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Probe Type Permanent Magnet Flowmeter

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Abstract: Prototype Fast Breeder Reactor (PFBR) is a 500MWe, sodium cooled, pool type, mixed oxide (MOX) fuelled reactor. Sodium flow measurement in various loops of the reactor is of prime importance from the operational and safety aspects. To measure the flow of electrically conducting sodium in large secondary circuit pipes, probe type permanent magnet flowmeters (PTFM) are used. PTFM works on the principle of generation of motional EMF by magnetic forces exerted on the charges in a moving conductor. This paper deals with three dimensional Finite element modeling of PTFM. Magnetic field distribution across the flowmeter pipe and the effect of sodium flow on the magnetic field are analyzed. Flowmeter output for different sodium flow rates is predicted and analyzed.

Keywords: ALNICO-5,Probe, Flowmeter.

1. Introduction

Fast breeder reactors constitute the second stage of India's three stage nuclear programme for effective utilization of the country's limited reserves of natural uranium and exploitation of its large reserves of thorium. A 40MWt/13MWe loop type Fast Breeder Test Reactor (FBTR) was commissioned in 1985 at Kalpakkam. In next step in Fast breeder reactor development, a Prototype Fast Breeder Reactor is being constructed at the same site. Liquid sodium is used as coolant in both loop type FBTR and pool type PFBR (Chetal et al., 2006). Due to safety and operational requirements, sodium flow is measured in secondary circuits, purification loops, at primary pump outlet and sub assembly outlet inside the reactor. Conventional methods of flow measurements can't be used due to high temperature ambience and reactive sodium environment, hence electromagnetic flowmeters such as PMFM and eddy current flowmeter (ECFM) are used for flow measurements (Sharma et al).

Permanent Magnet flowmeters have been used in pool type BN- 600 and BN-800 reactors in by-pass lines to measure the primary circuit coolant flow rate (Kamanin and Kuzavkov, 1989) and in Phenix reactor in secondary circuits. Permanent magnet flowmeters have also been used in loop type reactors like SNR-300, KNK, MONJU (Hans et al, 1979), Rapsodie and FBTR for flow measurement. Special probe type permanent magnet flow meter is used to carry out coolant flow monitoring through fuel sub assembly outlet in the shut down condition for BN-350 and BN-600 reactors (Kamanin and Kuzavkov, 1989).

Electrically conductive materials moving in a magnetic field experiences electromotive force acting in a direction perpendicular both to the magnetic field and to the motion. This phenomenon was first tried for flow measurement of electrically conducting fluid (water) by Faraday in Thames River (Jae-Eun Cha et al). His experiments failed due to short circuiting of signals by river bed. First successful measurement of speed of an electrically conducting material by measuring the EMF was done by Smith and Slepian in 1917 for finding the speed of ships relative to the sea from measurements of the voltage induced between two electrodes on the hull in the presence of magnetic field emanating from the ship (Shercliff, 1962).

Theory for measuring the flow of electrically conducting fluids in pipes (electrically conducting or non-conducting) was first developed by Shercliff (Shercliff, 1962). He developed the two dimensional weight functions to represent the contribution of fluid velocity profile to flow signal across pipe cross sections of different shapes. The effect of pipe wall conductivity on flow signal and effects peculiar to flow measurement of liquid metals were discussed for two dimensional approximations.

Above discussed electromagnetic flow meters are in use in various sodium circuits and their behavior are well known. The windings of coil of eddy current flow meter are made of thin Mineral Insulated cable and hence vulnerable to malfunction. It also poses additional fabrication difficulties. So, Permanent Magnet Flow meter as an alternative to eddy current flow meter which is expected to be a rugged and robust from manufacturing and operation front is suggested. The design does not have any coils and associated driving circuit, which make the sensor more reliable. This paper describes the proposed design features, FEM based analysis and sensitivity estimation using COMSOL.

