Application of Physical Modeling When Calibrating High Range Electromagnetic Flowmeters

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Abstract. At high flowrates the drift of the magnetic field characterized by the criterion $Re_m = \mu_0 \cdot \sigma \cdot v \cdot D$ can be revealed in the readings of the electromagnetic flowmeters if its magnetic field is insufficiently extensive. The modeling of the high range flowmeters presented involves using a transducer sample which is small in scale as compared to a full-scale flowmeter maintaining similarity of the measuring section and magnetic field distribution. The hydrodynamic and MHD criteria (Re, Re_m), corresponding to full-scale flow conditions can be provided at much lower flowrates. The experiments were carried out at the IRS-M sodium calibration test facility, its main loop and two parallel auxiliary loops supplied by calibrated electromagnetic flowmeters being used. The value Re_m=7,5 has been achieved on the model of the measuring section with the pipe DN150 at a total flowrate G = 360 m^3/h, which corresponds to the parameter of the flowmeter installed in the emergency heat removal system of the BN-800 reactor (G_{max} = 720 m^3/h, DN300). Calibration characteristics have been determined for different electrode pairs, the longitudinal extension of the magnetic field being L_m=0,7DN. An estimate of the nonlinearity introduced by the quadratic term in the dimensionless representation is obtained, $E = K \cdot (1 - \alpha \cdot Re_m) \cdot G$. The coefficient α can be used further to adjust the characteristic of the full-scale flowmeter.

Key Words: MHD, fast reactor, electromagnetic flowmeter, sodium, calibration.

1. Introduction

SSC RF-IPPE has considerable experience in the field of sodium flow measurements. Systems for measuring the flow through main circulating pumps and fuel subassemblies of the BN-800 reactor, which were created in cooperation with "OKBM Afrikantov", are successfully employed at the power plant. These systems combine the electromagnetic and correlation measurement methods [1, 2]. Metrological tests were conducted on the IRS-M calibration facility (SSC RF IPPE).

When high range (G~1000 m^3/h) electromagnetic flowmeters are developed, there arises a serious problem of their graduation. With the increase in the flow rate and diameter of the pipeline, the value of the magnetic Reynolds number can exceed the value 1, and the effect of the magnetic field drift can be observed. The value of this criterion is determined by the ratio

$$Re_m = \mu_0 \cdot \sigma \cdot D \cdot v \qquad (1).$$

If the magnetic field of the flowmeter is not extended enough, the distortion in the magnetic field near the signal electrodes leads to the nonlinearity of the calibration characteristics [3, 4, 5].

Known recommendations for the longitudinal size of the magnetic system (L_{mag} ~ 3D) often mean unacceptable weight and size parameters for DN300-DN800 pipelines. Direct calibration of high range flowmeters requires creation of costly large-scale testing facilities. The aim of this work is to demonstrate the capabilities of physical modeling in relation to the development and calibration of large flowmeters.

2. Representation of nonlinearity

Modeling involves using a smaller flowmeter as compared to a full-scale sample, with the preserved similarity of measuring section and magnetic field distribution for which the relevant hydrodynamic and magnetohydrodynamic criteria (Re, Re_m) are provided at substantially lower flowrates.

The main objective of the modeling is to estimate the nonlinear component of the output signal and to optimize the signal electrodes arrangement, taking into account magnetic field drift.

The nonlinear component can be represented in a simplified form, assuming that the distortion of the primary magnetic field B_o by induced currents is proportional to the induced electromagnetic force. The relationship between the output signal E and the flow rate G can be represented as:

$$E = K \cdot G \cdot (B_o - \beta \cdot E) \qquad (2)$$

where β - “feedback” coefficient describing secondary magnetic field.

