MAGNETOHYDRODYNAMICS Vol. 52 (2016), No. 1-2, pp. 53–60

A COMBINED LIQUID SODIUM FLOW MEASUREMENT SYSTEM

R. Khalilov[1], *I. Kolesnichenko*[1,2], *A. Mamykin*[1], *A. Pavlinov*[1]

[1] *Institute of Continuous Media Mechanics,*
Ural Branch of Russian Academy of Science, Perm, Russia
[2] *Perm National Research Polytechnic University, Perm, Russia*
e-Mail: khalilov@icmm.ru

The paper present a liquid sodium flow measurement system developed and designed for the liquid sodium loop [1]. This system includes in fact three independent flowmeters combined in one single device. Two of these are based on electromagnetic (conduction and induction) methods, and one uses a thermocouple cross-correlation flow measurement method. All three methods were tested in calibration experiments.

Introduction. A liquid-metal sodium facility for studying liquid sodium flows has been developed at the Institute of Continuous Media Mechanics in Perm (Russia). The facility consists of a liquid-metal loop and different systems ensuring the highest level of safe and reliable operation. Liquid sodium flows are generated by cylindrical induction pumps [2].

In order to control the liquid sodium flow rate in the loop branches, Liquid Sodium Flow Measurement System (LSFMS) devices are used. Each LSFMS device includes in fact three independent flowmeters combined in one single device. Two of these devices are based on electromagnetic (conduction and induction) methods and one uses the thermocouple cross-correlation flow measurement method. Such methods are used for flow measurements in liquid metals (see, e.g., [3]). Combining several methods allows us to improve the accuracy and reliability of the measurements, as well as to avoid the influence of temperature fluctuations on the measurement process.

1. LSFMS design. The LSFMS contains three different probes for measuring the liquid sodium flow rate: conduction – *2*, *3*, induction – *4* and cross-correlation – *5*. The probes are placed in a consecutive order in a certain removable section of the cylindrical channel *1* (Fig. 1). For the purposes of the ICMM sodium loop, two LSFMS devices were created and calibrated.

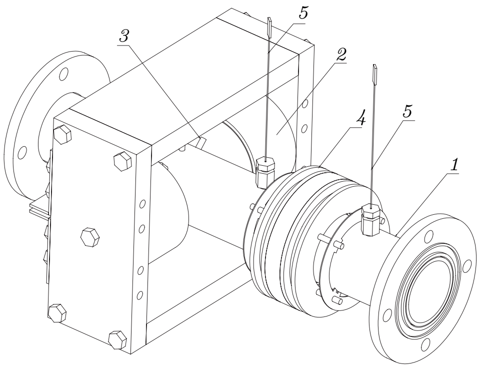

Fig. 1. Flowmeter.

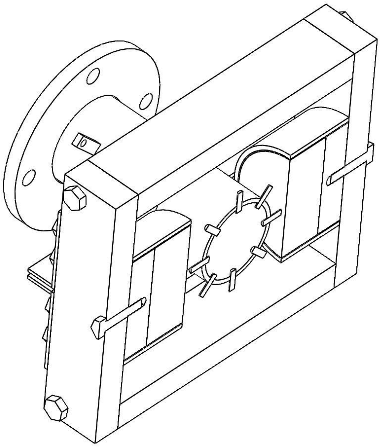

Fig. 2. Conduction flowmeter.

1.1. Conduction flowmeter. A conduction flowmeter consists of a magnetic system equipped with two neodymium cylindrical magnets (diameter 100 mm, height 40 mm). The magnets embrace the channel from two sides so that their magnetic field is directed perpendicular to the flow of liquid sodium (Fig. 2).

The channel is equipped with four pairs of stainless steel contacts: one pair is placed perpendicular to the magnetic field direction, the second is aligned with the magnetic field, and the remaining two pairs are oriented at the 45° angle. The four contact pairs are needed to reduce the influence of the hydrodynamic velocity profile asymmetry on the flowmeter performance [4]. The electrodes are welded into the channel wall at such depth as to keep a 60 mm distance between them.

