Electromagnetic flowmeter for wide-temperature range intensive liquid metal flows

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Abstract.

The electromagnetic velocity sensor of Ricou and Vives with permanent magnet is well known. The probe is difficult to use at industrial conditions like metallurgy or nuclear power plants close to the Curie temperature. This article describes a reliable technique to provide controlled magnetic field distribution at the measurement area, generated by induction coils and concentrated by magnetic cores. The effect of magnetic field displacement, as well as weight and size of the assembled device, were minimized using numerical calculation of the field distribution for the case of a conducting media of different conductivity moving with different velocities. Calibration experiments showed high accuracy of measurements with low sensitivity to external electromagnetic noise.

1. Introduction

There are a large number of liquid metal velocity sensors designs. Each of them has its own advantages and disadvantages. Potential probes [1, 2] and flowmeters [3] are widespread. Their advantages are 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. Electromagnetic flowmeters of sodium loop ICMM UB RAS are made using NdFeB permanent magnets with magnetic cores which create strong localized magnetic field of about 0.3 T. Electromagnets must be used for higher temperatures [4]. There are techniques based on the measurement of cross-correlations between the signals of thermocouples placed along the flow [5, 6]. The disadvantage is the need to immerse the thermocouples into the flow. It is also possible to note modern methods based on measuring the Lorentz force [7] and the induced motion [8], which are in the stage of research and experimental application.

The flow of an electrically conductive medium in area with the applied magnetic field leads to the generation of an electromotive force (EMF) on the channel walls, which is proportional, in the first approximation, to the average flow velocity [9]. The potential difference ∆φ induced between the two electrodes, which are spaced by ∆l, is governed by Ohms law:

\[ \vec{j} = \sigma (\vec{E} + \vec{u} \times \vec{B}_m) \approx \sigma (-\frac{\Delta \phi}{\Delta l} \vec{c}_p + \vec{u} \times \vec{B}_m), \]

where \( \vec{j} \) is the electric current density, \( \vec{u} \) the fluid velocity, \( \vec{c}_p \) the unit vector between the tips of the wires, and \( \vec{B}_m \) the applied magnetic field. Under the assumption of absence of induced...
and external electric currents for orthogonally oriented $\vec{B}_m$, $\vec{e}_p$ and $\vec{u}$, the equation 1 reduces to the simple linear relation $u = \Delta \phi / (B_m \Delta l)$.

Construction of flowmeters based on this principle requires consideration of a number of complicating factors. Firstly, in the case of large magnetic fields, on the one hand, the sensitivity of the sensor increases, and on the other hand, the Hartmann number $Ha = \frac{\sigma L^2 B^2}{\mu \nu}$ increases: the flow profile changes significantly and the braking effect appears. Secondly, in the case of high conductivity of a liquid medium and high speeds, the magnetic Reynolds number $Re_m = \mu \mu_0 \sigma L V$ increases: magnetic field displacement from the measuring volume appears and, therefore, the nonlinearity of the characteristic comes out. Thirdly, the displacement effect is dependent on the electrical conductivity which varies with temperature. Also, if the channel of the flowmeter is made of an electrically conductive material, then the EMF induced in the fluid is shunted by a wall through which the electrical currents are closed. The shunting factor is expressed in terms of the wall $\sigma_w$ and liquid $\sigma_l$ conductivities ratio and the ratio of the external $D_{out}$ and internal $D_{in}$ diameters as follows:

$$K_{sh} = \frac{E_{wall}}{E_{free}} = \frac{2D_{in}/D_{out}}{1 + D_{in}^2/D_{out}^2 + \frac{\sigma_w}{\sigma_l}(1 - D_{in}^2/D_{out}^2)}$$

2. Methods

2.1. Flowmeter design

In order to provide safe temperature conditions for electronic circuits the flowmeter was separated on two units connected by signal and power cables.

