Development of Electromagnetic Devices for Sodium Cooled Fast Reactor Application

B.K. Nashine*, Prashant Sharma, G. Vijayakumar, Vijay Sharma, S. Narmadha, S. Chandramouli, V. Prakash and P. Selvaraj
Indira Gandhi Centre for Atomic Research, Kalpakkam (T.N.) – India
*bknash@igcar.gov.in

Abstract
Liquid sodium is used as coolant due to its suitable neutronic and thermal properties in fast reactors. Good electrical conductivity of sodium is used for development of electromagnetic devices such as electromagnetic pumps & flowmeters and level probes for use in sodium cooled fast reactors, where conventional devices used in chemical plant cannot be used due to high chemical activity of sodium and high temperature. Design, development and testing of a Sodium Submersible Annular Linear Induction Pump (ALIP) was carried out recently. The developed pump can be used for sodium draining from main vessel of pool type of Sodium Cooled Fast Reactor (SFR) and any other application where pump has to be submerged in sodium. The developed pump does not require any external cooling when submerged in radioactive sodium of 200^{o}C. The winding of submersible ALIP can withstand 550 ^{o}C. The submersible ALIP was tested in sodium loop for obtaining pump characteristics. AC Conduction pump for low flow application in sodium loop has been developed. Design, analysis and manufacturing aspects are brought out in the paper. Development of three different types of compact electromagnetic flowmeters based on Samarium Cobalt permanent magnet, electromagnet formed from soft iron in combination with mineral insulated cable and small probe type permanent magnet flowmeters were successfully demonstrated. Samarium Cobalt magnet helps in reducing the size and weight of flowmeter due to its high energy product. Flowmeter having electromagnet coil made from mineral insulated cable has high temperature withstand capability of around 500 ^{o}C. The electromagnet coil in combination with soft iron replaces permanent magnet, hence it provides diversity in flow measurement in critical applications. The probe type flowmeter uses small permanent magnet encapsulated in a slender probe which can be inserted inside the pipe where sodium flow measurement is required. Eddy current based ex-vessel level probe was developed for measurement of sodium level in the vessel without insertion of probe inside the vessel. It works on the principle of eddy current and using this probe, sodium level inside the stainless steel vessel can be obtained by keeping the probe outside the vessel. This technique of discrete sodium level measurement is first of its kind. This paper enumerates development of sodium submersible ALIP, newly developed flowmeters and development of ex-vessel sodium level probe. Test results obtained from sodium testing are also brought out in the paper and FEM analysis carried out for different devices are also depicted.

Key Words: Electromagnetic pumps, electromagnetic flowmeters

1. Introduction

Liquid sodium has been used as coolant due to its suitable neutronic and thermal properties for fast reactors around the world [1]. Besides having suitable neutronic and thermal properties, liquid sodium is also a good conductor of electricity. Various electromagnetic devices such as electromagnetic pumps [2, 3], flowmeters, level probes have been developed for their application in sodium cooled fast reactors. These electromagnetic devices use property of high electrical conductivity of sodium for their functioning. Sodium submersible annular linear induction pump (ALIP), an electromagnetic pump, has been developed for sodium draining from main vessel of FBR during decommissioning of reactor or whenever situation warrants. This submersible ALIP whose winding can withstand 550 °C temperature can be also used in other applications where pump is required to be submerged in sodium such as in integrated cold trap system, failed fuel location module system etc. AC conduction pump, other version of an electromagnetic pump, was developed for sodium system where low flow operation is required. Permanent magnet flowmeter using Samarium Cobalt magnet was developed to reduce the size and weight of the flowmeter compared to conventional flowmeters. Electromagnetic flowmeter has been developed for high temperature (> 500 °C) application and probe type flowmeter using small disc magnet has been developed for measurement of sodium flow through large pipes. Ex-vessel discontinuous type level probe which works on eddy current method has been developed for measurement of sodium level inside the vessel by keeping the probe outside the vessel. The paper brings out salient features of design, analysis, manufacturing and testing of all these electromagnetic devices developed in IGCAR.

