Performance Prediction of Eddy Current Flowmeter for Sodium

Prashant Sharma*, S.K.Dash, B.K.Nashine, S. Suresh Kumar, R. Veerasamy, B. Krishnakumar, P. Kalyanasundaram, G. Vaidyanathan

*Corresponding author: Hall-3, FRTG, Indira Gandhi Centre for Atomic Research Kalpakkam-603 102, INDIA
pacific@igcar.gov.in

Abstract: Sodium is used as a coolant in Fast Breeder Reactors. Eddy Current Flowmeter (ECFM) is used for measurement of sodium flow in the primary pump and at the outlet of the subassemblies. Eddy Current Flowmeter (ECFM) works on the principle of change in the magnetic field profile due to induced eddy currents as a result of sodium flow. It consists of a central primary winding, energized from an A.C. source, flanked on either side by two identical secondary windings connected differentially. The two secondary windings are balanced so that the output is nominally zero when the flowmeter is immersed in static sodium. The flow of sodium distorts the external field so that the electromotive forces generated in two windings differ by a magnitude proportional to the sodium velocity. ECFM is having axi-symmetric structure so a 2-D Axi-symmetric model has been used. In order to have coupling between the electromagnetic field and the fluid flow, two modules namely- AC/DC Azimuthal Induction Currents and Fluid Mechanics-Incompressible Navier Stokes have been utilized. The model developed using COSMOL has been validated against experimental results and a close agreement has been found. The developed model can lead to reduction in experiments required for calibration of the sensor.

Keywords: eddy current flowmeter, sodium flow measurement, COMSOL

1. Introduction

Liquid metal cooled Fast Reactors form the mainstay of future Indian nuclear programme. Sodium as a coolant has been used in nearly all the Fast Breeder Reactors (FBR) built so far e.g. Rapsodie, Phenix, Super-Phenix, BN-600 and FBTR. Sodium flow is measured in fast reactors mainly at pump outlet in the primary circuit, in secondary sodium circuits and also at the outlet of sub-assemblies to detect flow blockage [1, 2, 3]. All these flowmeters utilize the electrical conducting nature of liquid sodium. For measuring sodium flow in secondary sodium circuits Permanent Magnet Flowmeters working on Faraday's principle are used. For measuring sodium flow at the primary pump outlet and at the outlets of the subassemblies Eddy Current Flowmeter (ECFM) is used. The advantages with ECFM are- its light weight, its ability to withstand temperatures up to 600ºC and that it can be easily withdrawn from reactor top for maintenance. The output voltage of ECFM for a given flow depends upon the frequency of the input constant current source and also on temperature of liquid sodium. If frequency is chosen properly and if proper signal conditioning is done then it is found that the output of the sensor becomes only a function of flow independent of the temperature of liquid sodium [4]. Determination of this frequency using experimental techniques is time consuming, therefore a finite element based simulation model of the sensor using COMSOL 3.4 [5] was made and verified against experimental data. This paper deals with details of the simulation model and its validation against experimental data.

2. Description of ECFM

The schematic of ECFM is shown in figure 1. It consists of a primary winding energised by an alternating constant current source. The primary winding (P1) is surrounded by two identical secondary windings (S1 & S2) on either side. When sodium is static the alternating flux produced by the primary winding induces equal voltages in both the secondary windings due to transformer action. When sodium is in motion, voltage is induced in moving annular sodium ring. This voltage in annular sodium ring induces voltage in S1 and S2 coil which is subtractive to transformer voltage in upstream coil and additive to transformer voltage in downstream coil. As a result of this, the voltages induced in the two secondaries differ from each other and this difference is proportional to the sodium velocity.

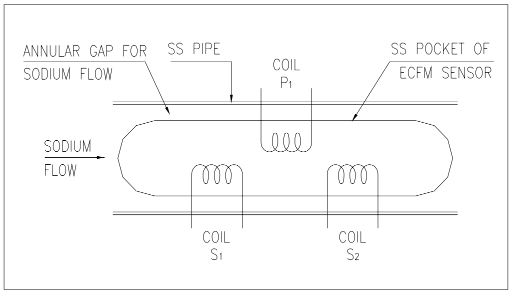

Figure 1: Schematic representation of ECFM

The eddy currents in sodium are also a function of temperature of liquid sodium and hence the output voltage becomes a function of both the temperature and flow. In order to utilize the sensor for flow measurement, the effect of temperature on output voltage needs to be nullified. Based on the working principle of the device and the experiments conducted it was found that if instead of just taking the difference of the two signals, the ratio (V2-V1)*100/(V1+V2) is taken as the final output, it becomes independent of temperature. The ratio (V2-V1)*100/(V1+V2) which is a function of flow only is termed as the sensitivity of the flowmeter. V2 is the voltage in the downstream coil and V1 is the voltage in the upstream coil. In order to protect the device from the influence of external magnetic fields a magnetic shield has been provided in the flow measuring device.