2. Description of Probe type Permanent Magnet Flowmeter (PTFM)

Probe type permanent magnet flowmeter consists of two permanent magnets made up of ALNICO-5 and enclosed in a SS tube resistant to corrosive nature of liquid sodium. Permanent magnets are magnetized so that the magnetic lines are perpendicular to sodium flow. A pair of SS leads is connected to SS pipe to measure the electrical potential generated in sodium due to its motion in magnetic field. Schematic of the flowmeter is shown in Fig.1 and sectional view across the magnet is shown in Fig.2

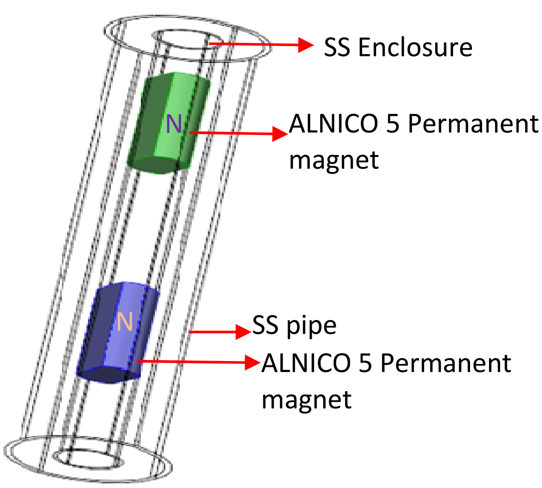

Fig.1 Schematic of Probe type permanent magnet flowmeter.

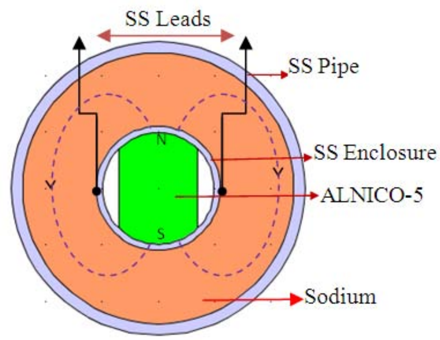

Fig.2 Sectional view across magnet cross section

3. Use of COMSOL Multiphysics

In Probe type PMFM, magnetic field, sodium flow and induced motional voltage are orthogonal to each other, hence a three dimensional modeling is required for its true representation. In COMSOL magnetostastics application mode is used to simulate the magnetic field inside the SS pipe in which sodium is flowing. Sodium is considered as solid electrical conductor, which is moving in steady magnetic field produced by two ALNICO-5 magnets. Maxwell's equations for magnetostastics case can be rewritten in following manner [2].

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

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,

$$B = \nabla \times A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$
$$E = -\nabla V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

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

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

4. Results

Magnetic flux density values in SS pipe cross section due to presence of ALNICO-5 permanent magnet is not uniform as it depends on the magnetic circuit design. It can be seen from Fig.3 that magnetic flux density values decrease as we go away from the PTFM and this makes the probe a local flow measurement device.

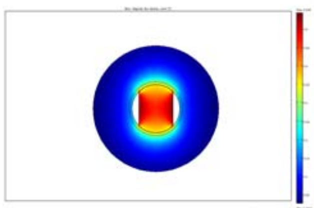

Fig.3 Magnetic flux density plot in SS pipe cross section.

Motion of liquid sodium in presence of magnetic field produced by ALNICO-5 permanent magnets leads to generation motional EMF in sodium. Plot of generated electrical potential for sodium flowing at 1 m/s in 50 mm diameter SS pipe is shown in Fig.4. Generated electric potential at SS enclosure along the length of the PTFM is shown in Fig.5. Generated electric potential across the SS leads is 3.55 mV for sodium flowing at 1 m/s in 50 mm diameter SS pipe.

