priede[2]

[1] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01314 Dresden, Germany
[2] Applied Mathematics Research Centre, Coventry University, United Kingdom

Abstract

Accurate and reliable flow rate measurements are required for various liquid metal systems such as the Na or Lead-flows in fast reactors, the PbBi-flows in transmutation systems, or the flows in liquid metal targets. For liquid metal flows, a contactless measurement is preferable. In this paper we report on the recent development of two types of such flow meters. The former operates by detecting the flow-induced disturbance in the phase distribution of an externally applied AC magnetic field. Such a phase-shift flow meter was developed with an emitting coil at one side of the duct and two sensing coils at the opposite side. The second approach uses a rotatable single cylindrical permanent magnet, which is placed close to the liquid metal duct. The rotation rate of this magnet is proportional to the flow rate.

Introduction

Design and improvement of the thermal hydraulics of liquid metal reactor systems is often based on numerical simulations of the heat and mass transfer processes of the related flow field. However, velocity measurements in opaque liquid metal flows still represent a challenging task as commercial measuring systems are not available for such melts. During the last decades, significant progress has been achieved in the field of non-invasive measuring techniques. A recent review regarding the principles of different velocity measurement systems and their applicability has recently been reviewed in [1]. Commercial electromagnetic flow meters are typically based on the flow-induced electrical voltage measurements by electrodes in direct contact to the melt in a steady magnetic field [2]. In view of the typical problems coming along with applications at liquid metal flows such as high temperatures, interfacial effects and corrosion, the main disadvantage of this type of flow meter is the electrical contact to the liquid metal, which is necessary to measure the electric potential difference. Therefore, contactless operating measurement techniques are very attractive for liquid metal applications. Such flow rate sensors are based on the flow-induced disturbance of an externally applied AC magnetic field which manifests itself by a modified amplitude or a modified phase of the AC field. The phase-shift sensor [3,4,5,6] consists in applying an external alternating magnetic field and measuring the flow-induced phase-shift at two measuring positions, as it is done, for example, in the so-called flow tomography [7,8].

In addition, a simple and robust sensor design has been developed employing a single rotating magnet, the rotation rate of which is proportional to the flow rate in the pipe [9]. Compared to the concept of the Lorentz force velocimetry [10,11], the signal of the rotating magnet is independent on the electrical conductivity of the flowing melt, hence independent on the temperature. Both flow rate sensors have been demonstrated at liquid metal test loops for which comparative flow rate measurements are already existing.

1. Test facilities

1.1 Sodium-loop at HZDR

First experiments were carried out at the Sodium-loop at HZDR. The flow is driven by an electromagnetic linear pump which provides a maximum velocity of 1.5 ms^{-1} over the cross section, which in turn corresponds to a flow rate of 3.0 ls^{-1}. The fluid flow is guided by stainless steel channels (σ=1.3x$10^6$$Sm^{-1}$) with a cross-section of 45 x 40mm^2 on the vertical test-section and 45 x 45mm^2 on the horizontal test-section. Sodium provides a high electrical conductivity (σ=0.9x$10^7$$Sm^{-1}$) at a loop operation temperature of 150°C.

1.2 PbBi-loop at SCK-CEN

The phase-shift flow meter was tested at a LBE pipe flow during a measuring campaign at the WebExpIr-loop of SCK-CEN [12]. The characteristic measurement conditions of the sensor are mainly determined by the properties of the fluid such as the electrical conductivity (σ=0.86x$10^6$$Sm^{-1}$ at 175°C, [13]) and the range of the mean velocity of the fluid in the channel (0.7-1.6ms^{-1}). The WebExpIr-loop consists in circular tubes made from stainless steel (σ=1.3x$10^6$$Sm^{-1}$) with an inner diameter of 54.5mm in the test section where the measurements were conducted. A direct method of calibration was used by comparing the output signals of the developed contactless flow meter and an industrial-proven and commercial constituted vortex-flow meter. A zero adjustment of the flow meter for the case of the liquid metal being at rest was not possible, because the cross section of the pipe was not completely filled in that situation. Therefore, all measurements include an offset in the phase-shift, because especially at the beginning of the measurement the liquid metal level in the pipe and the flow rate increased concurrently.