Electric currents induced in a magnetic field by the motion of liquid sodium interact with the magnetic field and produce an electromotive force (e.m.f), the value of which is measured using a pair of electrodes U_i. For symmetric flow, this value is proportional to the sine of the angle between the magnetic field induction vector and the electrodes' trace line. The use of a few pairs of electrodes improves the accuracy of the full flow rate measurements for non-symmetric flow. In our case, the flow rate is estimated as

$$Q = a \cdot U_0 + b \pm \Delta q,$$

where

$$U_0 = \frac{U_1 \sin 90^\circ + U_2 \sin 45^\circ + U_3 \sin 0^\circ + U_4 \sin 135^\circ}{\sin 0^\circ + \sin 45^\circ + \sin 90^\circ + \sin 135^\circ}$$

(the sine of the angle determines the contribution of every pair of contacts to the flow rate value), a, b, Δq are the coefficients obtained in the calibration experiment.

1.2. Induction flowmeter. The induction flowmeter consists of three coils embracing the channel of circular cross-section. The central coil induces a magnetic field, and the two coils register the magnetic field (Fig. 3).

The principle of measurement is based on the distortion of the resulting magnetic field by the moving conductive liquid metal flow. The coils are made from high-temperature wire. The central coil has 250 turns, and the register coils have 500 turns. In our experiments, instantaneous e.m.f. values in both coils of each LSFMS device were obtained. Due to the interaction between the AC magnetic field generated by the primary coil (frequency 50 Hz) and the liquid sodium flow, the magnetic fluxes in the symmetric measuring coils become non-symmetrical.

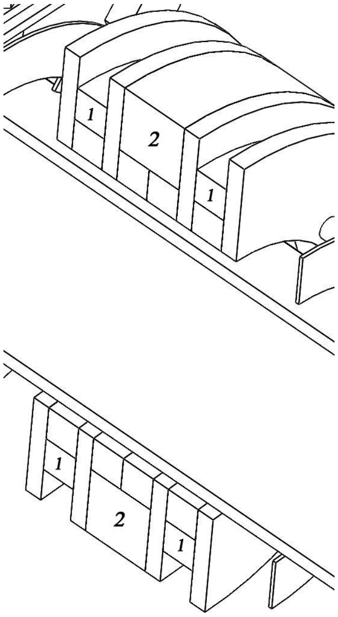

Fig. 3. Induction flowmeter. *1* – register coils; *2* – coil for magnetic field generation.

The outputs of each induction flowmeter are connected to the high-resistance inputs of a 24-bit data acquisition board NI 9239 by a shielded twisted probe. The data are sampled at a frequency of 2 kHz. The value characterizing the sodium flow rate is determined via the amplitudes of signals from the measuring coils (A_1 and A_2) as $Q_{\mathrm{ind}} = (A_1 - A_2)/(A_1 + A_2)$ for each flowmeter. After such calibration, the expected result is as follows. The flowmeter data are independent of the temperature-dependent sodium conductivity and of the amplitude of the voltage in the primary coil. In [5], a five-coil device designed to measure the flow rate of conducting fluids in a cylindrical pipe is presented. The magnetic field is generated by the central coil, and the remaining coils are measuring coils. The central couple of the measuring coils is back-to-back coils and their signal is proportional to the conducting fluid flow velocity V and to the conductivity σ. The last couple of the measuring coils is connected in consecutive order and their signal is proportional to the conductivity σ of the medium. Thus, the ratio of these two signals is proportional to the conducting medium velocity only. The demand for four measuring coils was motivated by the necessity to process the hardware signal. With the modern signal measuring devices, we can use only a pair of measuring coils for our investigation. The signal from these devices is converted into a digital signal for further processing.

1.3. Cross-correlation flowmeter. The cross-correlation flowmeter consists of two quick-response thermocouples of 1 mm thickness located at the geometric center of the pipe cross-section and spaced from each other. Mean velocity estimations are performed by calculating the cross-correlation function of the temperature fluctuations taken from these thermocouples. In 1992, detailed investigations of this method were carried out to evaluate its applicability, to estimate its accuracy and sensitivity by comparing the obtained measurement data with the most reliable data from the laser Doppler anemometer [6]. The error of the method was only 5%. Since then, the method has been successfully appplied in various experimental studies.

It has been found that in the case of turbulent convection, there occur local temperature inhomogeneities travelling with the flow. Passing sequentially through the two temperature probes, these inhomogeneities induce temperature perturbations on the probes with some time lag. Analyzing the average time lag and taking into account the distance between the probes, one can determine the mean flow rate in the gap between them. In order to find the average time lag between the temperature perturbations recorded by the neighboring probes, it is necessary to find the maximum of the cross-correlation function [7] derived for the signals from the thermocouples:

$$\operatorname{corr}(f,g)[n] = \sum_{m=-\infty}^{+\infty} f[m]g[n+m],$$

where f, g are the signals from the thermocouples.

