

Eddy current flowmeter for sodium flow

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Abstract. The eddy current flowmeter for liquid metal passing through the cylindrical channel is studied experimentally and numerically. The alternating magnetic field is created by an annular-shape coil and resulting field is measured by two symmetric coils. The dependence of the signal on the magnetic field frequency was obtained for a solid duralumin cylinder. The phase shift and amplitude ratio linearly depends on the flowrate in a wide range of parameters. The workability of the method was tested on a liquid sodium, flowing along a cylindrical channel. The dependencies for liquid sodium and solid duralumin cylinder differ due to the existence of a non-uniform velocity profile along the radius of the fluid. This necessitates an additional calibration procedure on the liquid metal in addition to research on the solid conductor. The developed flowmeter is used to measure the flowrate in the sodium loop.

1. Introduction

There are a large number of liquid metal velocity sensors designs [1]. Each of them has its own advantages and disadvantages. Potential probes [2, 3] and flowmeters [1] are widespread. Their advantage is the simplicity of implementation and the wide possibilities of the velocity pulsations characteristics measurement. Disadvantages are the need for a good electrical contact with liquid metal and the vulnerability of permanent magnets to high temperatures. There are techniques based on the measurement of cross correlations between the signals of thermocouples installed along the flow [4, 5]. The advantage of the method is a direct measurement of velocity without the need of a calibration. The disadvantages are the need to immerse the thermocouples into the flow, as well as the reliable applicability of this technique only for the flows with a sustainable direction. It is also possible to note modern methods based on measuring the Lorentz force [6] and the induced motion [7], which are in the stage of research and experimental application.

At the same time, there are induction velocity measuring methods based on eddy currents generation [8]. They were actively studied and used for many years (e.g. [1, 9–13]). Some devices are immersed into the flow and represent a streamlined capsule combining both the generating and measuring part [14]. There are also more compact designs, which are actually the local velocity sensors [15]. They use a permanent magnet to generate the initial magnetic field and Hall sensors to measure its perturbations. With all the advantages of these designs, their main drawback is their vulnerability to high temperatures due to the complexity of the cooling systems. Therefore, they are used at relatively low temperatures.

The flowmeters with external placement of generating and measuring parts received the main development. The main advantage of such systems is the possibility of implementing the measuring coils thermostabilization system and the cooling of the entire system. This allows



them to be used even at high temperatures. Additionally, such flowmeters provide the ability to implement the liquid metal electrical conductivity measurement [9], or the registration of a gas phase in the liquid metal [16]. In most designs, the coils are put on a cylindrical pipe, although there are designs in which they are located on the side of the pipe [17]. Also, there are designs that use a single measuring coil, and an alternating magnetic field is generated by a traveling magnetic field pump [18]. More often, it is necessary to implement a more universal scheme, which can be used independently of other parts of a main experimental setup. Such a scheme was actively investigated theoretically (e.g. [11, 19–21]) and experimentally (e.g. [22–24]).

One of the main advantages of this scheme, in our opinion, is the ability to process the acquired signal so as to exclude the influence of temperature on the measurements. Electrical conductivity of the liquid metal, which significantly determines the characteristics of the process, depends on the temperature. In most measurement schemes, it is necessary to calibrate the device not only at different velocities or flowrates, but also at different temperatures of the liquid metal. In this scheme, when measuring signals S_1 and S_2 from two symmetrical coils can be recorded simultaneously, the following manipulations can be performed. The value $A_1 = S_1 - S_2$ represents the component of voltage due to motion induced voltage and the value $A_2 = S_1 + S_2$ represents the component of voltage due to transformer action. Thus, their ratio $A = A_1/A_2$ is independent on the electrical conductivity of the medium [13, 25]. This essentially lightens the calibration process of the device and improves the accuracy of the results. The usage of this method was simplified relatively recently with the active introduction of computers into the experiment. Computers provide real-time calculations and output of measuring flowrate value allowing to control the process. Nevertheless the possibility of eliminating the electrical conductivity dependence was known for a relatively long time (e.g. [9]). But in the absence of computers, this technique was implemented using complex electronic circuits. Thus, for example, two pairs of measuring coils and compensation circuit were used in [9]. In addition to using the described technique, it is possible to determine the flowrate by a conventional method by means of a phase shift (e.g. [12]).