Hence:

$$E = \frac{K \cdot B_o \cdot G}{1 + K \cdot \beta \cdot G} \qquad (3)$$

If $K \cdot \beta \cdot G << 1$ (relatively weak nonlinearity), it is possible to use approximation in the form:

$$E = K \cdot B_o \cdot G \cdot (1 - K \cdot \beta \cdot G) \qquad (4)$$

When testing the model sample in the range of flowrate G, calibration characteristics is determined as

$$E = K\cdot (1 - \xi\cdot G)\cdot G \qquad (5)$$

and further presented with the use of the magnetic Reynolds number as

$$E = K\cdot (1 - \alpha\cdot Re_m)\cdot G \qquad (6)$$

where α is the dimensionless coefficient defining the deviation from linearity.

It follows from the condition Re_m = idem for the base flowmeter and the model sample, when electromagnetic medium properties are identical, that the relation for the ratio of volumetric flowrates is given by:

$$G_{mod}/G_{base} = D_{mod}/D_{base} \qquad (7)$$

where D_{mod}, D_{base} – the internal diameters of the measuring sections of the model and base sample, respectively.

The ratio of the wall thickness to the inner diameter when the wall materials are identical is to be kept.

3. Metrology equipment

Experiments on modeling the nonlinear effects were carried out at the IRS-M sodium calibration facility having Pattern Approval Certificate (of Measuring Instruments). The facility has two circuits. The spiral induction EM pump SIP 8/20 and the annular linear induction EM pump ALIP 4/80 are installed in the primary and secondary circuits respectively. Precise regulation of the flow rate in the primary circuit can be performed using the magnetohydrodynamic throttle. To smooth flow fluctuations, a stabilization tank is used.

The main parameters of the facility:

- Working fluid – sodium;
- Total coolant volume – 1,2 m^3 ;
- Working temperature – up to 500 °C (550 °C momentarily);
- Maximum flow rate of the coolant in circuit 1 – 20 m^3/h;
- Maximum flow rate of the coolant in circuit 2 – 150 m^3/h;
- Maximum head pressure – 0,8 MPa (8 kg/cm^2);

Flow rate measurements by the volumetric-time method are carried out by using a certified measuring tank equipped with contact level sensors. The upper limit of the flow rate measured by the volumetric-time method is 30 m^3/h with an accuracy of 0,3%.

To extend the range of the flow measured by means of the facility up to 150 m^3/h, there are five parallel pipelines Ø 48x4 equipped with monitoring electromagnetic transducers BZ1 – BZ5 (see FIG. 1) linked by two headers and connected in series to the second circulation loop. Each of the monitoring transducers is pre-calibrated by the volumetric-time method in the range of up to 30 m^3/h.

FIG. 1. Monitoring electromagnetic flowmeters BZ1-BZ5.

Two additional loops with electromagnetic pumps ALIP 4/125 and lock valves are connected in parallel to the second circuit of IRS-M. Each of them provides flow rates up to 130 m^3/h and is equipped with electromagnetic flowmeters calibrated by the monitoring transducers of IRS-M. The facility IRS-M scheme is presented at FIG. 2.