3. Construction and Details of ECFM

This flow sensor is compact with an overall size of 14mm dia. x 150mm length and consists of three coils (made from mineral insulated SS sheathed copper and Nichrome cables) wound on bobbin made of magnetic steel SS 410 and enclosed in a S.S. tube enclosure. Figure 2 shows the details of ECFM.

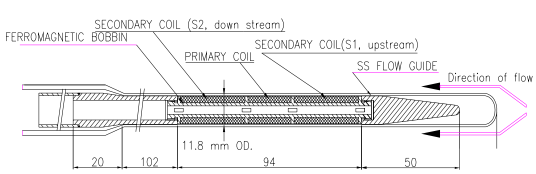

Figure 2: A Typical Eddy Current Flowmeter Probe

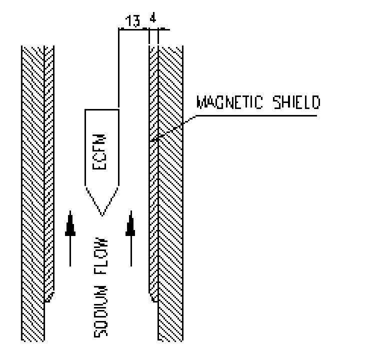

Figure 3: ECFM along with Subassembly and magnetic shield

4. Simulation:

The simulation of ECFM was done using the FEM based software COMSOL 3.4. Simulation was done for various flowrates, temperatures and frequency in order to determine the output vs flow characteristics and the optimum frequency of operation. The optimum frequency is defined as that frequency at which the variation with temperature in sensitivity of the flowmeter is minimum.

The simulation of ECFM has been done in 2-D axisymmetric mode and the complete set of equations for a Newtonian, constant property fluid flow includes the Navier-Stokes equations of motion (*i.e.*, momentum equation, Eq. (2)), the equation of mass continuity (Eq. 3), Maxwell's equations (Eq. (4)-(5)), and Ohm's Law (Eq. (6)). In differential form they constitute the following system of equations:

$$\rho\left(\frac{\partial u}{\partial t}+(u.\nabla)u\right)=-\nabla p+jXB+\mu_f\nabla^2u+\rho g \quad \dots (2)$$

$$\frac{\partial \rho}{\partial t}+\nabla.\rho u=0 \quad \dots (3)$$

$$\nabla \text{ X E} = -\frac{\partial \text{B}}{\partial \text{t}} \quad \dots (4)$$

$$\nabla \text{ X B} = \mu_{\text{m}} \text{ j} \quad \dots (5)$$

$$j=\sigma(E+u \text{ X B}) \quad \dots (6)$$

where the MHD body force j X B is included in the Navier-Stokes equation. The displacement current has been neglected from Ampere's Law, which is a valid approximation for nonrelativistic phenomenon typical of the response of an inertial liquid. ρ is the density u is the velocity vector, p is pressure, B is the magnetic flux density, σ is the conductivity of the fluid, μ_m is the magnetic permeability, j is the electrical current density, E is the electric field intensity, μ_f is the viscosity of the fluid, g is the acceleration due to gravity. Along with Eqs. (2)-(6) the following additional relations are also applicable:

$$\nabla \cdot B = 0 \qquad \ldots (7)$$

$$\nabla \cdot j = 0 \qquad \ldots (8)$$

The magnetic induction equation is derived by taking the curl of Ohm's Law:

$$\nabla \times j/\sigma = \nabla \times E + \nabla \times (u \times B) \qquad \ldots (9)$$

If $\nabla \times E$ is replaced by Faraday's Law (Eq. 4) and $\nabla \times j$ is replaced by the curl of Ampere's Law (Eq. 5), then, using the vector identity:

$$\nabla \times (\nabla \times B) = \nabla(\nabla . B) - \nabla^2 B \qquad \ldots (10)$$

The following equation is obtained:

$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) + \frac{1}{\mu_m \sigma}\nabla^2 B \qquad \ldots (11)$$

Equation 11 is known as the induction equation, and suggests that the motion of a conducting liquid in an applied magnetic field will induce a magnetic field in the medium. The total field is the sum of the applied and induced magnetic fields. These equations are then solved and the resultant induced voltages in the two coils calculated. The difference of the induced voltage in the downstream and upstream coils is directly proportional to flow.