These studies show the possibility of successful implementation of the methodology in practice. However, the operation of this method is essentially determined by geometric factors, the frequency of the alternating magnetic field, and the characteristics of the medium. The set of these characteristics is unique for each implementation, that reduces the universality of the previously obtained results. This was the motivation to study the method of flowrate measurement applicable for our sodium loop [26]. We chose a scheme with a generating coil and two symmetrical measurement coils of the annular shape located on a cylindrical channel (figure 1(a)). The aim of the work was to find out the dependence of the the measuring module sensitivity on the supply current frequency and to check its operation on the liquid sodium flow. The existence of the skin effect should, on the one hand, dictate the choice of the lowest available frequency as the best. On the other hand, it limits the range of measured flowrates [21]. Therefore, the main effort in our work is directed to experimental study of the process and to test method's sensitivity.

2. Methods

The main element of the experimental setup is a measuring module that registers the interaction between the moving electrically conductive medium and a magnetic field (figure 1). The module contains a generating coil 1 and two measuring coils 2 (figure 1(a)). The generating coil has an average diameter of $D_s = 100\text{mm}$, a thickness of $H_s = 20\text{mm}$ and a width of $L_s = 20\text{mm}$. The coil has $N_s = 260$ turns of a copper wire having diameter of $d_s = 1\text{mm}$ and insulation. The generating coil is connected to the low-frequency generator "G3-109" which provides high voltage stability for a wide range of frequencies. The coil was fed by harmonic signal of varied frequency f_s and a fixed voltage $U_s = 1.6\text{V}$ and current $I_s = 0.39\text{A}$ during the

experiments. The measuring coils have an average diameter of $D_m = 112\text{mm}$, a thickness of $H_m = 20\text{mm}$ and a width of $L_m = 10\text{mm}$ and were located symmetrically with respect to the center of the generating coil. The number of turns of measuring coils is $N_m = 500$. Copper wire of $d_m = 0.4\text{mm}$ in diameter was used for both measuring coils. The distance $L_b = 20\text{mm}$ between the center of the generating coil and centers of the measuring coils was chosen based on the results of the calculations. The generating and measuring coils were placed on a heat-resistant fiberglass frame.

EMF generated in two measuring coils S_1 and S_2 were recorded using the National Instruments NI 9239 data acquisition board. Signal analysis gave, firstly, the phase shift P , which was determined using a fast Fourier transform. Secondly, ratios between the amplitudes of the signals $A_1 = S_1 - S_2$, $A_2 = S_1 + S_2$ and $A = A_1/A_2$ were calculated.

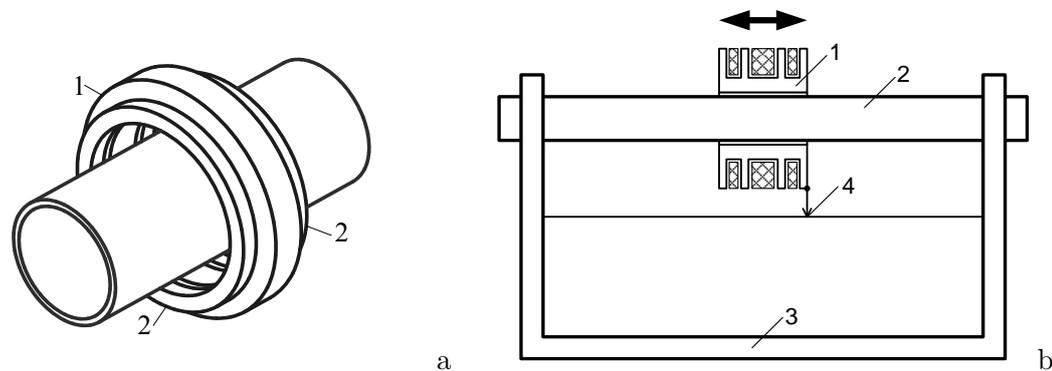


Figure 1. (a) – Sketch of the module assembly, (b) – motion of the measuring module relative to solid duralumin cylinder (not to scale).