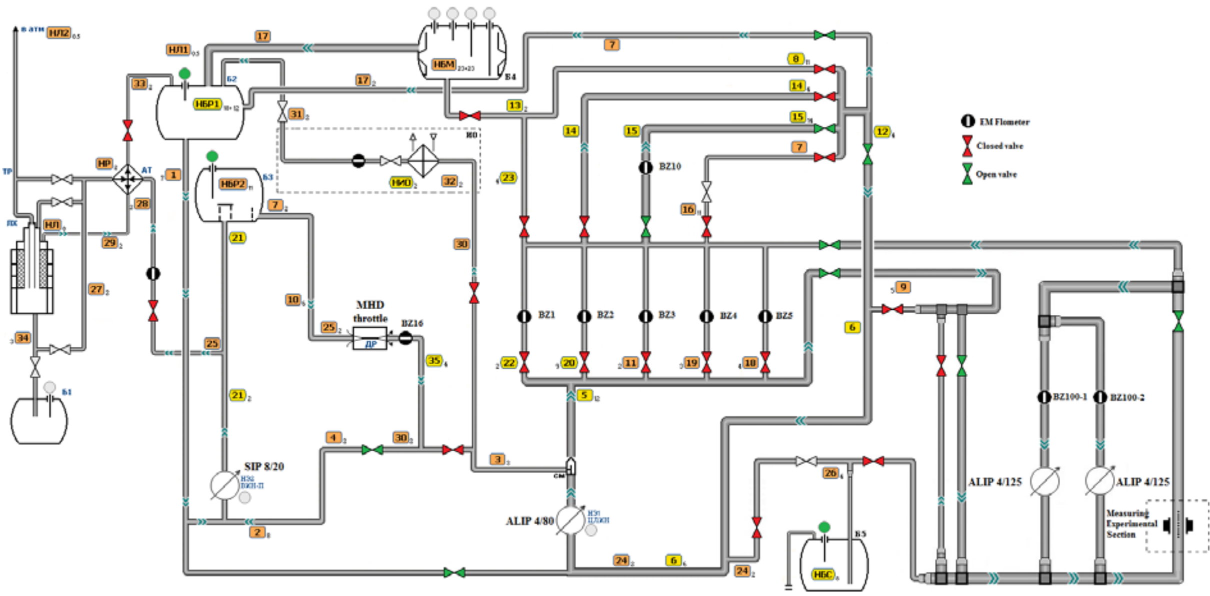

FIG. 2. The facility IRS-M scheme.

4. Flowmeter model and some test results

At this stage, the model is realized in DN150 measuring section, the maximum flow rate supplied through it by the base and two additional loops reaches 370 m3/h. The model includes a permanent magnet system with a pole-face ~ 0,7DN (100 mm) long and 7 pairs of electrodes located at a distance of 25 mm from each other. The first pair of electrodes is located in a section coinciding with the edge of the pole-face (FIG. 3).