5. Simulation in COMSOL

The device is having axi-symmetry, therefore, 2-D axi-symmetry model has been used. The graphical model is shown in figure 4. Azimuthal induction currents and Incompressible Navier-Stokes are the two application modes utilized. Time harmonic analysis has been done for the AC/DC case where as transient analysis has been opted for Navier-Stokes application mode. The actual windings are made up of mineral insulated (MI) cables, since it is difficult to model many number of turns, only the surface current density has been provided over the coil sub-domain with conductivity of the coil sub-domain set to zero. The modeling of flowmeter requires coupling between magnetic field and the velocity so that the distortion in magnetic field profile as a result of motion of conducting sodium can be modeled. This is achieved by specifying u & v terms in the sub-domain settings as shown in figure 5.

The frequency of simulation is specified in scalar variables. After the simulation, the induced voltage in the two secondary windings is calculated by performing boundary integration of electric field on the boundary of the secondary coil and then multiplying the output by the number of turns.

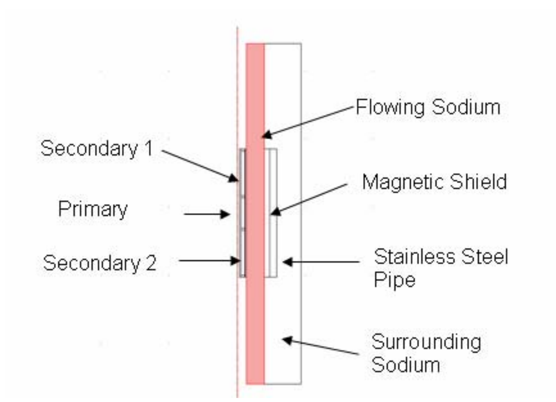

Figure 4: Geometrical Model of ECFM in COMSOL

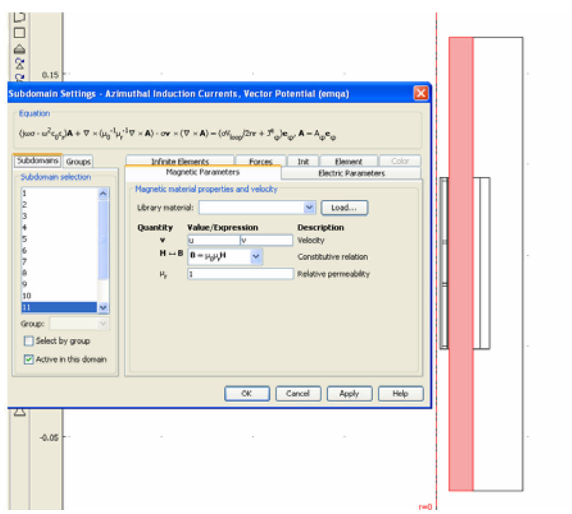

Figure 5 : Subdomain properties for achieving coupling between flow and magnetic field

6. Simulation Results and Comparison with Experimental Results

Figure 6 (a) & (b) depicts the comparison between the experimental and simulation results at temperatures of 500ºC and 400ºC respectively.