The flowmeter’s head unit with a channel of nominal diameter $DN = 89 \text{ mm}$ is shown on Fig.1(a). The head unit consists of a channel 1 made of stainless-steel AISI 321 and inductor, creating a magnetic field in the channel. The inductor consists of a magnetic core 2 and induction coils 3 connected electrically in series. All elements are rigidly fixed on the frame. To prevent overheating of the induction coils, the magnetic core is enclosed in a heat insulator. The temperature is controlled by a set of thermocouples in several regions: the temperature of the liquid metal in the measurement volume, the temperature of the magnetic core, the temperature of the induction coils, and the surface temperature of the heat insulating casing.

In the required range of temperatures and ratios of the electrical conductivities the shunting coefficient (see eq.2) of this channel is of the order of $K_{sh} \approx 6 \div 9\%$ and its temperature change is automatically taken into account by the algorithm given below.

Figure 1. Sketch of the flowmeter’s head unit (on the left) and block diagram of internal connections (on the right).

The electronic unit (Fig.1(b)) provides the following functions:

- inductor stabilized DC power supply,
- amplification of thermocouples and EMF signals,
- measured signals to the flow rate conversion and the thermal regime of the head unit monitoring to prevent its overheating,
- signals coding and transmitting to the upper level control system over the communication line.

The flowmeter has:
- analog DC current 4..20 mA output interface, proportional to the value of measured flowrate in range 0 ÷ 100% for the load resistance $R_{cl} \leq 500 \, \Omega$;
- digital interface RS-485 which allows to acquire the measured and transformed values by a Modbus-RT protocol;
- digital indication of the measured flow rate on the display.

2.2. Magnetic field displacement problem solving

The method of taking into account the nonlinearity of the flowmeter characteristics due to the magnetic field displacement dependence on the conductivity (temperature) of the medium [10] implies a complication of both the calibration procedure and the measurement technique itself.

**Calibration technique.** In the process of calibration the volumes of liquid metal are pumped through the flowmeter with various combinations of average flow rate and temperature. Each combination gives values of $E_i[V]$ (measured EMF value), $T_i[°C]$ (temperature around the measuring volume) and $Q_i[m^3/h]$ (reference value of the average flow rate during the operation, obtained by the tanks level sensors signals analysis). Subsequent regression analysis of $E_i, T_i, Q_i$ arrays gives the values of the $A, C, \beta$ calibration coefficients (procedure is shown below). The values of $\rho_0, \rho_1, \rho_2$ coefficients are taken from the liquid metal electrical resistance temperature dependence approximation $\rho(T) = \rho_0 + \rho_1 \cdot T + \rho_2 \cdot T^2$ from reference books. $T_0$ - minimal operating temperature.

- The initial value of $\beta \approx -8 \cdot 10^{-5}$ is set.
- $B_i = 1 + \beta(T_i - T_0)$ is calculated.
- The transition to the new variables: $X_i = Q_i/\rho(T_i)$, $Y_i = \frac{E_i}{Q_i \cdot B_i}$
- The least squares method gives a linear approximation $Y_i = A - C \cdot X_i$ ($A, C$ coefficients and standard deviation $\epsilon$)
- Actions are repeated with a different $\beta$ values to minimize the $\epsilon$.

The final values of $A, C, \beta$ together with used values of $\rho_0, \rho_1, \rho_2, T_0$ are fixed in the flowmeter read-only memory, calibration procedure is over.

**Measurement technique.** During normal operation of a calibrated device, the nonlinearity is taken into account as follows:

- The instantaneous values of $E$ (average compensated EMF with the turned off magnetic field EMF subtracted) and $T$ (average temperature) are transferred in digital form from the ADC output to the PLC input.
- For the instant temperature the values of $\rho(T)$ (instant electrical resistance) and $B(T) = 1 + \beta(T - T_0)$ (nonlinear correction) are calculated.
- Auxiliary coefficients $Q_0 = \frac{A \rho}{2C}$ and $E_0 = \frac{A B}{2} \cdot Q_0$ are calculated.
- The resulting value of the instantaneous flowrate is $Q = Q_0 \cdot (1 - \sqrt{1 - \frac{E}{E_0}})$. 


