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Development of probe type permanent magnet flow sensor (PPFMS) for sodium flow measurement

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ABSTRACT

Sodium is used as coolant in Liquid Metal Fast Breeder Reactors (LMFBRs) because of its excellent nuclear, thermal and physical properties. Sodium flow measurement in various loops of the fast breeder reactor is of prime importance from the operational and safety aspects. Permanent magnet type flow meters and Electromagnetic type flow meters were widely used for sodium flow measurement in reactors. In certain applications where outside of the sodium pipes is not accessible to exterior-type flowmeters, it is desirable to use a probe type flowmeters. Special Probe type permanent magnet flow meters are utilized to measure the sodium flow in large diameter pipe line. These types of flow meters can also be used to monitor the coolant flow through fuel subassembly. In this context a prototype probe type

Permanent Magnet Flow Sensor (PPMFS) was designed and developed at Fast Reactor Technology Group (FRTG), Indira Gandhi Center for Atomic research (IGCAR).The performance of the probe was tested against high temperature operation in existing sodium loop in Steam Generator Test Facility (SGTF). This paper discuss about working principle of the sensor, development of PPFMS and a methodology for the calibration of this sensor and the corresponding results.

Keywords— *Probe type Permanent Magnet Flow Sensor; ALNICO-8, Calibration of probe, sodium flow*

1.0 INTRODUCTION

Measurement of sodium flow plays a vital role in various process requirements in addition to aiding the safe and reliable operation of sodium loops. The accurate measurement of sodium flow is very critical for safe operation of nuclear reactor, as reduction or absence in sodium flow may lead to severe accidents. Hence various type flowmeters i.e. Eddy current flowmeter (ECFM), Permanent magnet flowmeter (PMFM) have been designed, developed and deployed in primary as well as secondary circuits of sodium cooled fast breeder reactor.

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 [1] and in Phenix reactor in secondary circuits. Permanent magnet flow meters have also been used in loop type reactors like SNR-300, KNK, MONJU [2], 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 [1].

Sodium flow measurement in large diameter pipe is an important objective in reactor applications. Presently, the developed PMFMs are used to measure flows up to pipe size of 200 NB, but for larger pipe sizes its design becomes bulky. For very large diameter pipes (≥ 400 mm) the magnet dimensions become large for establishing a uniform magnetic field to reduce non-linearity in flow meter output. Probe type Permanent Magnet Flow Sensor (PPMFS) offers an alternate solution for measuring the flow without the above said drawbacks. The probe type flowmeter is inserted directly into the pipe through which the fluid flows in order to measure the velocity of fluid inside the pipe. In order to do the feasibility studies of the conceived design, it is decided to fabricate a single probe and test it in pipe sections of smaller diameter. Subsequently the probe was manufactured and its performance was qualified by high temperature sodium testing.

2.0 WORKING PRINCIPLE OF PPMFS

Probe type Permanent Magnet Flow Sensor works on the principle of Faraday's law of electromagnetic induction. Fig.1 shows the cross sectional view of pipe with PPMFS. The interaction of magnetic field with the moving electrical conductor (sodium) results in the generation of voltage. The induced voltage is a direct measure of the velocity, which was measured by pair of electrodes with simple electronics. The disk shaped ALNICO-8 magnets, magnetized in diametrical direction are contained in a non- magnetic stainless steel (SS) sheath of probe to which the electrodes have been welded. The magnetic field extending into annular space induces voltage which is linear with flow velocity over a wide range.