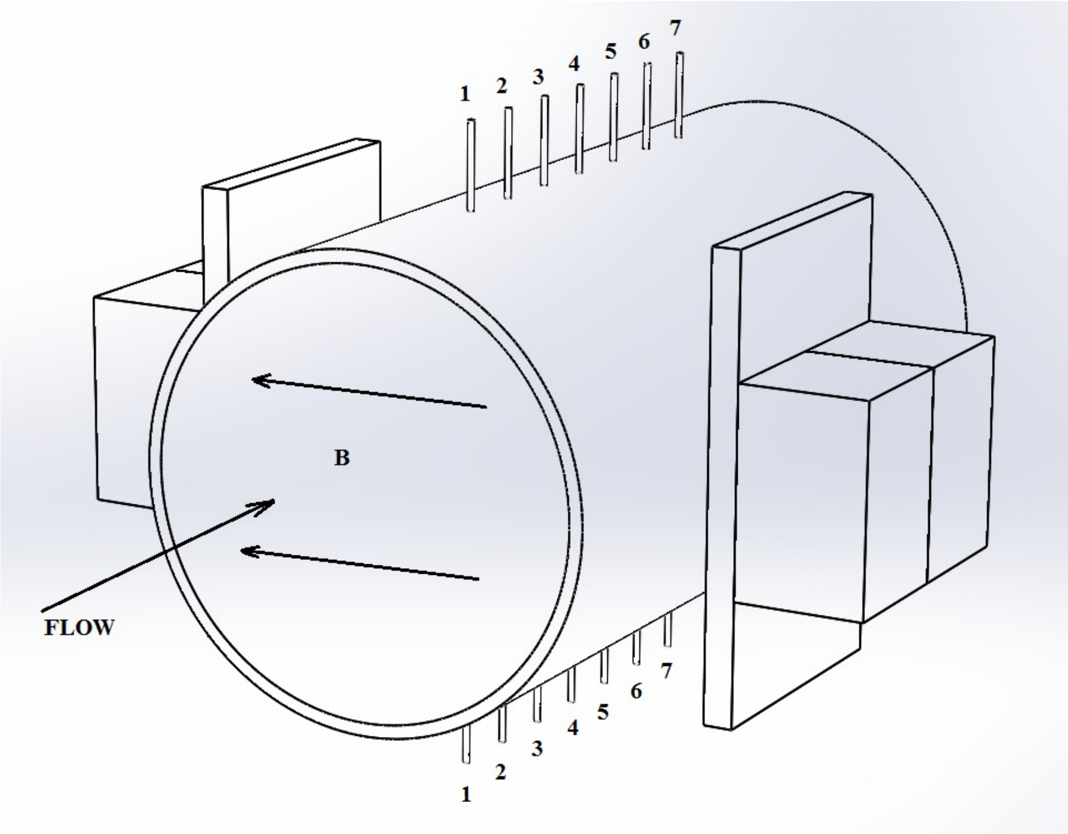

FIG. 3. Flowmeter model.

The distribution of the magnetic field was measured by the PIE.MG R-2M teslameter, the average magnetic induction in the section crossing the center of the magnetic system is equal to 25 mTl ± 10%. Some results are presented at FIG. 4.

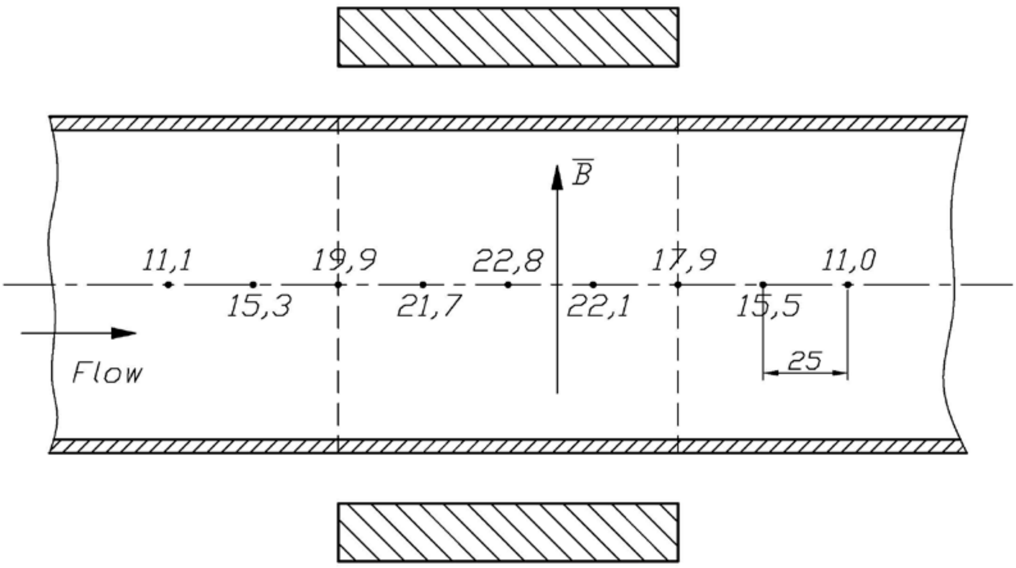

FIG. 4. The axial distribution of magnetic field, mTl.

In the experiment, the dependence of the output signal on the flow rate was determined for different pairs of signal electrodes. Data were processed using OLS, the coefficients for the quadratic representation according to (5), (6) are given in Table I. Calibration characteristics for different pairs of electrodes are shown in FIG. 5.

TABLE I: COEFFICIENTS FOR THE EXPRESSIONS (5) AND (6).