2. LSFMS calibration. In order to define the calibration constants and to verify the LSFMS devices in the operating flow range, a special setup was created (Fig. 4) and series of calibration experiments were performed. The flow of sodium is created by a pressure difference between two tanks connected by a pipeline with the LSFMS devices mounted on it in sequence. One of the tanks is filled with sodium and overpressured by argon (0.3–0.8 atm). The other one is empty and vacuumed. The valve of one of the tanks controls the flow intensity. During the calibration, the sodium flow runs in consecutive order through all the flowmeters, and the signals from the probes are simultaneously recorded. Each tank has a system of contact level gauges, whose records can be used to compare the integral characteristics of the flowmeters. The setting error for the contact level gauges in each tank is no more than 1 mm. The internal diameter of the tank is 530 mm, and a 1 mm change in sensor setting level corresponds to a 220 ml change in tank volume.

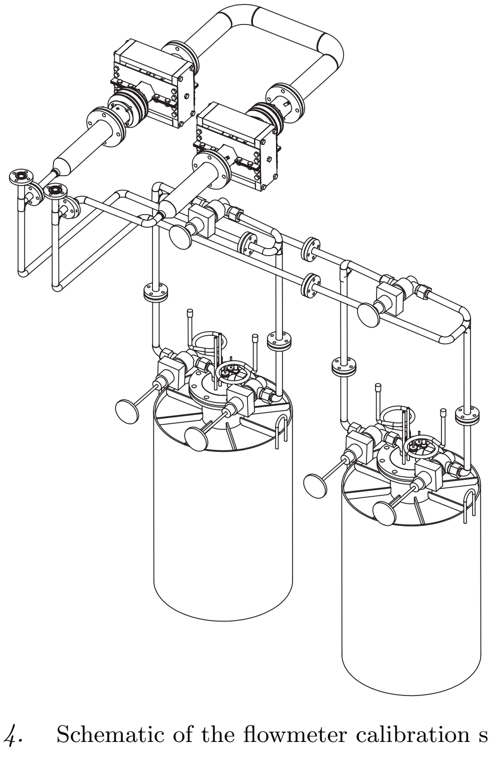

Fig. 4. Schematic of the flowmeter calibration setup.

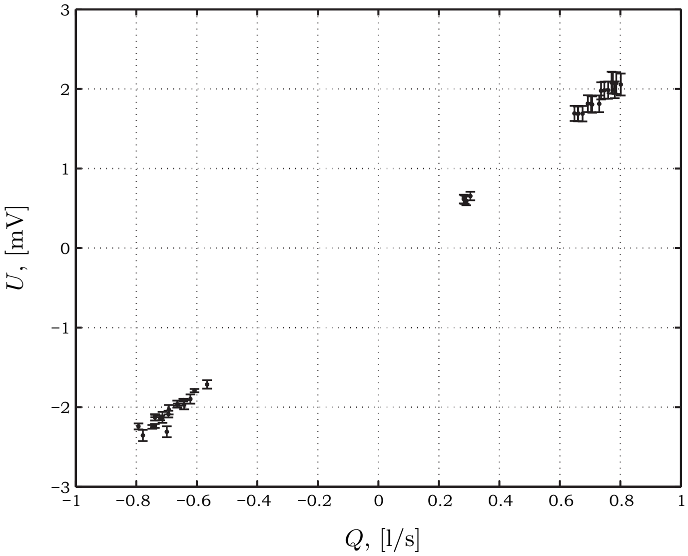

Fig. 5. Conduction flowmeter calibration results.

Reference benchmarks to evaluate the volume of the flowing sodium are taken at each subsequent level gauge positions in the tank. The distance between these benchmarks is 180 mm. Therefore, the relative accuracy of the sodium level determination in the tank is 0.55%. With the error caused by the sodium surface oscillations observed in the tank during the liquid sodium flow, the total error is 2%. The timing error is negligibly small compared to the total error, because it is measured in an automatic regime using the high-frequency data acquisition board (discretization frequency is 50 kHz). At an operational frequency of 2 kHz and a flow rate of 1 l/s, the relative error is of about 0.001%.