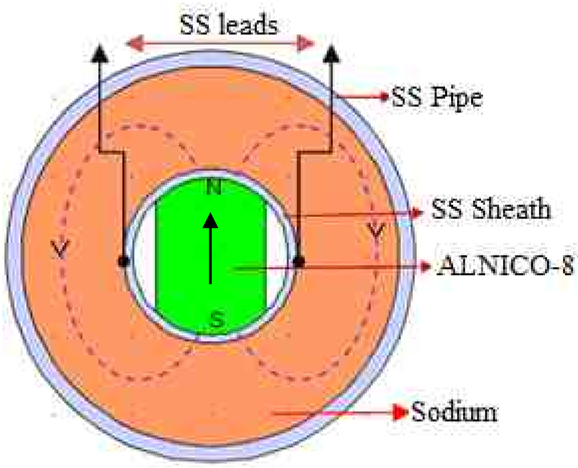

Figure 1- Cross sectional view of the pipe with PPMFS

3.0 CONSTRUCTION OF PPMFS ASSEMBLY

The PPMFS consists of probe adaptor, top plug, outer sheath, two disc shaped permanent magnet with two pairs of electrodes, middle spacer, MI cable lead connector, bottom spacer, spring and bottom connector. A groove has been provided in the probe ID in order to route the MI cable to the sensor electronics through the probe adaptor. The designed PPMFS is having a diameter of 22 mm and length 218 mm. Fig.2 shows the schematic view of probe type PMFS. Since the probe is directly immersed in sodium, magnet will be subjected to high temperature operation. Hence special care has been taken for selecting the magnetic material. Subsequently ALNICO-5 and 8 magnets were considered due to their operating temperature i.e 525 º C & 550 º C. ALNICO-8 magnet has been chosen for this particular sensor due to its excellent magnetic properties i.e remanance, coercivity, maximum energy product, operating temperature and Curie temperature. Stability of the ALNICO-8 magnet is much better than ALNICO-5 Studies on long time stability of ALNICO-8 magnet at different temperature (400 º C to 600 º C) was done by Muller [3]. The permanent magnets are assembled in such a way that magnetic field lines are perpendicular to sodium flow.

The interaction of magnetic field with moving electrical conductor (sodium) results in the generation of voltage which is measured by pair of electrodes. Mgo (Magnesium oxide) insulated stainless steel (SS) sheathed cable with SS conductor has been chosen as electrodes in order to withstand the high temperature sodium environment (550^{0}C). Similar materials were selected for both the probe as well as conductor is to avoid thermo electric effect. Electrodes were routed from inside of the probe through grooves which has been provided for electrode routing in order to avoid direct exposure of MI cable to sodium. Special care has been taken during electrode welding to avoid short circuit between probe outer sheath with the MI cable conductor.

It was envisaged that the field strength of permanent magnets alters due to aging at high temperature. This requires periodical recalibration of the flow sensor. In order to avoid removal of sensor for recalibration a suitable method for in-situ calibration is recommended. Calibration of PMFM by cross correlation is one such method. To facilitate this method two identical sensors in series separated by a stainless steel spacer was proposed and the same was fabricated. Length of the spacer is fixed to prevent the interaction between the magnetic fields of two magnets. Each magnet with one pair of electrodes will acts as a flow sensor. The probe with two flow sensors separated by a known distance will be used to determine the velocity of flowing sodium by transit time technique. This method will be used for recalibration of probe periodically. The major advantage of this method is the calculated velocity is independent of magnetic strength. The other reason for having two flow sensors in a single probe is redundancy and for sensitivity comparison.

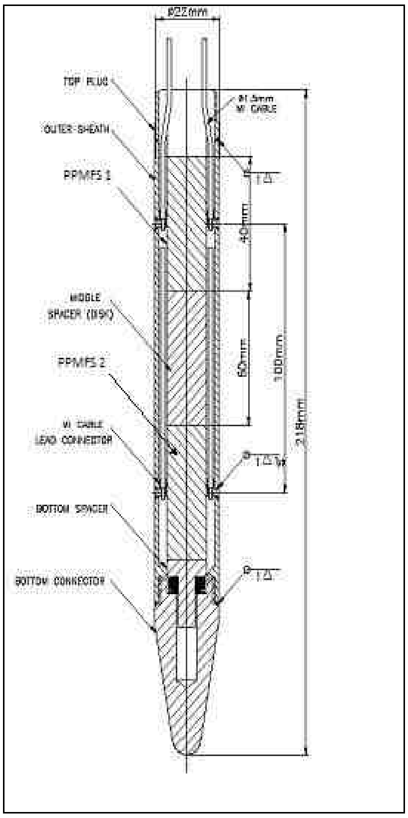

Figure 2 - Schematic view of probe type PMFS

4.0 FABRICATION OF PPFMS

Since the PPMFS consists of many intricate miniature parts the machining and fabrication was done using special purpose machines. To get maximum sensitivity output from the sensor the wall thickness of the outer sheath was decided to be 1 mm throughout the probe except for the groove region whose thickness is 0.5mm. The welding of the MI cable conductor with the lead connector and lead connector with probe outer sheath was more challenging due to its size. Due to the above said constraint laser welding technique was adopted. The weld joints were tested and qualified by helium leak test. All the other joints were also subjected to dye penetrant test and qualified. The critical Butt weld joints at the adaptor region whose size is 1” Sch. 40 pipe was radio graphed and qualified by Quality Assurance Division (QAD). Finally helium leak test under vacuum was carried out for the sensor assembly and leak rate observed was less than 10^{-8} Std cc/sec. Fig. 3. shows the photograph of probe type PMFS after fabrication.

Figure 3- Photograph of PPFMS after fabrication.