2. Design of Submersible Annular Linear Induction Pump (SALIP)

The design of sodium submersible ALIP is based on the equivalent circuit approach similar to that of a rotary induction motor. The equations for output pressure and other parameters have been described in [2, 4]. In conventional ALIPs, the insulation of winding consists of Class-C (temperature index – 200 °C max) insulation and windings are cooled by external blowers to limit winding temperature lower than thermal withstand capacity of winding insulation. Conventional ALIP cannot be used for sodium submerged condition because of low thermal withstand capacity of winding. To overcome the above mentioned constraint, ALIP with winding made from mineral insulated stainless steel sheathed cable (MI Cable) [5] is designed, manufactured and tested in a sodium loop. This pump can be submerged in sodium pool at 200 °C and can work without external winding cooling because MI cable winding has thermal withstand capacity up to 550 °C. Some of the parameters of the designed sodium submersible ALIP are given in Table 1.

TABLE 1 : PARAMETERS OF THE DESIGNED SUBMERSIBLE ALIP

Normal Flow rate	2.0 m^3/h
Head to be Developed at Nominal flow Rate and Temperature	0.4 MPa
Rated Voltage	150 V, 3 Phase, 50 Hz
kVA Rating	30 kVA
Line Current	105 Amps (phase current – 60 Amp)
Insulation	Mineral Insulated SS Sheathed Copper Conductor

2.1 Manufacturing of Submersible ALIP

The manufacturing of ALIP was carried out in two stages. In stage-1, winding of MI cable was done and in stage-2 assembly of magnetic laminations and inner duct was carried out. In the stage-2, pre-assembled lamination stacks were inserted and thereafter welding of side plates and outer casing was carried out. Thermocouples for measurement of winding and duct temperature were also fixed. Figure 1 shows the photograph of SALIP after completion of second stage fabrication. The final completed SALIP is depicted in Fig. 2. The manufactured SALIP is hermetically sealed by a stainless steel casing so that it is capable of working in sodium submerged condition at temperature more than 200 °C.

Following tests were conducted on SALIP during fabrication to ensure quality production as per the applicable standards and specifications:

a) Electrical Continuity and resistance measurement test of winding
b) Insulation Resistance Measurement test on winding
c) High Voltage Test on winding
d) Pneumatic Test on duct
e) Helium Leak Test on duct

Fig. 1: Submersible ALIP with MI Cable winding and CRGO laminations

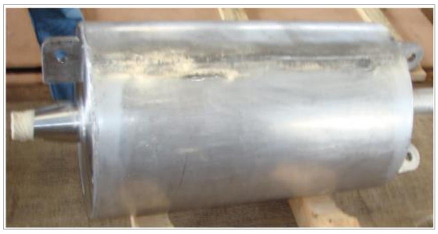

Fig. 2 : Manufactured Submersible ALIP with outer stainless steel enclosure

2.2 Performance Evaluation of Submersible ALIP

The validation of design was carried out by conducting tests on the manufactured pump in a sodium facility. Experimental head developed vs flow characteristic of the pump is shown in Fig.3. Functional testing of submersible ALIP was carried out in sodium submerged condition at rated sodium temperature of 200 °C.

The following tests were conducted on the SALIP during the sodium testing (phases 1 & 2).

a) Operation of the pump at different voltages and flows to obtain the differential pressure vs flow characteristics of the pump.
b) Confirmation of the thermal performance of the pump
c) Performance of cavitation tests on pump
d) Demonstration of long term operation of submersible ALIP in the sodium loop at specified sodium temperature
e) Operation of submersible ALIP in sodium submerged condition in sodium pool

The successful tests on SALIP has proved the design and has given confidence that the developed submersible ALIP in submerged condition is capable of draining out primary sodium at 200 °C from the main vessel of pool type sodium cooled fast reactor.

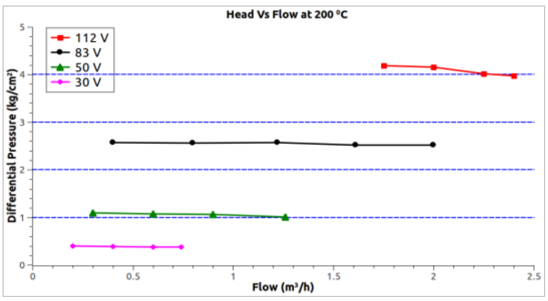

Fig. 3: Differential Pressure Vs Sodium Flow through SALIP

3. Design & Manufacturing of AC Conduction Pump

Electromagnetic pumps generate required head due to interaction of magnetic field and electric currents in liquid sodium. In conduction electromagnetic pumps, the electric current in sodium flows via conduction from an external circuit which requires physical connection of the external circuit to the duct. AC Conduction pump (ACCP) is one such conduction pump, used for pumping liquid sodium.