In the first series of experiments the solid cylindrical volume of duralumin 2 (figure 1(b)) was used as an electrically conductive medium. The metal has the electrical conductivity $\sigma_d = 11.6 \cdot 10^6 \text{Sm/m}$ at temperature $T_d = 25^\circ\text{C}$. The temperature T_d was varied during this series of experiments. The diameter of the cylindrical volume is $D_d = 70\text{mm}$ and the distance at which measurements were taken is $L_d = 890\text{mm}$. The cylindrical volume was placed on the frame 3. The measuring unit 1 was placed on a cylindrical volume 2 and could be moved freely along the cylinder axis. The sliding contact 4 was used to get reference values of the relative movement. It consisted of a nichrome wire stretched parallel to the cylinder and a copper contact mounted on the measuring module. The ends of the nichrome wire were connected to a DC voltage source. When the measuring module was moved along the cylinder, the voltage between one of the ends of the nichrome wire and the contact varied proportionally to the distance. Analysis of the voltage signal gave the value of the movement velocity of the conductive cylinder V_d relative to the measuring module. In the first series of experiments, the dependencies of the signals $A_d(Q)$ and $P_d(Q)$ on the flowrate of the moving medium $Q = V_d \pi (D_d/2)^2$ were determined for different temperatures T_d of the medium. The frequency f_s varied from 20 to 500 Hz. In this case, the value of the skin layer $\delta_d = \sqrt{1/\pi\mu_0 f_s \sigma_d}$ ranged from 33 mm to 6.6 mm at $T_d = 25^\circ\text{C}$.

In the second series of experiments a liquid sodium passing through the cylindrical pipe 2 (figure 2) was used as an electrically conductive medium. The experiments were carried out at a fixed temperature $T_n = 150^\circ\text{C}$ and a fixed frequency $f_s = 50\text{Hz}$. The liquid sodium has the electrical conductivity $\sigma_n = 8.86 \cdot 10^6 \text{Sm/m}$ at this temperature. In this case the value of the skin layer has a fixed value equal to $\delta_n = \sqrt{1/\pi\mu_0 f_s \sigma_n} = 24\text{mm}$. The pipe 2 with an internal diameter of a $D_n = 68\text{mm}$ was made of stainless steel, the thickness of its wall is $d_w = 4\text{mm}$, the electrical conductivity is $\sigma_{ss} = 1.38 \cdot 10^6 \text{Sm/m}$ at a temperature T_n . Measuring module 1 has been mounted and fixed on the pipe 2. The pipe was built into the system 3, consisting of two

tanks. A pumping of liquid sodium between these tanks was carried out by a pressure difference using argon. Contact probes 4 mounted in the tanks recorded liquid sodium volume levels. It was possible to determine the flowrate of liquid sodium Q through the pipe by analyzing the signals from these probes. The experiment is described in more detail in [27]. In the second series of experiments, the dependence of the signals $A_n(Q)$ on the flowrate of the moving medium Q was determined.

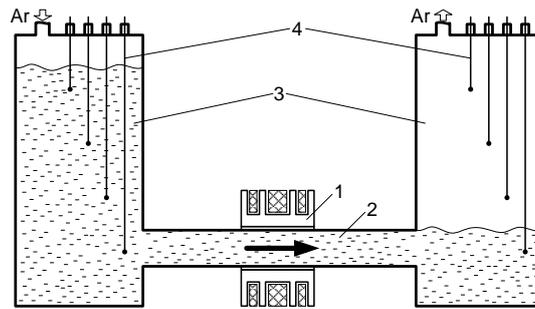


Figure 2. Measuring module installed on a pipe connecting two tanks, filled with a liquid sodium: scheme of a calibration experiment (not to scale).

Preliminary numerical simulations of the magnetic field created by the generating coil 1 of the measuring module (figure 1(a)) were carried out. The measuring coils 2 are connected to high-impedance inputs of DAQ system, so they do not disturb the resulting magnetic field and are excluded from the simulation. The simulations are based on solving the Maxwell equations system where generating coil is a magnetic field source which is being disturbed by a liquid metal flow. The pipe and surrounding area are taken into account. The simulations are carried out for the stationary isothermal case.