2.3. Calibration facility

The flowmeter calibration is carried out by volumetric-time method on ICMM UB RAS sodium facility (see Fig. 2(b)). Liquid metal flow through the channel of the flowmeter is provided by pressure-difference between two tanks (300 l each). One of the tanks is filled with sodium and overpressured by argon (0.02 ÷ 0.10 MPa). The other one is empty and vacuumed. Each tank has a system of contact level gauges, whose signals are recorded by a high-speed data acquisition system and used to determine the reference flowrate value. The flowmeter polling is provided synchronously. Both tanks are placed in a thermocase with electric heaters supplied by thermal control devices. This allows to maintain the sodium temperature in the required range throughout the calibration procedure.

3. Results

Calculations of magnetic field distribution into the measurement volume were done for different configurations of magnetic cores and different combinations of liquid media conductivity and flowrate. Electrodynamics was simulated by ANSYS Emag software. Magnetic cores and coils of different size and geometry were considered to produce a strong localized magnetic field in the orthogonal cross-section of a stainless-steel pipe filled with moving or resting volume of conducting media (see Fig. 2(a)). The magnetic field profiles along the pipe’s diameter for stationary and moving cases are shown on Fig. 3. Minimum value corresponds to the center of the pipe. In the case of moving media it’s absolute value decreases while it’s position moves towards the direction of flow. Increasing the size of the core in direction of the flow suppresses the displacement effect, but on the other hand it dramatically increases the core weight.

It is clearer to analyze dependency of magnetic field in the center of the channel on mean velocity. The obtained quadratic-like dependency is shown on Fig. 4(a). These points were calculated for the final configuration of the core and show less than 10% decrease in magnetic field that can be resolved by the proposed calibration and measurement techniques. The assembled inductor was tested experimentally and shown magnetic field distribution coincident with numerically obtained results for stationary case.

Calibration experiments were performed on ICMM UB RAS sodium facility at different reference values of flowrate and temperatures. An example of calibration data points is shown on Fig. 4(b). The value of registered EMF-signals is large enough and is consistent with analytical
Figure 3. Magnetic field profiles obtained for stationary case (on the left) and for liquid sodium flow of mean velocity $V = 1 \text{ m/s}$ and temperature $T = 170^\circ\text{C}$.

Figure 4. Relative magnetic field displacement at the center of the measurement volume obtained by numerical simulation of electrodynamic statement of the problem: sodium, $T = 170^\circ\text{C}$ (on the left), calibration data points experimentally obtained at $T = 200^\circ\text{C}$: points of different colors correspond to different series, the solid black line is a linear fit (on the right).

and numerical estimates. At the beginning and at the end of each pumping operation there is a non-stationary flow regime. The corresponding intervals can be automatically excluded by error filtering during experimental data processing. Due to integrated industrial frequency noise filtration the close spaced apparatuses like actuators and magnetohydrodynamical pump did not have a significant impact on measurements. The obtained characteristic is strongly symmetrical. The standard deviation of the calculated flowmeter’s characteristic from experimental data did not exceed 3%.

4. Conclusions

Electric potential difference probe using globally applied magnetic field has been developed and manufactured to measure mean velocity ($Q \leq 40 \text{ m}^3/\text{h}$) in a high-temperature ($T \leq 450^\circ\text{C}$) flow of liquid metal. Magnetic field displacement numerical calculation allowed to determine the core configuration which provides acceptable magnetic field localization in the measurement volume for the whole required range of temperatures and flow rates. This reduced weight and size of the device essentially. Long-time tests showed the efficiency of the inductor thermal
protection. Calibration experiments confirmed weak magnetic field displacement at ultimate flow rates. This will reduce the weight and size of the inductor in the next modification of the device. Series of tests were carried out, which showed high accuracy of measurements with low sensitivity to external electromagnetic noise. The design of the core allows to install the larger cross-section channels to reduce hydraulic resistance with the aim of measuring higher flowrates (up to \( \approx 200 \text{ m}^3/\text{h} \)). This flowmeter, because it has the property of finding the magnitude and direction of velocity, allows the measurement of mass transfer in the heat exchangers of nuclear reactors using alkaline metals as coolant fluids. It also makes possible the dosage of molten metal during different technological processes in metallurgy.

Acknowledges
This work was supported by the RFBR grant 17-48-590539_r_a.

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