3.1 Design and Analysis of AC Conduction pump

AC conduction works on single phase power supply and the pumping force in ACCP is derived from the interaction between an alternating current flowing in the liquid metal (sodium) and a perpendicular magnetic flux produced by an AC magnetic circuit. ACCP consists essentially of a transformer for providing current through liquid sodium and magnetic field in the duct region. The transformer core is constructed of silicon steel laminations clamped together. The primary coils are wound on the lower limb of transformer core, while secondary circuit is formed by laminated copper strips which are butt brazed to opposite sides of pump duct to form a closed loop around the middle limb of the core. AC conduction pump of rating 2 m^3/h and 2 Kg/cm^2 was designed using magnetic circuit approach and analyzed with FEM code. Figure 4 illustrates the schematic details of 2 m^3/h ACCP and Fig. 5 indicates three dimensional view.

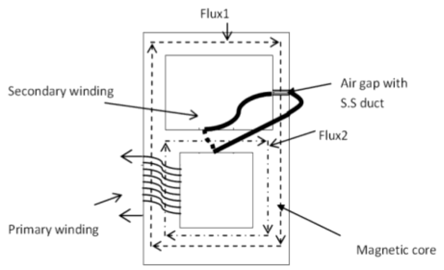

Fig. 4: Schematic of AC Conduction Pump

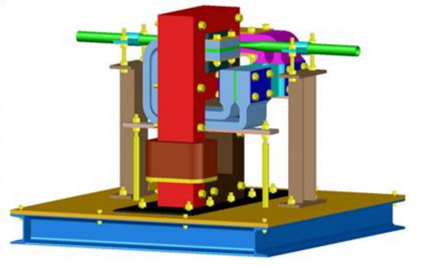

Fig. 5: Three dimensional view of ACCP

Flux produced by primary winding of ACCP is used for generating high current in secondary winding and required flux in SS duct. FEM modeling is used to determine the flux density in SS duct and current in short circuited secondary winding for fixed input voltage. Flux density plots in SS duct and magnetic core of ACCP are shown in Fig.6 and Fig.7 respectively. It can be seen that due to demagnetizing effect of secondary current, the flux density values in central limb of ACCP are less and most of the flux is going to the upper limb SS duct. This flux passes through the sodium and generates the Lorentz force on the liquid sodium.

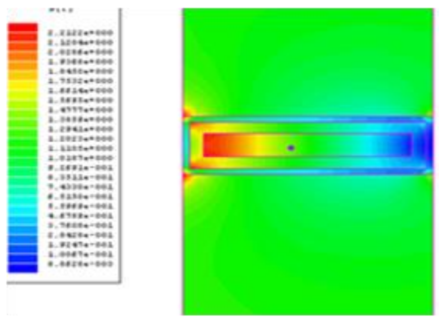

Fig. 6: Magnetic flux density in SS duct.

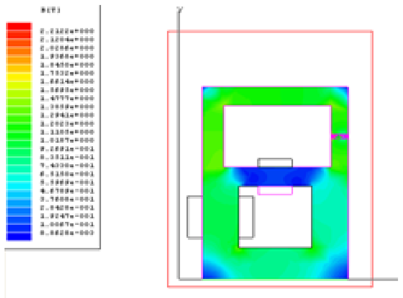

Fig. 7: Magnetic flux density in magnetic core

3.2 Manufacturing of ACCP

Manufacturing of ACCP was done and various components such as SS duct, primary windings, secondary windings of ACCP were tested at manufacturer's site. Chemical tests were conducted for material of all components of ACCP. Integrity of SS duct was checked both before and after welding with copper bar with pneumatic test (7 kg/cm^2 at room temperature using argon) and helium leak test. Manufactured ACCP is shown in Fig. 8, Fig. 9 and Fig. 10.