3. Results and discussion

Calculations showed that the magnetic field generated by an annular-shape coil is highly inhomogeneous in the region of the electrically conductive medium. Increasing the frequency of the magnetic field f_s does not change the profile, but it significantly changes the maximum value of the axial distribution (figure 3(a)). This result indicates that increasing the frequency reduces the overall sensitivity of the technique. Also, the axial dependence helps to choose a distance L_b between measuring coils and the center of the generating coil. As mentioned earlier, it is not possible to place measuring coils close to the generating coil, because it is necessary to ensure the presence of a structural gap for installation and thermostabilization. A large distance from the generating coil will reduce the sensitivity of the method. The strongest magnetic field gradient is located on the first third of the dependence. It is best to place the measuring coils in this area. Also increasing the magnetic field frequency f_s significantly reduces the maximum value in the radial distribution (figure 3(b)) due to the skin effect. Thus, at higher frequencies the near-wall flow will give the greatest contribution to the resulting signal, which may distort the result. However, up to 50Hz this effect appears to be insignificant.

Increasing the electrical conductivity of the wall σ_w relative to the electrical conductivity of the liquid metal σ_n , the maximum value of the magnetic field also decreases, due to the skin effect (figure 4). Consequently, the use of a poorly conductive liquid metal (like lead) and a good conductive material for the wall (like copper) will significantly weaken the signal level. This is one of the reasons for choosing sodium as an electrically conductive medium and stainless steel for the wall. The electrical conductivity of sodium is about six times higher than the electrical

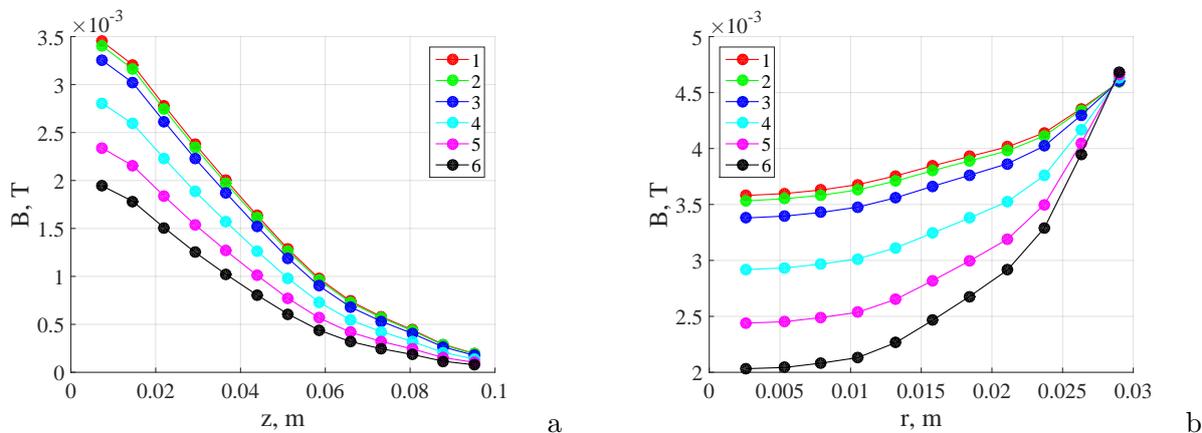


Figure 3. Magnetic field component B_z , calculated for different current frequencies f_s (a) – as a function of distance along z -axis, (b) – as a function of distance along radial direction r . Curves No. 1,2..6 are obtained at $f_s = 10Hz, 25Hz, 50Hz, 100Hz, 150Hz, 200Hz$ correspondingly.

conductivity of stainless steel, so in our case there is an insignificant weakening of the useful signal.