5.0 CALIBRATION SET UP

Probe type PMFS was calibrated in SGTF after making required modifications in the sodium circuit of SGTF. Fig.4 shows the test section for calibration of PPFMS and fig.5 shows the photograph of test section after PPMFS welding.

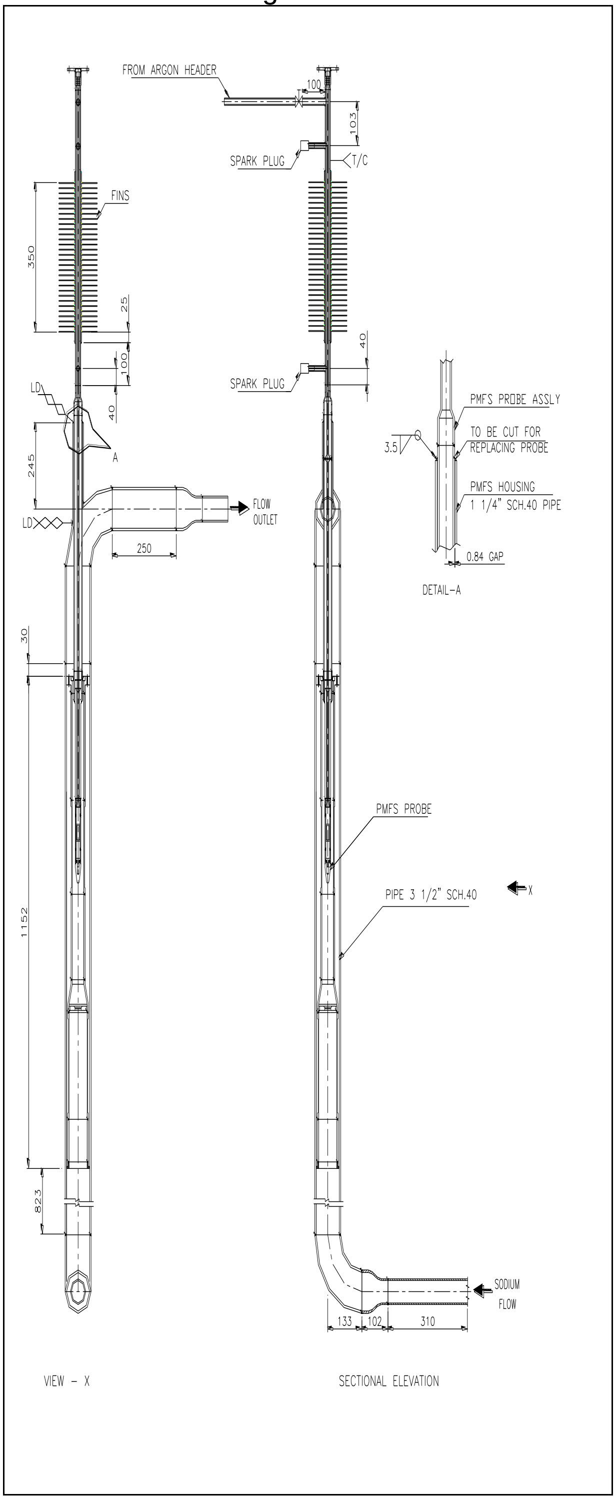

Figure 4 - Test section for calibration of PPFMS

Figure 5 - Photograph of PPFMS Test section in SGTF

6.0 SODIUM LOOP OPERATION

Fig. 6 shows the flow sheet of SGFT in FRTG, where the sensor was calibrated. This sodium loop was operated at the required flow by Annular Linear Induction Pump (ALIP) and the PPMFS was calibrated with reference to a reference Permanent Magnet Flow Meter (PMFM) (DFna2003) having a sensitivity of 0.141 mV/m^3/h and accuracy of $\pm$ 1.5%. Oil fired heater was in service as the heat source to maintain the sodium temperature and sodium to air heat exchanger (NaX) as the heat sink. Inert argon gas was maintained inside the probe and argon pressure monitored by pressure transmitter (TTar 2604). Cooling fins are provided at the top of PPMFS assembly to help freezing of sodium entering in case of failure of sensor welding. Spark plug type leak detectors are provided below and above the finned portion for the detection of sodium leak in the probe assembly. As an additional safety feature, thermocouple (DTms0359) is provided above the fins and it was continuously monitored. During calibration NaX bypass valve VPna2003 and ECFM drain valve VVna2045 was kept closed manually. SG tube was boxed up with nitrogen gas at 5 kg/cm^2.