Fig. 8 : Side view of ACCP

Fig. 9: Front view of ACCP

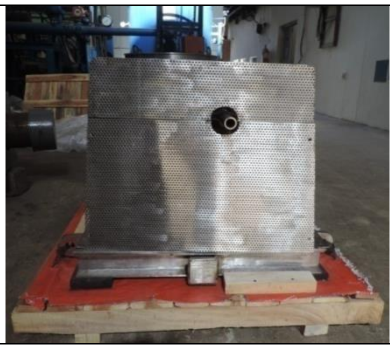

Fig. 10: ACCP with cover

4. Design and development of flowmeters

4.1 Design and Development of Samarium Cobalt based Permanent Magnet Flowmeter

Generally Alnico-V based Permanent magnet flowmeters (PMFMs) are used for flow measurement in pipes. Alnico-V based PMFMs become bulky and heavy when used for large pipes with diameter above 100 NB. As the sensitivity of such flowmeters is low, it leads to lower resolution in flow measurement. For future reactors, PMFM with Alnico-V magnet assembly is chosen for small pipes below 100 NB diameter. For sodium flow measurement in pipe lines 100 NB and above, PMFMs with high energy magnetic material such as Sm_2Co_{17} are used [6, 7]. A flowmeter for 100 NB pipe with samarium cobalt magnet assembly is designed, fabricated and tested in an existing sodium loop and the feasibility is established. Photograph of manufactured 100 NB SmCo flowmeter is shown in Fig. 11. Three dimensional modelling of SmCo 100 NB flowmeter is done using BH curves. Magnetic flux density in magnetic circuits of flowmeter is shown in Fig. 12

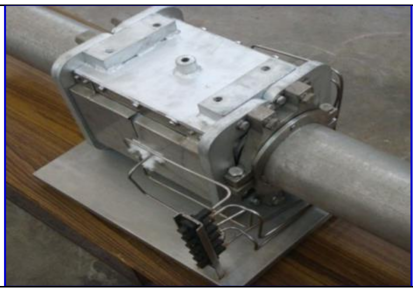

Fig. 11: 100 NB SmCo flowmeter

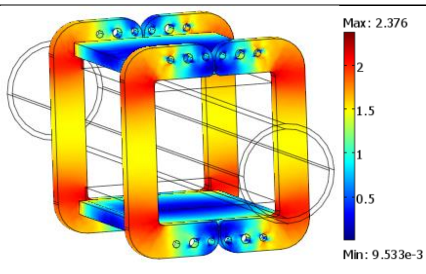

Fig 12: Magnetic flux density (T) in magnetic circuits of the flowmeter.

Sensitivity evaluation of SmCo based flowmeters was done with sodium experiments. Plots of SmCo PMFM sensitivity measured across three pairs of SS electrodes at 350 °C are shown in Fig. 13. Comparison of parameters of developed Alnico-V and SmCo PMFM are tabulated in Table-2

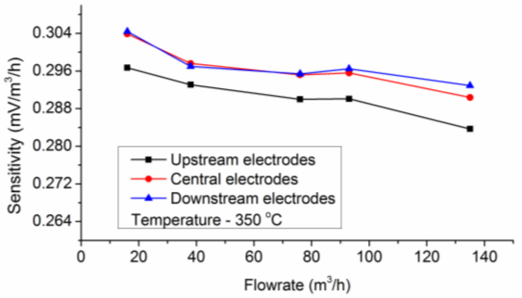

Fig.13: SmCo PMFM sensitivity verses flow rate at 350 °C.

TABLE 2 : COMPARISON SmCo AND ALNICO-V PMFM

Property	Alnico-5 PMFM	Sm_2Co_{17} PMFM
B_{avg} at center of SS pipe	0.0497 T	0.115 T
Magnet Temperature	<100 ºC	<100 ºC
Weight	110 kg	49.5 kg
Sensitivity	0.141 mV/m^3/h	0.285 mV/m^3/h
Volume of magnet	1512 cm^3	750 cm^3

It can be seen from Table 2 that SmCo flowmeter sensitivity increased by 102 % with net weight reduction of 55%.

4.2 Development and testing of Electromagnetic flowmeter flow meters

Permanent magnet flowmeters (PMFMs) are used in FBR for sodium flow measurement, due its simple construction and no requirement of power supply. However they are slightly bulky and have limitations in operation at high temperatures [8, 9]. Flow measurement at failed fuel location module demands operation at high temperature and compact flowmeter due to space constraints. Keeping this in mind development of an electromagnetic flowmeter was conceptualized. New design comprises of a SS pipe and a magnetic core made up of soft iron and MI cable. MI cable, which can withstand 550 °C, is wound on the soft iron magnetic core and is connected to a constant current DC supply to produce constant magnetic flux in magnetic core. Magnetic core is suitably mounted to produce transverse magnetic field perpendicular to flow of sodium. SS electrodes are mounted (welded) outside the SS pipe in diametrically opposite positions and perpendicular to the direction of both magnetic field and flow. The potential difference developed across the electrodes due to motion of liquid sodium in steady magnetic field is measured to obtain the flow of sodium in pipe. Photograph of EMFM is shown in Fig. 14. Sensitivity evaluation for EMFM was done at 250, 350, 450 and 550°C at different flow rates.