№ of the pair electrodes	**K, mV·h/m^3**	**ξ, h/m^3**	**α**
1	0,04403	$5{,}526 \cdot 10^{-4}$	$2{,}859 \cdot 10^{-2}$
2	0,04980	$4{,}568 \cdot 10^{-4}$	$2{,}364 \cdot 10^{-2}$
3	0,05251	$3{,}320 \cdot 10^{-4}$	$1{,}718 \cdot 10^{-2}$
4	0,05126	$1{,}769 \cdot 10^{-4}$	$9{,}153 \cdot 10^{-3}$
5	**0,04652**	$\mathbf{-7{,}504 \cdot 10^{-6}}$	$\mathbf{-3{,}883 \cdot 10^{-4}}$
6	0,03901	$-2{,}504 \cdot 10^{-4}$	$-1{,}296 \cdot 10^{-2}$
7	0,03511	$-3{,}691 \cdot 10^{-4}$	$-1{,}910 \cdot 10^{-2}$

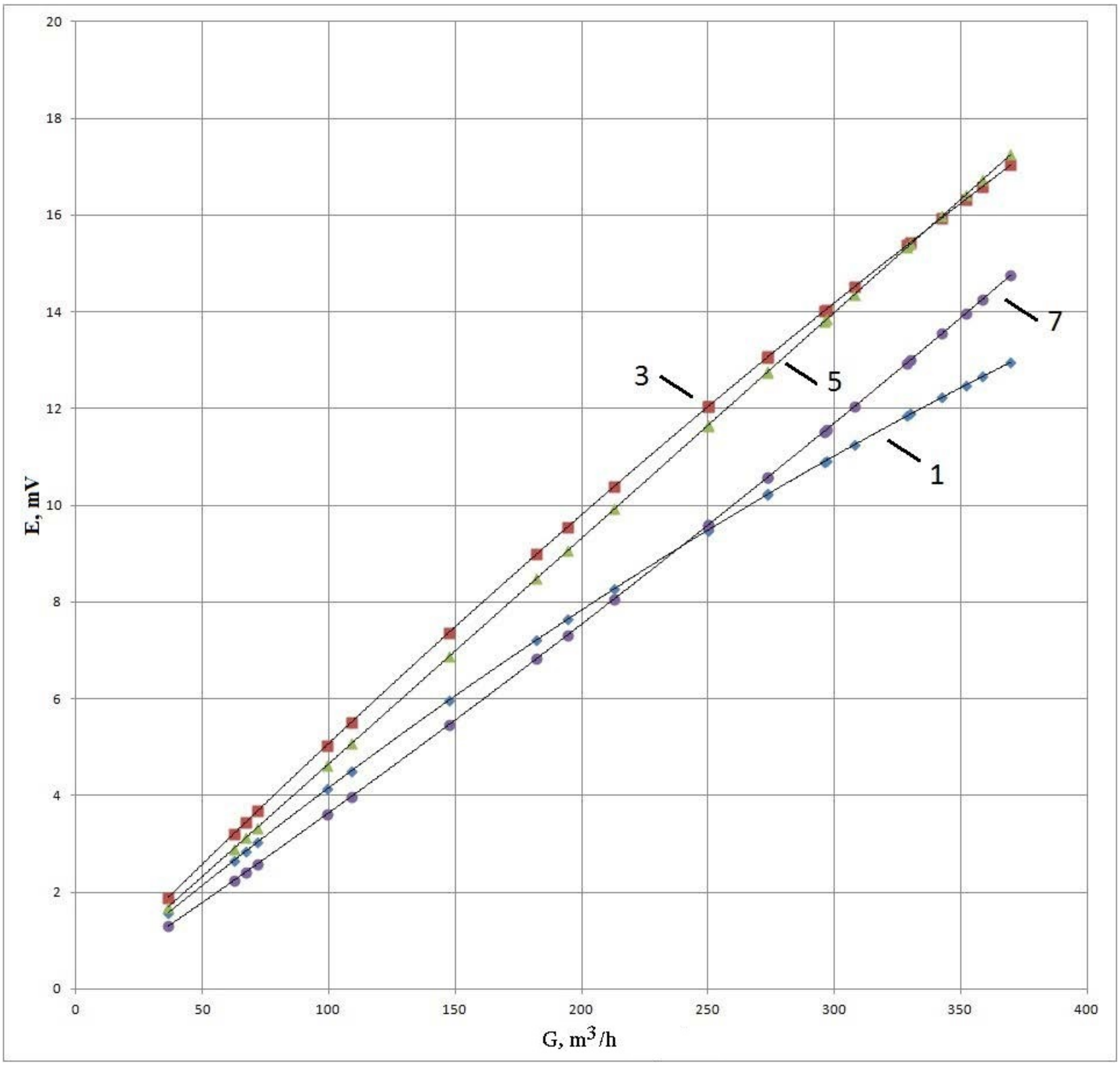

FIG. 5. Calibration characteristics for pairs of electrodes 1, 3, 5 and 7.

It is possible to note a remarkable nonlinearity for the pair of the central electrodes 3 and the expected strong nonlinearity with different signs of coefficients by quadratic terms for electrodes 1, 7 located at the edge of pole face and out of pole face accordingly. Regarding the calibration characteristic of pair 5 shifted downstream from the center at a distance of 0,35DN, the contribution of the nonlinear component at the maximum flow does not exceed 0,3%. It suggests the possibility to achieve the linearity by proper choice of electrodes ore its combination.

The presented experiment with the reached maximum value Re_m = 7,5 illustrates the potential of modeling to develop a flowmeter for the emergency core cooling system (SARH) of the BN-800 reactor with the nominal flowrate of 600 m^3/h, allowing for the maximum flowrate of 720 m^3/h if the diameter of the measuring section is DN300.

It should be noted that from the point of view of modeling the magnetic field spatial distribution the EM flowmeter with a low-frequency alternating field generated by a coil system has a certain advantage [6]. By carefully adjusting the coil parameters, it is possible to achieve more accurate compliance with the similarity of the magnetic fields than in systems with permanent magnets.

5. The calibration procedure using the modeling data

Calibration of the high range flowmeters should be implemented in 2 stages.