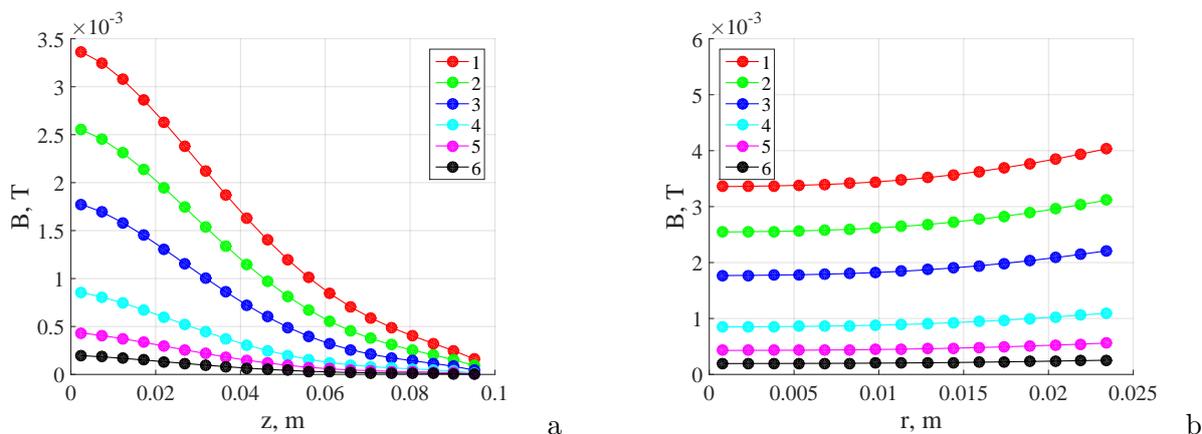


Figure 4. Magnetic field component B_z profiles calculated for different conductivity relations $k = \sigma_n/\sigma_w$ (a) – along z -axis, (b) – along radial direction r . Curves No. 1,2..6 are obtained at $k = 1, 1/5, 1/10, 1/25, 1/50, 1/100$ correspondingly.

The experiment on a solid conductor in the isothermal case showed that both the phase shift P (figure 5(a)) and the amplitude ratio A (figure 5(b)) give a linear dependence on the flowrate Q for different frequencies of the magnetic field f_s . The linear dependencies make it possible to calculate the slope coefficients k_P and k_A for these signals. Increasing the frequency leads to a weakening of the signal level. The part of electrically conductive medium that contributes to the measured signal decreases as the frequency increases due to the skin effect. This also forces to use small frequencies f_s for high conducting media.

Dependencies of the slope coefficients k_P and k_A on the frequency f_s show that these quantities behave differently (figure 6(a)). An increase to the maximum value is observed followed by a decrease for the phase shift. A decrease is observed for the amplitude ratio in the entire frequency range (figure 6(a)).

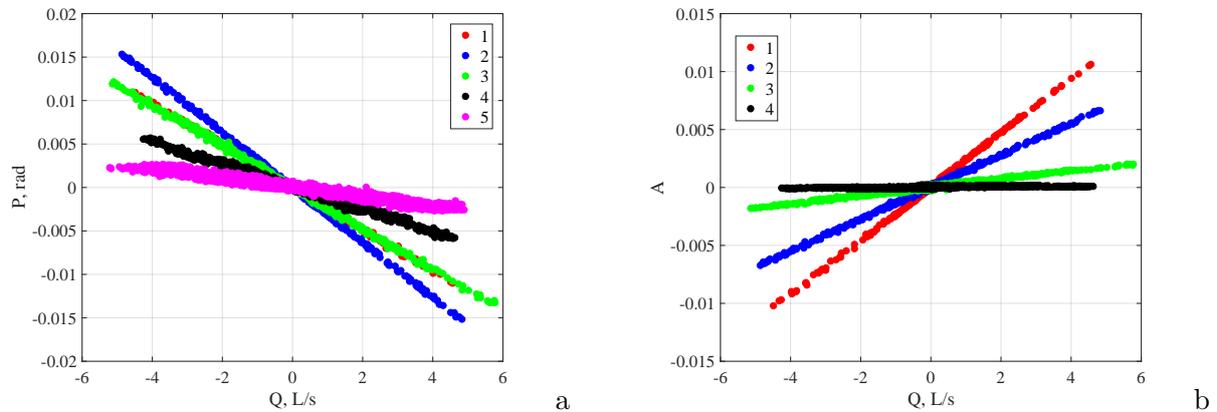


Figure 5. Phase shift P (a) and amplitudes relation A (b) measured at different generating coil current frequencies *vs.* flowrate Q . Curves No. 1,2..5 are obtained at $f_s = 20Hz, 40Hz, 80Hz, 150Hz, 300Hz$ correspondingly.

Experiments carried out on a liquid electrically conductive medium have also shown a linear dependence of amplitude ratio A on a flowrate Q (figure 6(b)). The dependencies for liquid sodium and solid duralumin cylinder differ. This is due to the existence of a non-uniform velocity profile along the radius of the fluid that flows along the cylindrical channel. In a solid conductor, such a profile is uniform that causes the difference. Perhaps at very high flowrates when the profile is strongly turbulized and tends to be uniform, the difference will become small.