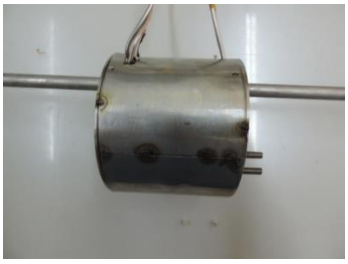

Fig.14: Photograph of EMFM

Sensitivity evaluation was done using Constant Volume Method. Fixed volume of sodium (0.505 m^3) was drained through EMFM pipe. Total mV seconds (mV.s) and the quantity of sodium drained was equated to obtain sensitivity of EMFM. Fig.15 shows typical EMFM output for flow rate of 1.4 m^3/h. Sensitivity of EMFM at different temperatures is shown in Fig. 16. It can be seen from Fig. 16, EMFM is having **s**ensitivity of 7.1 mV/m^3/h.

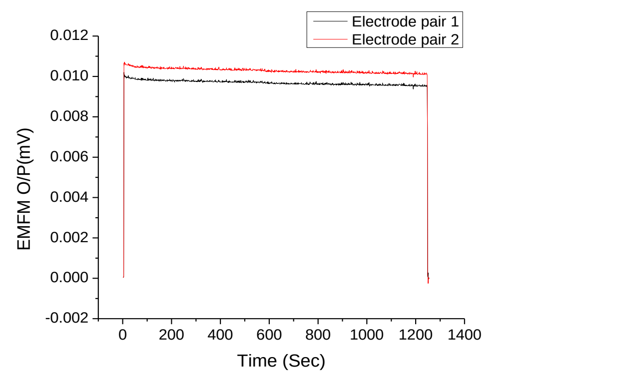

Fig.15: Typical EMFM output

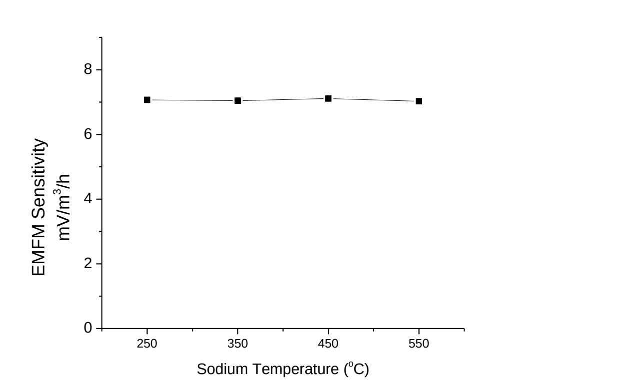

Fig.16 : Sensitivity of EMFM Vs Temperature

4.3 Design & Development of Probe Type Permanent Magnet Flow Sensor

Probe type Permanent Magnet Flow Sensor **(**PMFS) [10] offers an alternative for measuring the flow in large diameter pipes as conventional permanent magnet flowmeter (PMFM) requires magnets proportion to pipe size. Probe type PMFS mainly consists of a disk shaped permanent magnet, one pair of electrodes, an outer SS sheath. Figure 17 shows the cross sectional view of probe type PMFS. The disk shaped magnets are magnetized such that the magnetic field lines are perpendicular to sodium flow. The magnetic field extending into annular space induces voltage which is linear with flow velocity over a wide range. ALNICO-8 magnet has been chosen due to its excellent magnetic properties. To measure the electrical potential generated in sodium a pair of electrodes were welded with outer SS sheath. The electrodes are made up of MgO insulated stainless steel sheathed cable with SS conductor. Figure 18 shows the schematic of probe type PMFS. Figure 19 shows the photograph of probe type PMFS for calibration.

