Sensitivity Estimation of Permanent Magnet Flowmeter

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Abstract: Permanent Magnet Flowmeter (PMFM) is a non invasive device, which is used to measure the flow of electrically conducting sodium in Fast Breeder Reactor Circuits. PMFM works on the principle of generation of motional EMF by magnetic forces exerted on the charges in a moving conductor. In this paper modeling of PMFM with different pipe sizes is done to predict the flowmeter output for a given sodium flowrate. Magnetic flux density distribution inside the flowmeter pipe is studied for a typical PMFM. Velocity profile inside the pipe is assumed to be parabolic and developed electric potential across the SS pipe (in which sodium is flowing at constant flow rate) is calculated. The predicted sensitivities from COMSOL analysis are compared with experimental data

Keywords: Permanent Magnet flowmeter, Motional EMF, Sodium, Flow

1. Introduction

Permanent magnet flowmeter (PMFM) comprises of a pipe made up of stainless steel (SS), a magnetic structure made up of ALNICO-5 & Soft Iron and SS electrodes. The magnetic structure is suitably mounted to produce transverse magnetic field along the diameter of SS pipe. Electrodes are mounted outside the SS pipe in diametrically opposite positions mutually perpendicular to the direction of magnetic field and the direction of flow. The potential difference developed across the electrodes is calibrated to measure the flow of sodium in pipe. Schematic of PMFM is shown in Fig.1.

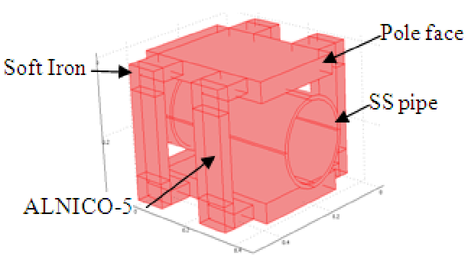


Figure.1 3D model of permanent magnet flowmeter.

1.1 Sensitivity of PM Flowmeters

Sensitivity of a flowmeter is defined as the ratio of milli-volt output across flowmeter electrodes for a unit flow rate (1 m^3/hr) in flowmeter pipe. The unit of sensitivity is **$mV/m^3/hr$**. Sensitivity of flowmeters depends on temperature of fluid flowing through the pipe and size of the pipe.

Potential difference developed across electrodes is calculated by dimensional measurements, average flux density measurement in the air gap of flowmeter assembly and by estimating the flow velocity at unit flow rate. Hall probe type gauss meter is used for magnetic flux density measurements. Flux density at various points across the cross section of pipe are measured and averaged. Potential difference developed in PMFM across a pair of electrodes can be calculated using Eq. 1[1].

$$E = B_g \times l \times v \times K_1 \times K_2 \times K_3 \times 10^3 mV \quad (1)$$

B_g = Magnetic flux density (Wb/m^2)
v = Velocity of sodium (m/sec)
l = Inner diameter of pipe (m)
E= Output in mV

1.2 Pipe wall correction factor (K1)

Since the pipe is made up of an electrically conducting material (SS) (which does not move with respect to magnetic field), it provides a parallel conducting path to the developed e.m.f. A correction is made for this shunting effect. This correction factor (k1) is given by Eq.2.

$$K_1 = \frac{2d / D}{1 + (d / D)^2 + \rho_f / \rho_w (1 - (d / D)^2)} \quad (2)$$

Where
d = Pipe internal diameter
D = Pipe outer diameter
ρ_f = Electrical resistivity of sodium
ρ_w = Electrical resistivity of pipe material

1.2 End effect correction factor (K_2)
This factor takes into account the effect of the finite length of pole face. This factor is a function of pole face length to the pipe inner diameter ratio.

1.3 Temperature correction factor (K_3)

$K_3 = 1-(T_m-30)*0.0003$ (3)
Tm= Magnet temperature during operation

2. Experimental setup for calibration

Experimental setup consists of two sodium storage tanks, purification setup, EM Pump and interconnecting pipelines. The sodium hold up of sodium tank (Test vessel) used for the calibration is 15.64 $m^{3.}$ PM Flow meter was installed in series in Test vessel dump line to calibrate the same in sodium. This installation provides more than 10D at upstream and more than 5D downstream straight length requirement. When dump valve is opened, sodium in Test Vessel flows to dump tank due to gravity. Calibration set up is shown in Fig.2.