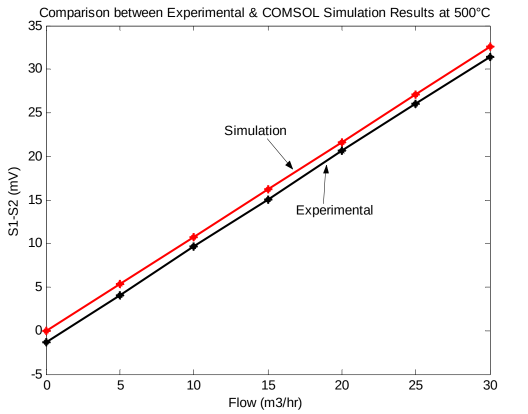

Figure 6 (a) : Experimental & COMSOL simulation Results at 500°C

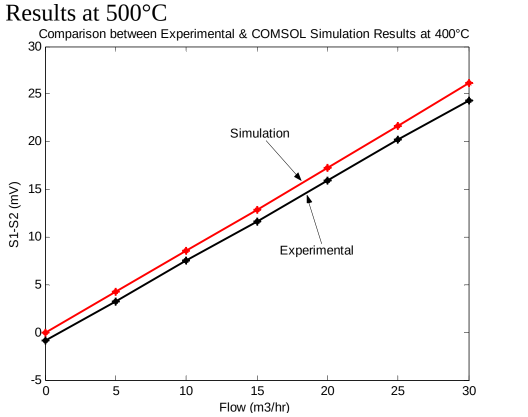

Figure 6(b) :Experimental & COMSOL Simulation Results at 400°C

Figure 7 shows the change in magnetic flux density profile along the length of the sensor with velocity.

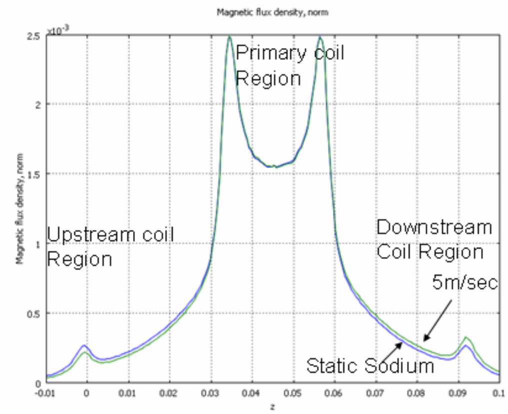

Figure 7: Flux density change with flow along the sensor length

In order to get the optimum frequency of operation at which the variation with temperature is minimum, a parametric simulation for various values of temperature and frequency was carried out. The plot of sensitivity vs frequency for various temperatures is shown in figure 8. The point where the curves corresponding to various temperatures intersect defines the optimum frequency of operation. The comparison with experimentally obtained curve is shown in figure 9.

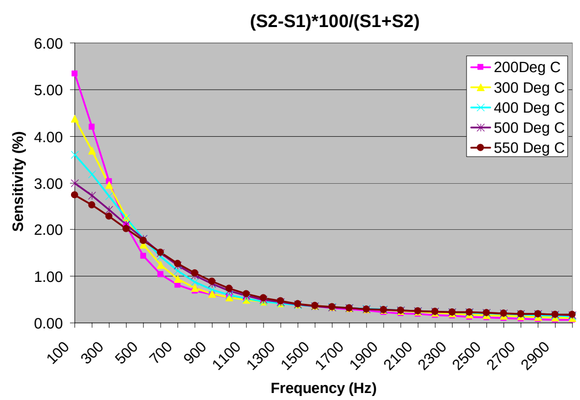

Figure 8: Sensitivity vs Frequency at different temperatures for determining the optimum frequency

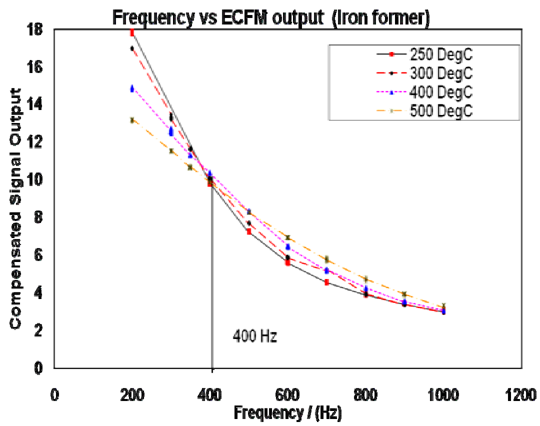

Figure 9: Experimentally obtained Frequency vs. Signal output with Iron former

In figure 8 it can be seen that the curves intersect at around 400Hz which is in close agreement with experimental results shown in figure 9.

7. Conclusion

The simulation of eddy current flowmeter using COMSOL is in close agreement with the experimental results and thus it can lead to performance prediction of the flowmeter more accurately in the design state leading to reduction in number of experiments to validate the design.

8. References:

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