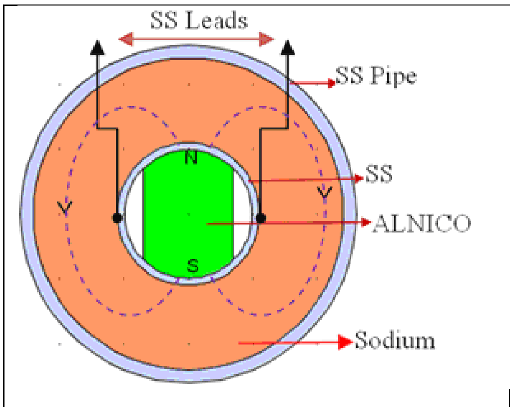

Fig. 17: Cross sectional view of the pipe with PMFS

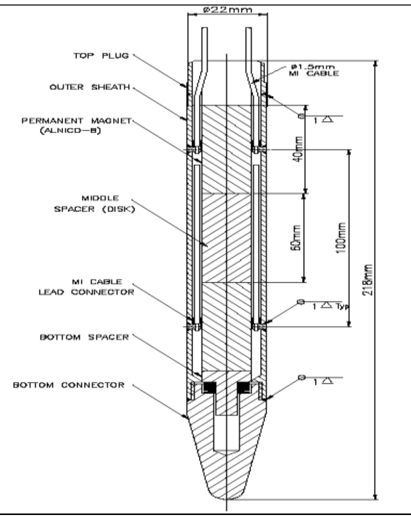

Fig. 18: Schematic of probe type PMFS

Fig. 19: Fabricated probe type PMFS for calibration

Sensitivity of PMFS was measured to be 0.306 mV / m^3 / h. Output of PMFS is found to be linear with flow in the range 10 m^3/h to 35 m^3/h and also stable in the temperature range 250 °C to 400°C. Output Vs flow for various temperatures is shown in Fig. 20. As output of PMFS is stable in the temperature range of application, it does not require temperature compensation and complex electronics for its working.

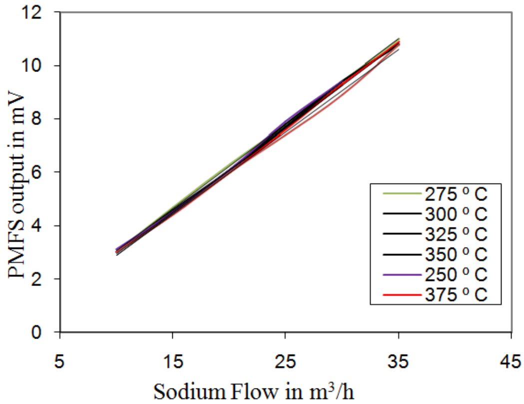

Fig. 20: PMFS output vs flow for various temperatures

5. Design & Development of Ex Vessel Discontinuous Level Probe

Mutual inductance type level probes are used for level measurement in fast breeder reactors and sodium experimental facilities. Discontinuous Mutual Inductance (MI) type level probes need insertion of level probe inside the vessel for measuring level of liquid sodium, hence require free space above the vessel for their insertion into the pockets [11]. To avoid insertion of level probe in vessels for measuring sodium level, a non invasive type Ex-vessel discrete level probe is designed, simulated and tested. Ex-vessel level probe consists of one primary winding and two differentially connected secondary windings wound on a magnetic core. The probe is placed outside a SS vessel in which presence of sodium is to be detected. Primary winding carries alternating high frequency excitation current, which produces an alternating magnetic field which passes from one leg to another leg of magnetic core through SS vessel and sodium. This magnetic field links with secondary coils and produces voltage in the secondary coil. When the sodium is present in vessel at the position where the level probe is placed, additional eddy currents are generated in sodium due to primary magnetic field. These circulating eddy currents generate their own field which opposes the primary magnetic field resulting in reduction of total flux linkage with secondary winding facing the SS vessel. Hence there is a reduction in secondary winding voltage facing SS vessel in comparison to secondary winding facing air. The sensitivity of level probe is defined as difference between secondary voltage with full sodium level and secondary voltages with no sodium level. Schematic of Ex-vessel level Probe is shown in Fig.21.

$$Sensitivity = Vs(withNa) - Vs(NoNa)$$

Vs = Output of differentially connected secondary windings.
$Vs_{(withNa)}$= Output of differentially connected secondary windings with Na in SS vessel.
$Vs_{(NoNa)}$= Output of differentially connected secondary windings without Na in SS vessel.