3. LSFMS calibration results.

3.1. Conduction flowmeters. In the calibration experiments, the sodium volume and the transfer time were measured. Then the flow rate was calculated with a specified precision. The voltage U_0, which is a combination of the potential differences between different pairs of electrodes, was registered concurrently for both conduction flowmeters. Fig. 5 presents the dependences of the voltage U_0 on the flow rate for each flowmeter. Note that the differences between the voltages U_0 of each flowmeter are of the order of 3%, which can be attributed to the accuracy of the electrodes and magnetic systems setting, as well as to the differences in values of the magnetic field generated by the permanent magnets. As a result, the following calibration coefficients have been found for each conduction flowmeter:

Flowmeter	a, [l/(sV)]	b, [ml/s]	Δq, [ml/s]
1	348	7	18
2	359	52	21

3.2. Induction flowmeters. The results obtained during the calibration experiments for one of the induction flowmeters are illustrated in Fig. 6. Slow damping of the flow rate Q_{ind} is observed when the liquid sodium flow is terminated. A series of additional experiments proved that the induction flowmeters are affected by a temperature gradient along the flowmeter channel. During the flow of liquid sodium, the thermal gradient is smoothed, but when the sodium flow stops, a

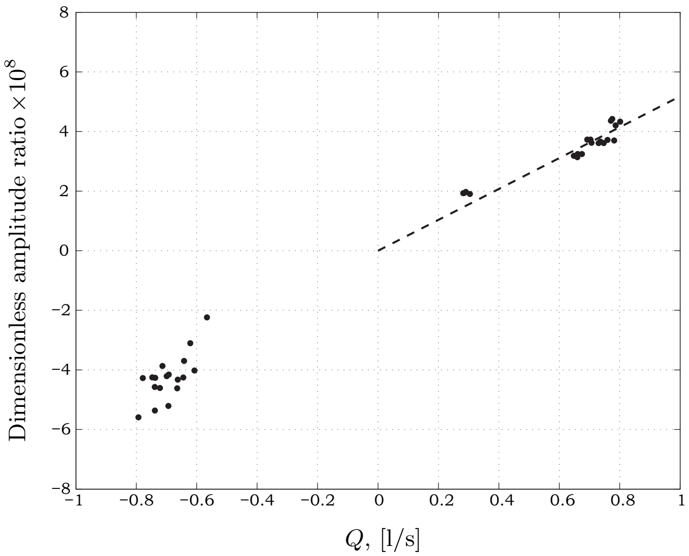

Fig. 6. Induction flowmeter calibration results.

temperature difference of 1–2°C appears on the external faces of the measuring coils. This gradient induces different thermal deformations of the measuring coil turns, giving rise to variations of the magnetic fluxes in these coils. Due to this, the sensitivity of the coils also changes. These factors provoke the occurrence of a parasitic component in the calculation of $V_{\rm ind}$. In the case of a steady-state flow in the loop, the axial temperature gradient diminishes, and the flowmeter data can be regarded as reliable.

Right after the sodium transfer, upon closure of the valves of the tanks, the strong temperature difference disappears in the flowmeter channel (everything has been smoothed by the flow, and a new thermal gradient has had no time to arise). Over such 5 sec intervals the balancing of the conduction flowmeters was undertaken. The ratio of the voltage amplitudes K in the measuring coils was defined for each flowmeter. For both flowmeters, these ratios changed insignificantly, and therefore, we could estimate the flow rates of the induction flowmeters as

$$Q_{\rm ind} = \frac{A_1/K - A_2}{A_1/K + A_2}.$$

Hence, there occurs an asymmetry of the conversion coefficient. With the positive flow rate, the sodium flow first runs through the zone of intensive magnetic field of the conduction system magnets, and so the flow profile changes. Owing to the skin-layer effect, the sensitivity of the induction flowmeters, with large channel radii, is higher than at the channel center, and this increases the signal $Q_{\rm ind}$ when $Q > 0$, cf. $Q < 0$. The LSFMS devices were used to measure only positive flowrates under the real operating conditions in the sodium loop.