1.3 Lead-loop at HZDR

The Lead-loop is a small experimental facility to study the properties of the developed flow meters under steady-state conditions. In order to prevent corrosion and abrasion during long time experiments the loop is consisting in temperature resistant stainless steel (material specifications: pipes-X2CrNiMo17-12-3, beads-X6CrNiMoTi17-12-2). The whole set-up has to sustain temperatures during operation in the range of 350°C to 500°C. Liquid metal was impelled in the closed test loop (inner pipe diameter along the test section: di=29mm, wall thickness 2.5mm, inner dimensions of the rectangular channel in the sphere of influence of the electromagnetic pump: 5x40mm) by an electromagnetic pump [14].

2. Flow rate sensors and their functional principle

2.1 Phase-shift sensor

The phase-shift sensor operates with an alternating magnetic field produced by the emitter coil on one side of the pipe. On the other side two receiver coils are placed (see Fig. 1a, b). The whole set-up is working like an intersected transformer with two secondary coils. We distinguish between the symmetric adjustment (l*=0mm) and the asymmetric adjustment with some shift l*≠0mm between the emitter and the receiver coils. The flow in the duct causes a change of the alternating magnetic field. In principle, the amplitude change as well as the phase change can be used for flow rate measurements. In the present implementation, the phase difference between two measuring points is used as measuring quantity. For more details, in particular a theoretical description of the measuring principle, we refer to [5].

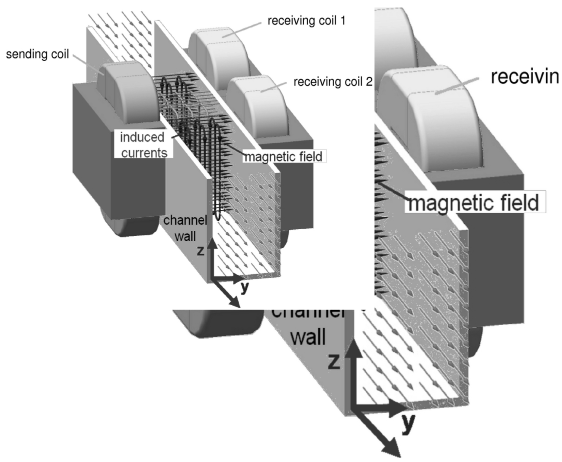

Fig. 1a: Set-up of the phase-shift flow meter

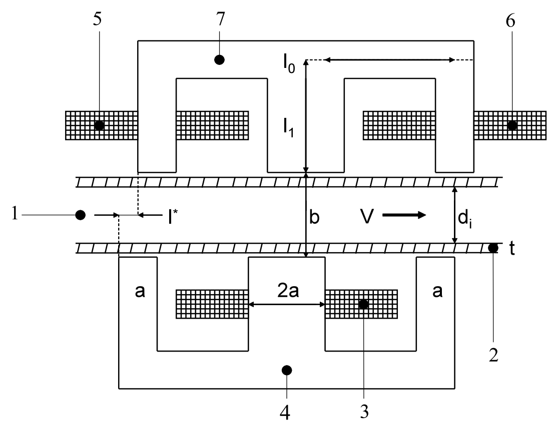

Fig. 1b: Sketch of the phase-shift flow meter in the asymmetric adjustment. 1-duct, 2-duct-wall, 3-emitter coil, 4,7-laminated magnetic iron, 5,6-receiver coils, l*-displacement length between emitter and receiver coils.

2.2 Rotating magnet

The second flow rate sensor (see Fig. 2a, b) considered here uses a single cylindrical permanent magnet magnetized perpendicularly to its axis. An almost frictionless bearing allows a free rotation of the magnet. The electromagnetic torque on the magnet caused by the liquid metal flow sets the magnet into rotation. However, the equilibrium rotation rate is determined by a vanishing total electromagnetic torque. The equilibrium rotation rate depends only on the flow rate and the geometry of the system while it is independent of the electromagnetic torque itself. Thus, the rotation rate is not affected neither by the strength of the magnet nor by the conductivity of the liquid metal provided that the friction on the magnet is negligible. For more details of this sensor we refer to [9].