- Stage 1. Defining the calibration characteristics of the model sample in the range of flow providing the Re_m values corresponding to base conditions, calculating the alpha coefficient for different pairs of electrodes, choosing the pair with minimum nonlinearity.
- Stage 2. Direct calibration of full-scale specimen in the initial part of characteristics (25-30% of the nominal value) for several values of temperature.

As a result of step 2, the linear coefficient K_0 and its temperature dependence are evaluated. The latter is not concerned with the effect of the magnetic field drift and is determined by the temperature dependence of the components of the ratio for the output signal [7] registered by the electrodes installed on the outer surface of the wall.

$$E = B \cdot V \cdot d \cdot \frac{2 \cdot d/D}{1 + d^2/D^2 + \frac{\sigma_w}{\sigma_f} \cdot (1 - d^2/D^2)} \quad (8).$$

Here *d* is the inner and *D* is the outer diameters of the measuring section.

The final full-scale calibration characteristics of the flowmeter can be represented in the form

$$E = K_0 \cdot \left(1 - \alpha \cdot \mu_0 \cdot \sigma \cdot G \cdot \frac{4}{\pi \cdot D}\right) \cdot G \quad (9).$$

Conclusion

By choosing the electrode pairs it is possible to achieve a nonlinearity within a fraction of a percent of the flow meter scale, the length of the magnetic field being of the order of one diameter.

Calibration of the high range flowmeter can be implemented by a combination of direct tests in the initial part of its range (25 - 30%) and tests of the model sample to account for the nonlinear component.

Currently, the IRS-M loops are being arranged with the aim to achieve a flowrate of up to 400 m^3/h through the DN100, DN80 test sections and Re_m values more than 10. This will allow the modeling and the calibration of flowmeters in a range of more than 1200 m^3 per hour.

The results of the experiments performed on a certified calibration facility can be used for verification of calculation programs taking into account the interaction of the flow of the conducting medium with the magnetic field.

Appendix 1: References

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