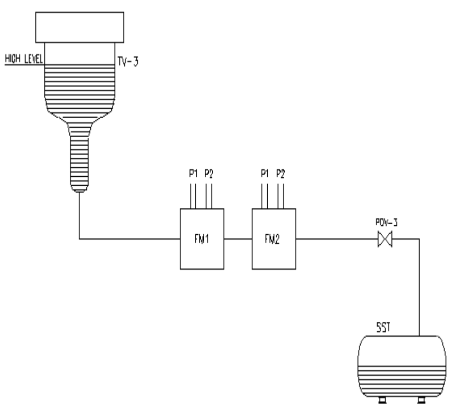


Figure.2 Experimental set up for calibration of PM Flowmeter

Voltage measuring electrodes were connected to a data acquisition system , which was connected to a PC. While draining sodium from Test vessel, milli volt output of flowmeter installed was acquired every second and stored. The sodium flow decreases gradually due to head reduction in test vessel and reduction in flow due to head variation was found to be 17%. Due to reduction in flow the milli volt output of PMFM will also reduce. Sensitivity of PMFM is calculated by averaging the potential difference acquired by data acquisition system.

3. PMFM analysis using COMSOL

PM Flowmeter is simulated in COMSOL using Magnetostastics and Navier-Strokes application modes. Magnetic field in SS pipe is considered to be independent of sodium flow in pipe, so first magnetostastics problem is solved. Then static magnetic potential is given as input and sodium flow is simulated using Navier-Strokes application mode.

3.1 Magnetic Circuit Simulation

In PMFM a magnetic circuit made up of ALNICO-5 and soft iron blocks is used to generate a transverse magnetic field. In COMSOL magnetostastics application mode is used to simulate the magnetic field inside the SS pipe in which sodium is flowing. Maxwell's equations for magnetostastic case can be rewritten in following manner [2].

$\nabla \times H = J = \sigma(E + v \times B)$ ………………… (4)
$\nabla \times E = 0$ …………………………………. (5)
$\nabla \cdot B = 0$ ………………………………….. (6)
$\nabla \cdot D = \rho$ …………………………………. (7)
$\nabla \cdot J = 0$ …………………………………... (8)

PMFM is used to measure the potential developed in electrically conductive sodium by the virtue of its motion in transverse magnetic field. Using definitions of the potentials,

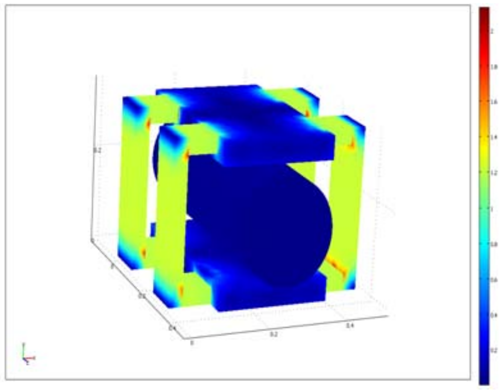
$B = \nabla \times A$ ……………………………….. (9)
$E = -\nabla V$ ………………………………... (10)

and the constitutive relation $B = \mu_0(H + M)$, Ampere's law can be rewritten for magnetostastics case as

$\nabla \times (\mu_0^{-1} \nabla \times A - M) - \sigma v \times (\nabla \times A) + \sigma \nabla V = 0$ ….. (11)

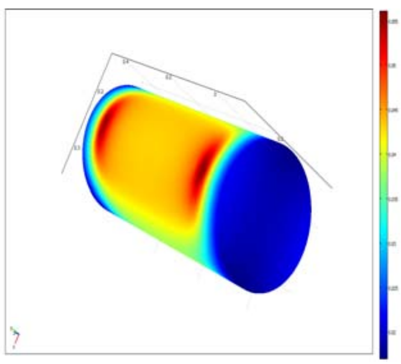
The term $\sigma v \times (\nabla \times A)$ represents the motion generated current density and is used to calculate the developed electrical potential. Magnetic flux density pattern generated by magnetic circuit is shown in Figure.3 (a) & (b).

Subdomain: Magnetic flux density, norm (T) Max: 2.128 T



(a) Min: $2.583e^{-3}$

Subdomain: Magnetic flux density, norm (T) Max: 0.0561



(b) Min: 0.0170

Figure.3 Magnetic flux density Plot. (a) In magnetic circuit. (b) In SS Pipe with sodium

It can be seen from Figure.3 (a) that magnetic flux density value in SS pipe is very low, when compared to magnetic flux density value in soft iron. Magnetic flux density value is not uniform across the length of the pipe, as it depends on the magnetic circuit design and pipe position with respect to magnets.