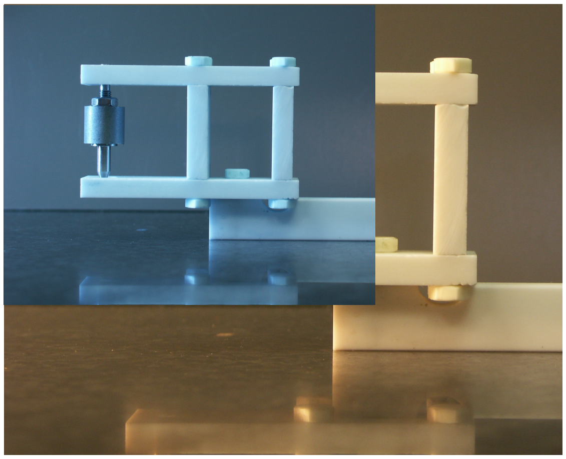

Fig. 2a: Single-magnet rotary flow meter.

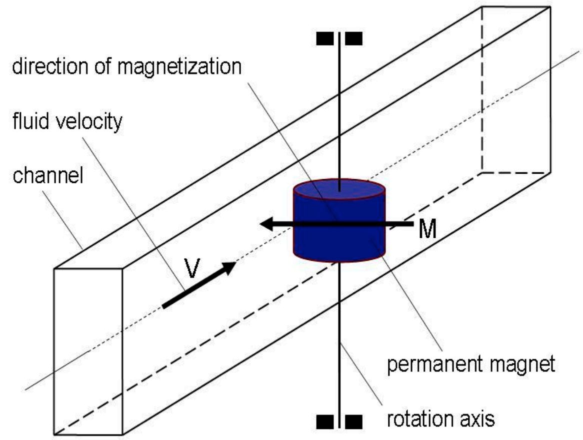

Fig. 2b: Sketch of the single magnet rotary flow meter.

3. Results and discussion

3.1 Experiments on the sodium-loop at HZDR

3.1.1 Phase-shift sensor

The applied phase-shift sensor, which was used for measurements on the Sodium-loop, operates with a sending coil (500 turns) placed on one side of the channel and two receiving coils (1000 turns each) on the opposite side. This flow meter operates like a split transformer with two secondary coils.
The phase shift between the voltages induced in the two receiver coils is measured using a lock-in amplifier with the internal averaging time of 100ms and the accuracy of at least 2%. Receiving and sending coils can be placed either directly against each other or shifted by some displacement l*.

Further we refer to these two arrangements as symmetric and asymmetric ones. The emitter coil is fed by an alternating current in the range of a few hundred mA up to three amperes. Both the sending coil and the receiving coils are furnished with laminated magnetic steel in order to concentrate and conduct the magnetic flux. The coil wires are covered by a double layer of high temperature resistant polyamide (T=260°C). Furthermore, the coils are encased by ceramic material MARCOR which withstands temperatures up to 800°C. This arrangement protects the sending- and receiving coils from the influence of the hot pipe or channel with the liquid melt to be measured.

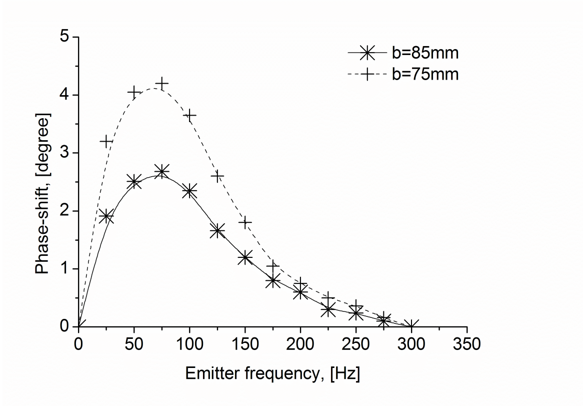

Fig. 3a: Frequency response of the phase-shift flow meter in the symmetric adjustment.

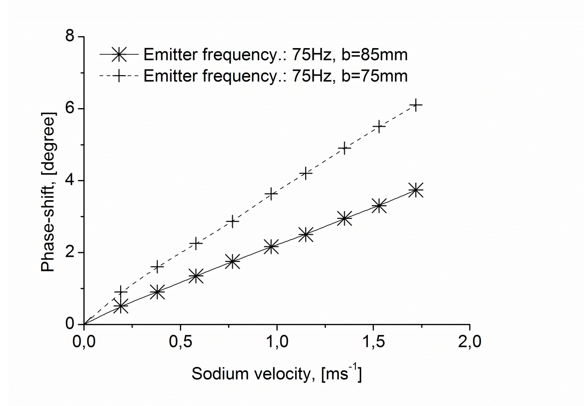

Fig. 3b: Phase-shift in dependence of the averaged velocity of the liquid sodium (symmetric adjustment).