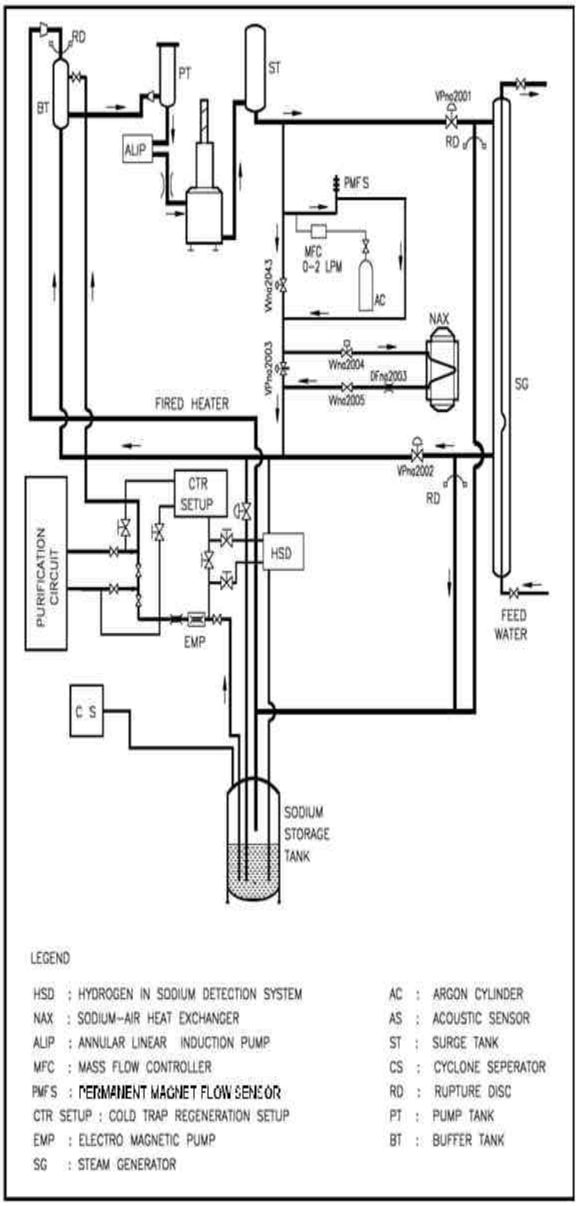

Figure 6 - Flow sheet of Steam Generator Test Facility

7.0 CALIBRATION OF PPFMS

During calibration, flow through the sensor was varied from 5 m^3/h to 35 m^3/h in steps of 5 m^3/h and the temperature of sodium was varied from 250 ^{o} C to 400 ^{o} C in steps of 25 ^{o} C. The milli-volt output measured from the electrodes of PPMFS 1 & 2 was compared with the reference PMFM located in the loop. Before varying the flow through the sensor, zero flow i.e static flow reading was recorded which is taken as back ground reading.

8.0 RESULTS AND DISCUSSION

Many experimental trials were taken by varying the parameters flow and temperature. The results of typical experimental campaign are discussed in this section. During this testing the flow through the sensor was varied from 5 m^3/h to 35 m^3/h and temperature of sodium was varied from 250 º C to 400 º C .The mV output generated by the two flow sensors (PPMFS 1 & 2) for various sodium flow as well as different temperatures were measured with two pairs of electrodes. The corresponding results were compared with reference PMFM (DFna 2003) located in SGTF sodium loop. The sensitivity of the PPFMS 1 and 2 was estimated to be 0.335mV/m^3/h and 0.342 mV/m^3/h. A detailed analysis was carried on PPMFS output in order to study the effect of flow on sensor output, effect of flow on sensitivity, effect of temperature on sensor output, effect of temperature on sensitivity. The performance of the sensor at all temperatures justifies the selection of permanent magnetic material for high temperature operation. The corresponding results are discussed below.

Effect of flow on sensor output

It was observed that as the flow through the sensor increases the output of both PPMFS 1 & 2 are increasing linearly. For establishing sensitivity of the sensor, sodium flow was varied from 5 m^3/h to 35 m^3/h in steps of 5 m^3/h. Both sensor outputs were recorded along with reference flow meter output. Sodium flow vs. PPMFS output at different temperature ranging from 250 º C to 425 º C in steps of 50 º C are shown in fig.7 to fig.10.It was observed that outputs of both the sensors are varying linearly with sodium flow.