3.3. Cross-correlation flowmeters. Under the assumption of significant temperature pulsations and steady-state flow, the cross-correlation velocity measurement method is an absolute method. In order to calculate the coefficient for the average flow rate determination over the entire cross-section of the channel, it is necessary to determine the velocity profile or to calibrate the device. Measurement errors are strongly influenced by the temperature pulsations. Using the test measurements data, we have plotted a curve illustrating the dependence of the

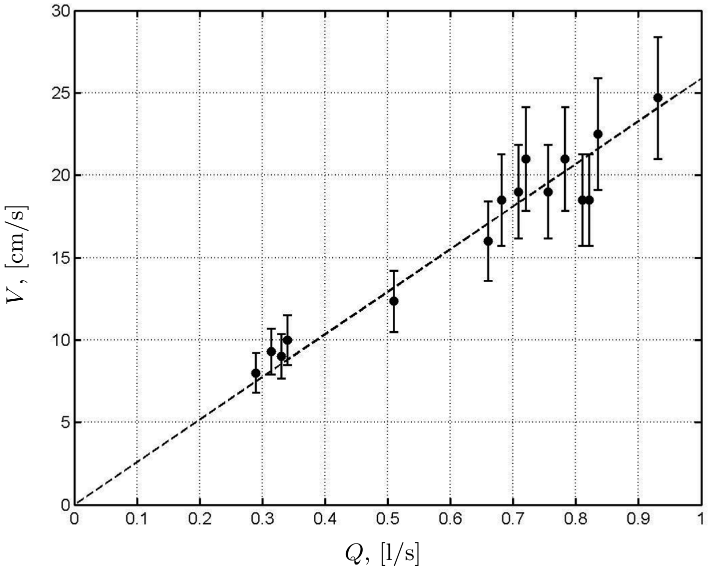

Fig. 7. Cross-correlation flowmeter calibration results.

local velocity V calculated from the time shift between the temperature pulsations on the flow rate Q (Fig. 7). The mean velocity was measured only in the central part of the channel cross-section S (the thermocouples were located on the axis). The proportionality factor defined as $K = Q/(VS)$ was equal to $K = 0.93$.

4. Conclusions. The combined liquid sodium flow measurement system comprising three independent flowmeters has been designed. Each method has its own limitations. The induction flow measurement method requires additional temperature stabilization of the measuring coils and, possibly, supplementary temperature measurements to correct the measured signal. Implementation of the thermocouple cross-correlation flow measurement method necessitates the use of elements capable of introducing additional thermal inhomogeneities into the flow. Furthermore, in some operating regimes of the facility, there occurs a flow with a uniform temperature, the velocity of which is difficult to measure using the cross-correlation method.

Two specimen systems were assembled and checked for proper operation. Series of calibration experiments were performed for both devices. All measurement procedures gave reasonable information about the common flow rate that has confirmed the correctness of the approach and the possibility of using the devices for flow measurements in the ICMM liquid sodium loop. However, the conduction method seems to supply the most reliable data because the system consisting of a few contact pairs enables one to take into account the flow asymmetry.

Acknowledgements. This study was supported by the Russian Foundation for Basic Research under project No. 14-08-96014.

References

[1] I. Kolesnichenko, R. Khalilov, A. Shestakov, P. Frick. ICMM two-loop sodium facility. *Magnetohydrodynamics*, vol. 53, (2016), in this issue.

[2] R. Khalilov, I. Kolesnichenko.. Annular linear induction pump for liquid sodium. *Magnetohydrodynamics*, vol. 51, (2015), no. 1, pp. 95–103.

[3] S. Eckert, A. Cramer, G. Gerbeth. Velocity measurement techniques for liquid metal flows. *Magnetohydrodynamics – Historical Evolution and Trends.* (Eds. S. Molokov, R. Moreau, H.K. Moffatt, Springer-Verlag, Berlin, Heidelberg, New York, 2007), 275 p.

[4] V.P. Kornilov, V.V. Ovsyannikov and L.L. Snezhko. Measuring the rate of flow in an electrically conducting fluid in the electromagnetic flowmeter converter. *Magnetohydrodynamics*, vol. 25, (1989), no. 3, pp. 361–366.

[5] L.P. Poberezhsky. Measuring of velocity and electrical conductivity of ionized gas flows. *Journal of Technical Physics*, (1963), no. 11-12, pp. 1464–1469.

[6] V. Molevalli, C.H. Marks, B.J. McCaffrey. Cross-Correlation Velocimetry for Measurement of Velocity and Temperature Profiles in Low-Speed, Turbulent, Nonisothermal Flows. *Journal of Heat Transfer*, vol. 114/337, 1992.

[7] A. Mamykin, P. Frick, R. Khalilov, I. Kolesnichenko, V. Pakholkov, S. Rogozhkin, A. Vasiliev. Turbulent convective heat transfer in an inclined tube with liquid sodium. *Magnetohydrodynamics*, vol. 51, (2015), no. 2, pp. 329–336.

Received 01.02.2016