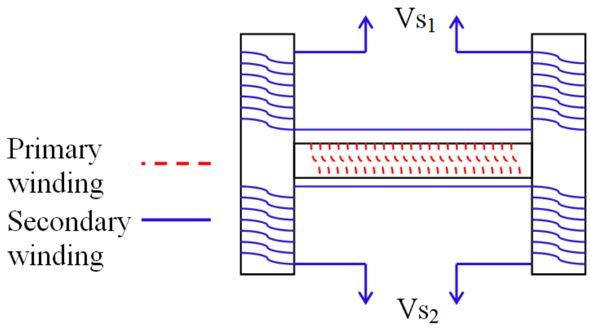

Fig. 21 : Schematic of Ex-vessel level Probe

5.1 Analysis & Experimental Results of Ex- Vessel Level Probe

Analysis for Ex- vessel level probe is done in COMSOL 3.5a. Primary windings of the probe are excited with a current source of constant amplitude and fixed frequency. Magnetic flux density generated due to constant alternating current in primary winding wound on central limb is shown in Fig. 22. Direction and amplitude of arrows show the direction of magnetic flux density and its amplitude in sensor. Ex vessel level probe was tested in Test Pot-1 of Thermal Shock Test Facility. Sodium temperature was varied from 200 ˚C to 500 ˚C. Level Probe output was recorded for full sodium and no sodium conditions. Frequency of input current to primary winding of probe is varied from 100 Hz to 3000 Hz to select the optimum frequency at which level probe shows maximum sensitivity. Sodium temperature is varied from 300 to 500 °C. It can be seen that level probe shows maximum sensitivity at 300 Hz. Variation in level probe sensitivity at different frequencies for different temperatures is shown in Fig. 23. It can be seen that sensitivity of level probe changes minimum with sodium temperature at 300 Hz. At 300 Hz, level probe sensitivity changes by 1.64 mV(6.6 % of max Value),when sodium temperature changes from 300 to 500 ˚C.

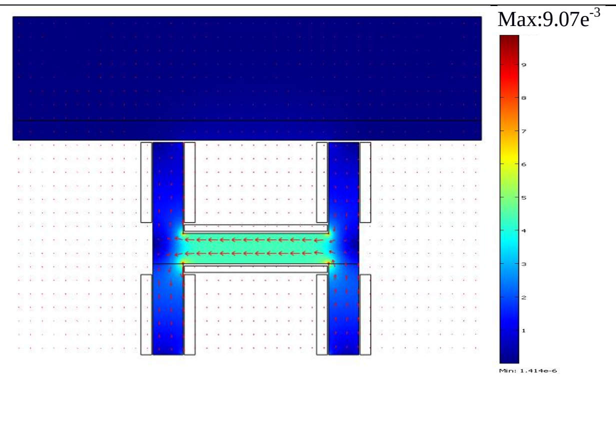

Fig.22 : Planar model in COMSOL.

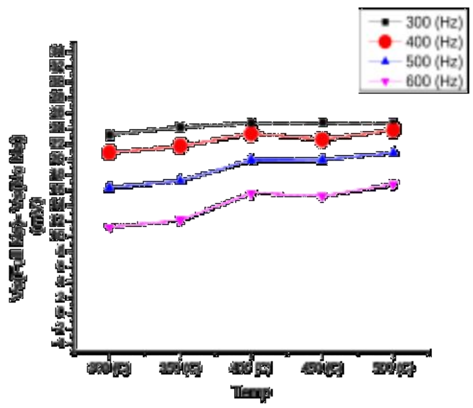

Fig. 23 : Variation in level probe sensitivity with temperature.

6. Conclusion

Various electromagnetic devices such as electromagnetic pumps, magnetic flow meters and sodium level probe recently developed for application in sodium cooled fast reactor are enumerated in this paper. The design and development of sodium submersible ALIP by employing MI cable for fabricating winding of ALIP has addressed the problem of development and non availability of high temperature electromagnetic pump (ALIP) for draining of primary radioactive sodium from main vessel of pool type sodium cooled fast reactor. The developed submersible ALIP can be also used for pumping sodium in integrated cold trap system submerged in primary sodium of pool type sodium cooled fast reactor and any other application where pumping is needed in pump submerged condition. Use of Samarium Cobalt magnet in flowmeter has facilitated reduction in weight and increase in sensitivity, similarly development of electromagnet based flowmeter has overcome constraints of high temperature operation. Probe type permanent magnet flowmeter overcomes measurement of sodium flow in large pipes. Development of eddy current based Ex-vessel allows the measurement of discrete sodium level in side vessel without need of penetration in the vessel. It also removes the constraints of requirement of over head space over the vessel for installation of conventional discrete level probe.

7. References

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