Fig. 3a presents measurements of the frequency response in the symmetric adjustment as a function of the width of the measurement gap for a given flow rate and an input current of 500 mA. The optimal frequency of the phase-shift sensor has to be chosen in such a way that the skin-depth of the emitter field is in the same range as the width of the channel. Comparing both measurements taken at a measurement gap of 85 mm and 75 mm we are able to determine a sensitivity factor K_b=1.6 experimentally. The same sensitivity factor can be found in Fig. 3b, which shows the linear dependence of the measured phase-shift between both sensing coils as a function of the averaged sodium-velocity in the cannel of the vertical test section of the Sodium-loop at HZDR.

3.1.2 Rotating magnet

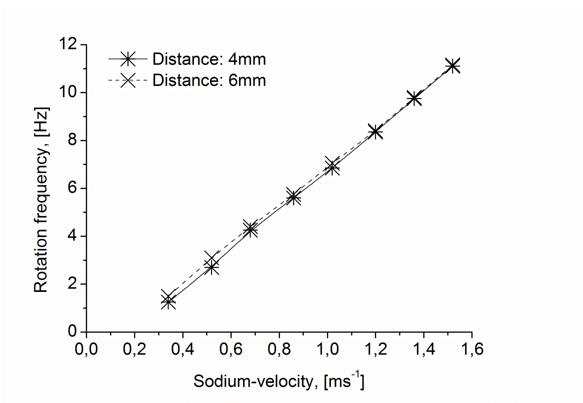

Fig. 4a: Rotation rate in dependence of the averaged sodium-velocity measured on the horizontal test-section of the sodium-loop at HZDR.

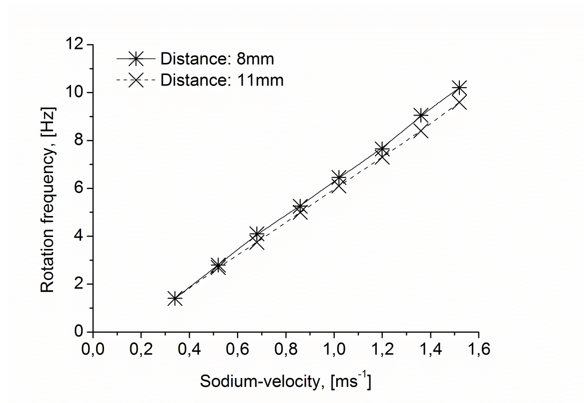

Fig. 4b: Rotation rate in dependence of the averaged sodium-velocity measured on the horizontal test-section of the sodium-loop at HZDR.

Eventually, Fig. 4 shows the measurements with the single-magnet rotary flow meter taken during a measurement campaign on the horizontal test-section of the Sodium-loop at HZDR. The dependence between rotation rate and the averaged sodium-velocity is linear. The currents induced in the electrically conducting channel walls during rotation of the magnet results in a breaking torque for the rotating magnet. Therefore, beside the effects of remanent magnetism, the extension of the measured line is not passing through the point of origin. The maximum measurement error is 0.1 ms^{-1}.

3.2 Experiments on the WebExpIr at SCK-CEN

The phase-shift flow meter was tested at a LBE pipe flow during a measuring campaign at the WebExpIr-loop of SCK-CEN [12]. The characteristic measurement conditions of the sensor are mainly determined by the properties of the fluid such as the electrical conductivity (σ=0.86x$10^6$$Sm^{-1}$) and the range of the mean velocity of the fluid in the channel (0.7 - 1.6 ms^{-1}). The WebExpIr-loop consists in circular tubes made from stainless steel (σ=1.3x$10^6$$Sm^{-1}$) with an inner diameter of 54.5 mm in the test section where the measurements were conducted. A direct method of calibration was used by comparing the output signals of the developed contactless flow meter and an industrial-proven and commercial constituted vortex-flow meter. A zero adjustment of the flow meter for the case of the liquid metal being at rest was not possible, because the cross section of the pipe was not completely filled in that situation. Therefore, all measurements include an offset in the phase-shift, because especially at the beginning of the measurement the liquid metal level in the pipe and the flow rate increased concurrently.