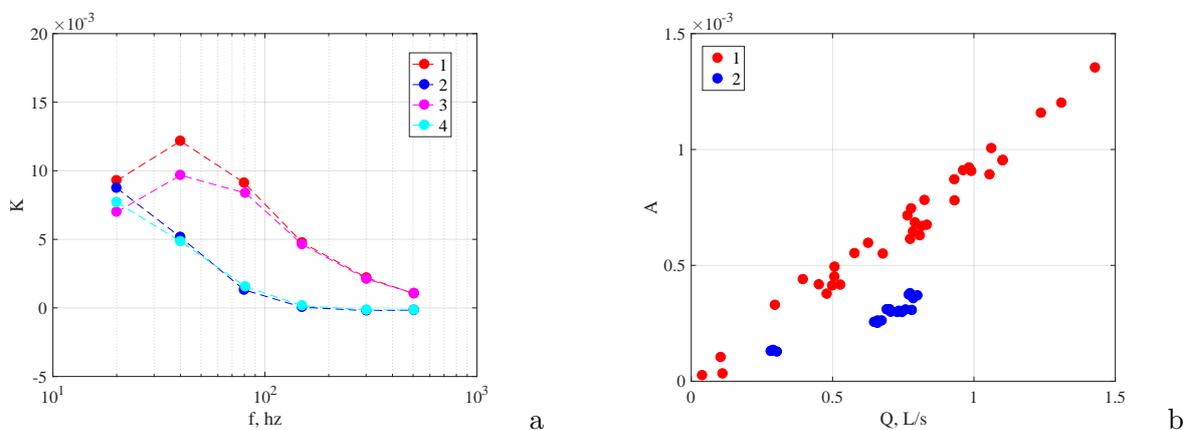


Figure 6. (a) – Slope coefficients k_P (1,3) and k_A (2,4) as a function of generating coil current frequency f_s at two different temperatures: $T = 23^\circ C$ (1,2) and $T = 93^\circ C$ (3,4), (b) – amplitudes relation A measured during experiments on the solid duralumin cylinder (1) and on the liquid sodium flow (2).

4. Conclusions

We consider an implementation of eddy current flow measurement technique for different feeding current frequencies. This technique for measuring the motion of an electrically conductive medium has a number of features. Annular-shape generating coil creates a magnetic field that decrease quite fast along the axis. This limits the distance at which the measuring coils can

be placed without losing module's sensitivity. They should be placed so close to the generating coil, as far as the design and the requirement for their thermal stabilization permit.

Experiments on a solid conductor made it possible to reveal a number of features of the technique that were difficult to obtain on a liquid metal because of limitations of the facility and large time costs when working with liquid sodium. The phase shift and amplitude ratio linearly depend on the flowrate in a wide range of parameters. The presence of a maximum in the slope-to-frequency dependence for the phase shift indicates the possibility of selecting such a frequency of the current of the generating coil, which will ensure the best sensitivity of the method. However, this parameter will depend essentially on the electrical conductivity of the medium. Therefore, its value should be determined during experiments on the medium for which the methodology is intended to be applied. The dependence of the slope coefficient on the frequency for the amplitude ratio did not reveal the presence of an extremum. Consequently, the greatest sensitivity of the technique should be expected at the lowest possible frequency. These data were obtained for a solid conductor of the aluminum alloy, which has a high electrical conductivity. Conductivity is lower for liquid conductors and therefore, such a maximum is likely to be absent for the available frequency range.

The chosen parameters allowed one to determine the flowrate of the conductive medium with sufficient accuracy. The signal level is well above the noise level. Using the results of experiments on liquid sodium we obtained the dependencies of the amplitude ratio on the flowrate which are close to linear. Since the difference between the results for solid and liquid conductors, which is due to the presence of a velocity profile for a liquid metal, it is necessary to perform additional calibration procedure on liquid metal in addition to studies on solid conductor. The amplitude ratio is preferable to the phase shift because of the lack of temperature dependence. So, the technique described in this study can provide reliable measurements of liquid metal flowrate.

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