3.2 Flow Simulation

Sodium flow in SS pipe is stimulated in Navier-Strokes application mode in steady state. Sodium velocity is taken as constant and Lorentz forces acting on sodium are neglected, so generalized momentum balance equation in terms of transport properties and velocity gradients can be written as

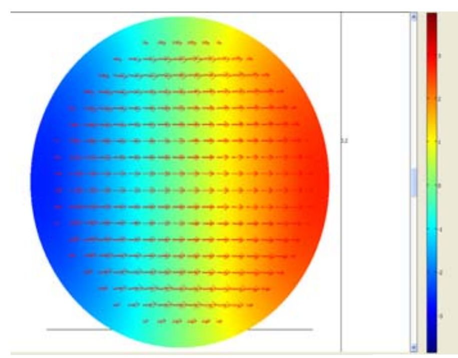
$$-\nabla \cdot [\eta(\nabla u + (\nabla u)^T) + \rho(u \cdot \nabla)u + \nabla p = 0 \quad \text{…….. (12)}$$

$$\nabla \cdot u = 0 \quad \text{………………………………….. (13)}$$

Where $\rho \frac{\partial u}{\partial t}$ =0 and Lorentz forces (F) acting on sodium are taken as zero.

Due to flow of electrically conducting sodium in transverse magnetic field, motional currents are induced in the sodium and electrical potential is developed in the sodium. Direction of motional current is perpendicular to both magnetic field and sodium flow. The maximum value of potential difference is developed across the line at the centre of SS pipe and perpendicular to both sodium flow and magnetic field direction. In Figure.4 direction of motional currents is represented by arrows and electrostatic potential developed in the pipe is represented by color plot

Subdomain: Electric potential (V)
Arrow: velocity current density Max: $3.968e^{-3}$

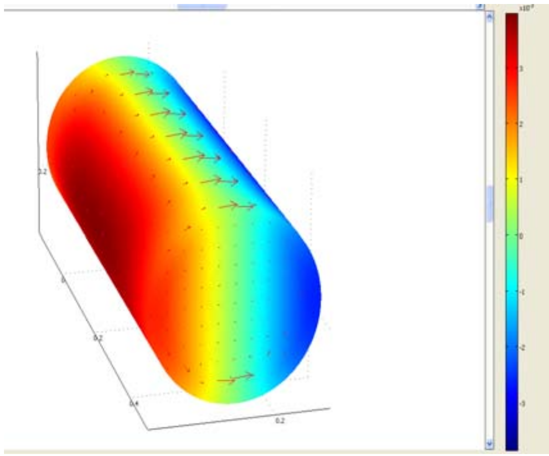


Min: $-3.968e^{-3}$

Figure.4 Direction of Motional currents are represented by arrows and electrostatic potential generated by motion of sodium in transverse magnetic field is represented by color plot.

It can be seen from Figures. 5 (a) that electric potential varies along the circumference of the SS pipe and remains nearly constant along the axial length. So the motional currents generated in moving sodium circulate along the circumference of SS pipe and the same can be seen in Figures. 5(b)

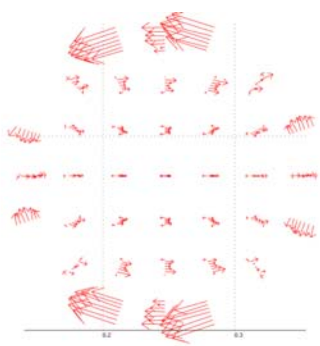
Subdomain: Electric potential (V)
Arrow: Total current density
Max: $3.968e^{-3}$



Min: $-3.968e^{-3}$

(a)

Arrow: Total current density



(b)

Figure.5 (a) Electric potential generated in SS pipe and moving sodium is shown with color plot and motional currents are represented with arrows. **(b)** Circulation of motional currents in SS pipe.

4. Results

Modeling of actual PMFM with 3D model consumes more memory and time. So, to have a feel and to visualize various electrical and magnetic parameters, one PFMF with 200 NB (Nominal Bore) SS pipe is chosen and modeled.

The analysis helps in observing and understanding the magnetic field distribution in SS pipe and motional currents path in sodium and SS pipe. Subsequently, sensitivity of 200,150 and 80 NB flow meters is calculated using 2D models.

In 2D simulations, 2D planar model is chosen. Cylindrical pipe of circular cross sectional area is replaced with a pipe of rectangular cross section with same area. Magnetic field was simulated by permanent magnets. The magnetic field is measured with Hall probe type gauss meter at different positions in pipe and average value is taken as input in Simulation. Electrically conductivity of SS pipe, end effects and operating temperature of ALNICO permanent magnet blocks are incorporated by using wall correction factors (K_1), End effect correction factor (K_2), Temperature correction factor (K_3). Magnetic flux density, conductivity of sodium and SS and sodium flow rate are used as the inputs in the model. Velocity currents produced in the sodium are used to calculate the voltage induced across the electrodes. Equivalent model of flow meter is shown in Figure.4