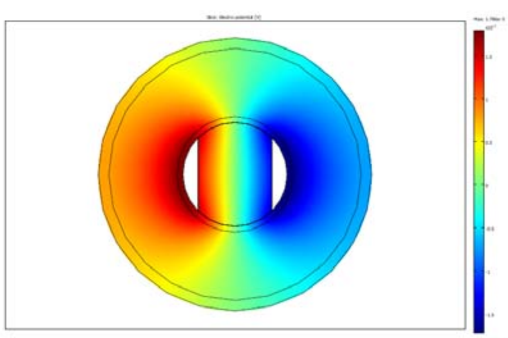

Fig.4 Electrical potential in Sodium

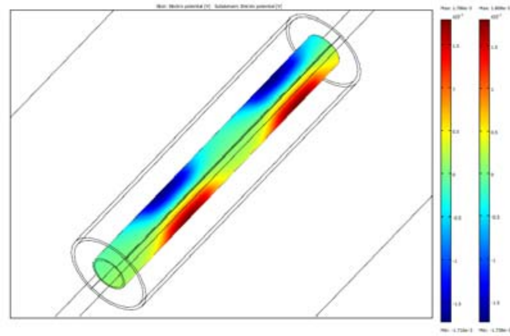

Fig.5 Electrical potential at SS enclosure along the length of PTFM

In sodium loops, temperature of sodium varies from 550 ^{o}C to 150 ^{o}C. The decrease in sodium temperature leads to increase in its electrical conductivity. The variation of PTFM output with electrical conductivity of sodium is shown in FIg.6. It can be seen that increase in electrical conductivity of sodium at a fixed velocity of 5 m/s leads to increase in generated electrical potential from 16.9 mV to 17.3 mV.

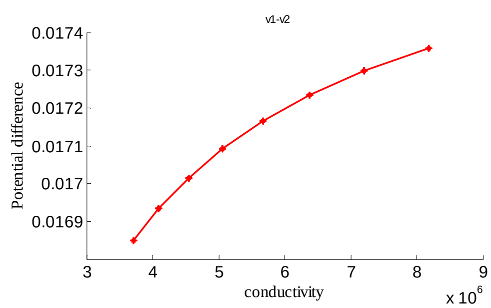

Fig.6 Generated electric potential verses electrical conductivity of sodium.

To increase the sensitivity of PTFM magnetic shield made up of ferromagnetic material and enclosing the probe is designed and optimized. Magnetic shield made up in shape of hollow cylinder with diameter of 30 mm increases the sensitivity of PTFM by nearly twofold. Magnetic shield represented by white ring in Fig.7 concentrates the magnetic field around probe.

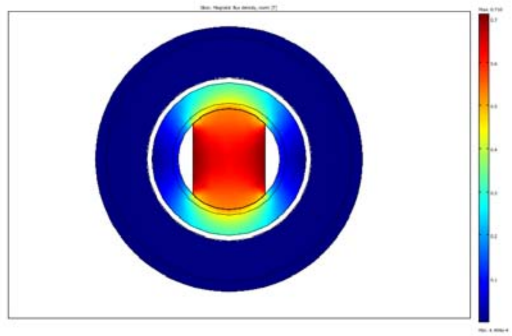

Fig.7 Effect of magnetic shield on magnetic flux density in SS pipe.

Electrical potential generated in presence of magnetic shield is shown in Fig.8. Sodium velocity inside as well as outside the shield is assumed to be same. Generated electric potential across the SS leads is 5.95 mV for sodium flowing at 1 m/s in 50 mm diameter SS pipe. The presence of magnetic shield around the probe increases its output by 67 %.

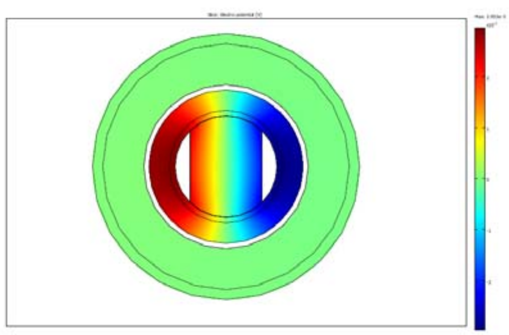

Fig.8 Electric potential in presence of magnetic shield.

7. Conclusions

Probe type permanent magnet flowmeter with ALNICO-5 magnetic material was designed and three dimensional Finite element model was analyzed in COMSOL.3.5a to estimate the sensitivity of the flowmeter for a fixed sodium flow at a particular velocity in 50 mm diameter SS pipe. Steady magnetic field produced by magnets with and without magnetic shield around the flowmeter probe is analyzed. Electric potential generated across SS leads due to sodium flow at 1 m/s in SS pipe of 50 mm diameter is 3.55 mV, which increases by 67 % to 5.95 mV due to the presence of magnetic shield around the flow meter. The proposed design will be fabricated and tested in sodium loop before final adaptation in reactor.

8. References

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