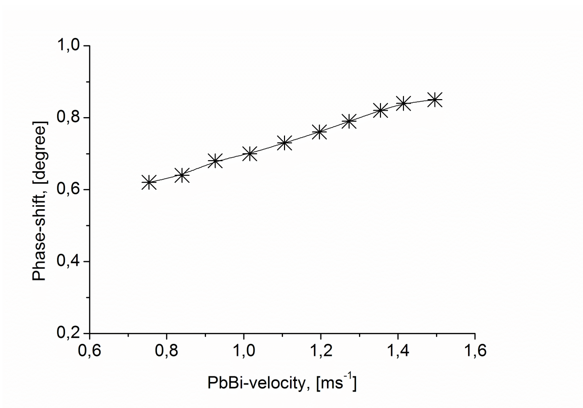

Fig. 5a: Phase-shift in dependence of the averaged LBE-velocity at an emitter frequency of 400Hz.

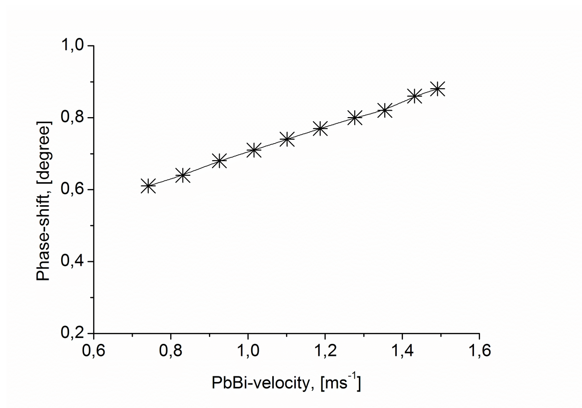

Fig. 5b: Phase-shift in dependence of the averaged LBE-velocity at an emitter frequency of 500Hz.

Fig. 5 displays an exemplary measurement obtained with a sensor current of one Ampere (Rms) at 400 Hz and 500 Hz, respectively. The observed rise of the loop temperature during experiments was never larger than 10°C corresponding to a decrease of the electrical conductivity to σ=0.85x$10^6$$Sm^{-1}$. The change of electrical conductivity did not cause a phase-shift which exceeds 0.01°. This value is exactly the minimum resolution of the lock-in amplifier. The temperature change caused by the pump has therefore no influence on the measurement results.

3.3 Experiments on lead-loop at HZDR

3.3.1 Phase-shift sensor

The electro-mechanical design of the phase-shift sensor which was used for measurements on the Lead-loop is almost identical to the phase-shift sensor applied on the Sodium-loop. Major differences exist in the available measuring gap of the sensor and the winding numbers of the applied inductances. For measurements the emitter coil (500 turns) coil is fed by an alternating current in the range of a few hundred mA. Comparable to the phase-shift sensor which was used for measurements on the Sodium loop the sending coil and the receiving coils (100 turns each) are furnished with laminated magnetic steel in order to concentrate and conduct the magnetic flux. Furthermore the temperature stable housing of the sensor is manufactured by ceramic material MARCOR which withstands temperatures up to 800°C.

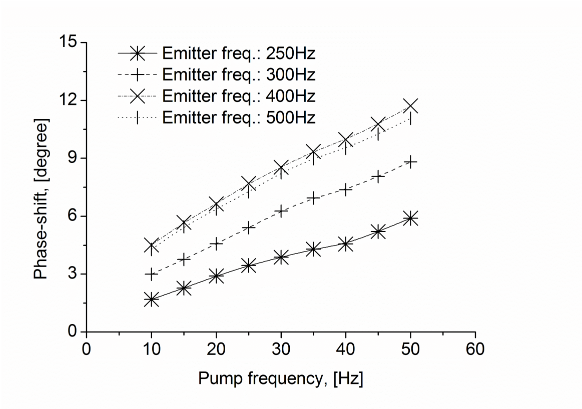

Fig. 6a: Phase-shift in dependence of the averaged lead-velocity for different emitter frequencies in an asymmetric adjustment (l*=0.5mm). Lead temperature: 400°C.