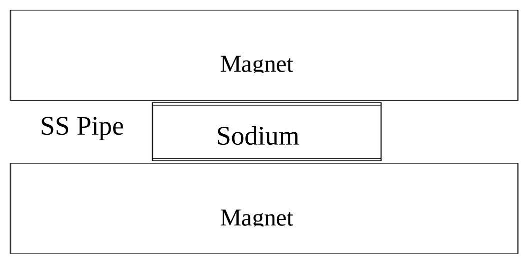


Figure.6 Equivalent model of flow meter

Velocity current density (Eq.14) and width of sodium pipe (L) are used for calculating the voltage measured at the electrodes of PMFM [3].

$$\frac{J_z}{\sigma} = v \times B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Jz = velocity current density in z direction
v=Voltage measured across PMFM electrodes
L= Distance between electrodes of PMFM.
σ *= Conductivity of sodium*

Voltage across the PMFM electrodes is calculated using Eq.15&16.

$$V = L\,(v \times B) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$V = L * \frac{J_z}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Dimensions of the 200 NB flowmeter pipe and flow rate of sodium are given in Table.1.

4.1 200 NB Flowmeter

Table.1 200 NB Flowmeter

Quantity	Value
Pipe size	200 NB
Magnetic Flux Density	0.0192 T
Pipe OD/ID	219.1 mm/202.7 mm
Flow Rate	1200 m^3/hr
Velocity of sodium	10.5 m/sec

For calculating average voltage across the electrodes, Eq.16 is averaged in subdomain containing sodium. Values of correction factors used and sensitivity calculated for 200 NB PM flow meter are given in Table.2.

Table.2 200 NB PM Flowmeter

Quantity	Value
Size	200 NB
K1	0.980
K2	0.97
K3 (Tm= 423 ^{O}K)	0.96
Rated flow	1200 m^3/hr
mV at rated flow from Analytical calculations	30.7
Sensitivity mV/m^3/hr from Analytical calculations	0.0256
mV at rated flow from COMSOL	32.754
Sensitivity mV/m^3/hr from COMSOL	0.027295
% variation of COMSOL calculation from Analytical calculations	6.62 %

4.2 150 NB PM Flowmeter

Dimensions of SS pipe, Magnetic flux density and correction factors for 150 NB PM Flowmeter and given in Table.3.

Table.3 150 NB PM Flowmeter

Quantity	Value
Magnetic flux density	0.03366 T
K1	0.977
K2	0.975
K3	0.964
Pipe size OD/ID in mm	168.3/154.1
Rated flow in m^3/hr	300

Sensitivity of 150 NB flowmeter and percentage variation from analytical results is given in Table.4

Table.4 150 NB PM Flowmeter

Quantity	Value
Size	150 NB
Rated flow	300 m^3/hr
mV at rated flow from Analytical calculations	21.27
Sensitivity mV/m^3/hr from Analytical calculations	0.0709
mV at rated flow from COMSOL	22.053
Sensitivity mV/m^3/hr from COMSOL	0.07351
% variation of COMSOL calculation from Analytical calculations	3.68 %

4.3 80 NB PM Flowmeter

Sensitivity of 80 NB Flowmeter is calculated using COMSOL. 3.4 and compared with experimental and analytical results. Magnetic flux density and dimensional details of 80 NB flowmeter are given in Table.5.

Table.5 80 NB PM Flowmeter

Quantity	Value
Magnetic flux density	0.06 T
K1(350°C)	0.9759
K1(250°C)	0.9799
K2 (350°C)	1
K2(250°C)	1
K3(350°C)	0.964
K3(250°C)	0.964
Pipe size OD/ID in mm	89/80 mm

Sensitivity of 80 NB PMFM is calculated with COMSOL. 3.4 and compared with experimental results and analytical results and same is given in Table.6.

Table.6 Sensitivity of 80 NB PMFM at 250 ^{0}C and 350 ^{0}C

Flow rate	**Experimental results(ER)**	**COMSOL results**	**Analytical results**	**Variation between FEM and ER**
43 (250 ^{0}C)	0.26114	0.2542	0.26097	-2.65 %
33 (250 ^{0}C)	0.26107	0.25427	0.26154	-2.60 %
27 (350 ^{0}C)	0.26043	0.25322	0.26196	-2.768 %
57 (350 ^{0}C)	0.25924	0.2532	0.26165	-2.32 %

5. Conclusion

Two dimensional Finite element analyses for sensitivity estimation is done for 200 NB, 150 NB and 80 NB pipe size PM flowmeters with COMSOL 3.4. Results of FEM analysis are compared with analytical results (calculated through closed form of equations with correction factors) for 200 NB and 150 NB Flowmeters. As evident from comparison tables, the variation is less than 4%. This can be attributed to non-consideration of end effect in COMSOL model.

For 80 NB flow meter, the FEM results are compared with available experimental results and found to have small variation. This is due to partial representative of actual flow meter geometry in 2D model. In general, simulation results suggest that simulation of PM Flowmeters can be used for predicting the sensitivity of flowmeters with different pipe sizes.

6. References

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