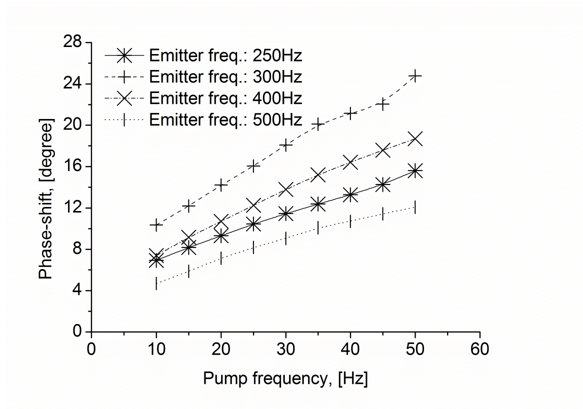

Fig. 6b: Phase-shift in dependence of the averaged lead-velocity for different emitter frequencies in an asymmetric adjustment (l*=1.5mm). Lead temperature: 400°C.

Fig. 6a and b, showing the linear dependence of the measured phase-shift between both sensing coils as a function of the averaged lead-velocity in the test section of the Lead-loop at HZDR. Furthermore it can be seen from both graphs that the optimal frequency of the phase-shift flow meter is clearly dependent from the displacement length l*. An increase of the displacement length leads to a decrease of the optimal frequency, but much more elevated measureable phase-shifts. A reliable calibrated measurement of the averaged velocity of the melt was not available, therefore all measurements are ordered to the adjusted pump frequency.

3.3.2 Rotating magnet

Fig. 7 shows the measurements with the single-magnet rotary flow meter taken during a measurement campaign on the test-section of the Lead-loop at HZDR. The dependence between rotation rate and the averaged sodium-velocity is according to Fig. 7a and b linear. The currents induced in the electrically conducting channel walls during rotation of the magnet results in a breaking torque for the rotating magnet. Therefore, beside the effects of remanent magnetism, the extension of the measured line is not passing through the point of origin. A reliable calibrated measurement of the averaged velocity of the melt was not available because of the elevated operation temperature of the loop. Comparative measurements using ultrasonic Doppler Velocimetry were not successful because of difficulties with the wetting between the steel pipe and liquid lead.

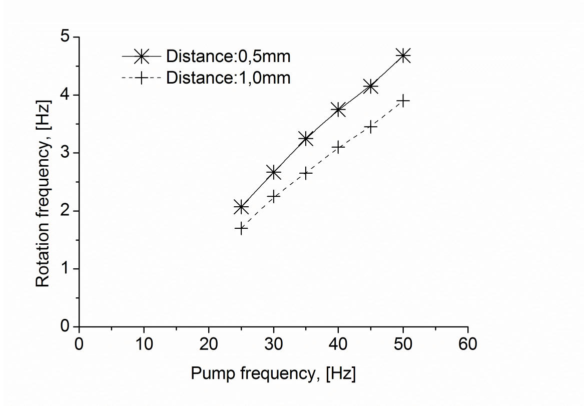

Fig. 7a: Rotation rate in dependence of the averaged lead-velocity measured on the Lead-loop at HZDR. Lead temperature: 400°C.

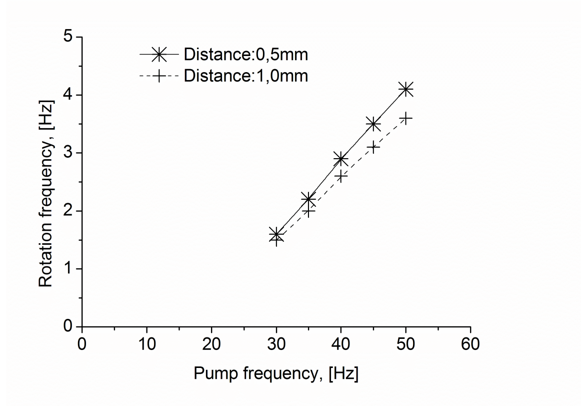

Fig. 7b: Rotation rate in dependence of the averaged lead-velocity measured on the Lead-loop at HZDR. Lead temperature: 500°C.

4. Conclusion

In this paper we reported about some new developments in the field of operational measuring techniques for liquid metal flows. Non-invasive electromagnetic flow meters have been developed at HZDR which enable flow rate measurements at elevated temperatures as required when dealing with liquid sodium, lead or LBE. The flow rate sensors have been successfully tested at different loops, in particular the phase-shift sensor at the WebExpIr facility of SCK-CEN. Both flow meters showing up a linear dependence of the output signals according to the real flow rate in pipes or channels.

The phase-shift sensor is capable of resolving rather low melt velocities, in the present case below 0.1 ms^{-1} both for electrically insulating and conducting pipes. The asymmetric adjustment gives larger signals than the symmetric adjustment. A main advantage of the sensor concept consists in its instantaneous reaction on changes of the flow rate. The maximum measurement error is 0.1 ms^{-1}.

The main advantage of the single-magnet rotary flow meter consists in its simplicity. The mechanical friction, as well as electrically conducting walls or remanent magnetism reduces the reaction time. Also, the mechanical stability of the bearing is of critical importance for the long-term reliability of the sensor. Likely, further effort on bearings with reduced friction may enlarge this application range. The maximum expected measurement error is 0.1 ms^{-1}.

However, the absolute calibration of the sensors remains, at least partly, as an open issue. In the set-up considered here the phase-shift measurements turned out to be less sensitive to marginal modifications of the measuring parameters compared to the determination of the magnitude response. An important issue not quantified until now is the sensitivity against changes of conductivity of the liquid metal because of the potential occurrence of bubbles, dissolved gases or oxides. This is of crucial interest for applications in technical systems since the appearance of such kind of inclusions cannot be suppressed there.

5. References

[1] S. Eckert, A. Cramer, G. Gerbeth, “Evolution of ideas and trends”, Magnetohydrodynamics S. Molokov, R. Moreau, H.K. Moffatt (Eds.), Springer/Kluwer, 275-294, (2007).

[2] J.A. Shercliff , “The theory of electromagnetic flow measurement”, Cambridge University Press, (1962)

[3] J. Priede, G. Gerbeth, D. Buchenau, S. Eckert, German patent DE 102006018623B4, (2008)

[4] J. Priede, D. Buchenau, G. Gerbeth , 5th Int. Symp. on EPM, Sendai, Proc. 735-740, (2006)

[5] J. Priede, D. Buchenau, G. Gerbeth , “ Contactless Electromagnetic Phase-Shift Flowmeter for Liquid Metals”, , Meas. Sc. Technologie, submitted, (2011)

[6] D. Buchenau, S. Eckert, G. Gerbeth, R. Stieglitz, M. Dierckx, “Measurement technique developments for LBE flows”, Journal of Nuclear Materials, submitted, (2011)

[7] F. Stefani, Th. Gundrum, G. Gerbeth, “Contactless inductive flow tomography”, Phys. Rev. E 70: 056306, (2004)

[8] Th. Gundrum, G. Gerbeth, F. Stefani, M. Xu, “Experimental aspects of contactless inductive flow tomography”, Magnetohydrodynamics, 42, pp. 153-160, (2006)

[9] J. Priede, D. Buchenau, G. Gerbeth, “ Force-free and contactless sensor for electromagnetic flowrate measurements”, Magnetohydrodynamics, 45, 451-458, (2009)

[10] A. Thess, E.V. Votyakov, Y. Kolesnikov, “Lorentz force velocimetry”, Phys. Rev. Let, Vol. 96, 164501, (2006)

[11] A. Thess, E. Votyakov, B. Knaepen, O. Zikanov, “Theory of the Lorentz force flowmeter”, New J. Phys., Vol. 9, (2007)

[12] D. Buchenau, S. Erlebach, G. Gerbeth, J. Priede, “Development and test of different contactless flowrate sensors for lead measurements“, Internal report-VELLA, JRA2, (2009)

[13] Yu. Plevachuk, V. Sklyarchuk, S. Eckert, G. Gerbeth, Journal of Nuclear Materials, 376, pp. 363-365, (2008)

[14] I. Bucenieks, “Perspectives of using rotating permanent magnets for electromagnetic induction pump design”, Magnetohydrodynamics, Vol. 36, pp. 181-187, (2000)