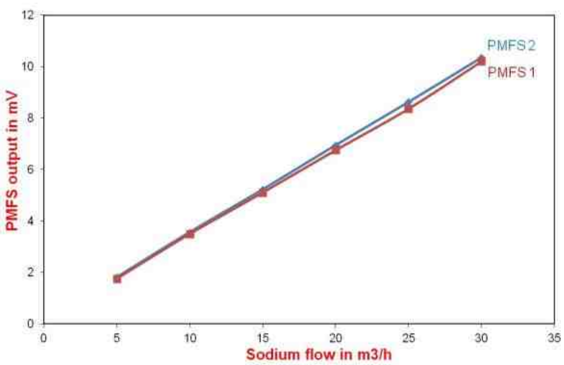

Figure 7- Sodium flow vs. PPMFS 1&2 output at 250 º C

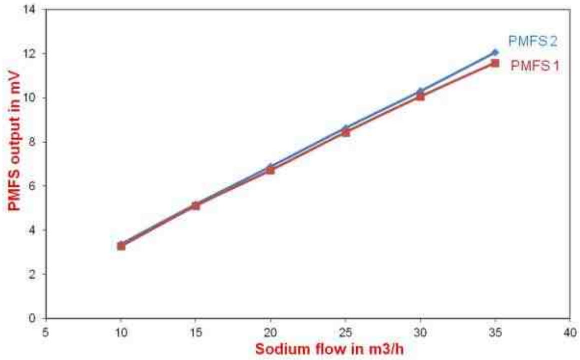

Figure 8 - Sodium flow vs. PPMFS 1&2 output at 300º C

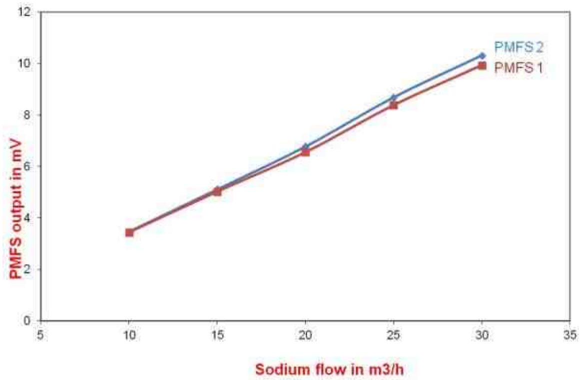

Figure 9- Sodium flow vs. PPMFS 1&2 output at 350 º C

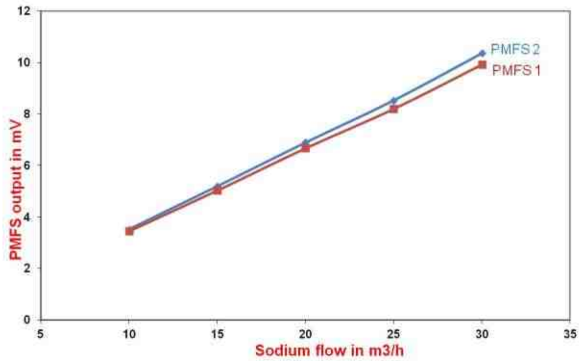

Figure 10 - Sodium flow vs. PPMFS 1&2 output at 400 º C

Effect of flow on sensitivity

Sensitivity of a PPMFS is defined as the ratio of milli-volt output for 1 m^3/h flow rate through the pipe. The unit of sensitivity is mV/m^3/h. It depends on electrical conductivity of fluid flowing through the pipe, size of the pipe & magnetic flux density across the pipe. The sensitivity of the PPFMS 1 & 2 was estimated to be 0.335mV/m^3/h and 0.342 mV/m^3/h. Sodium flow vs. sensitivity of PPMFS 1 & 2 was plotted for temperature of 400 º C is shown in the figure. Maximum non-linearity of sensitivity with respect to flow is 5.06%.

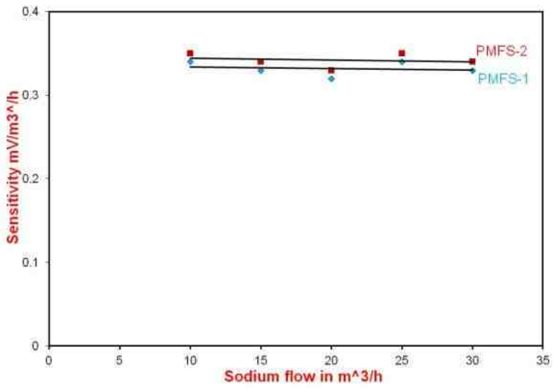

Figure 11 - Sodium flow Vs Sensitivity at 350 º C

Effect of temperature on sensor output

It was observed that the mV output generated from both the sensors is stable at all temperatures (250 º C - 400 º C). Hence flow can be measured without any temperature compensation. Sodium flow vs. output of PPMFS 1 & 2 for all temperatures were plotted and shown in Fig. 11&12. It was found that the output graphs were linear and following the same trend at all temperatures.

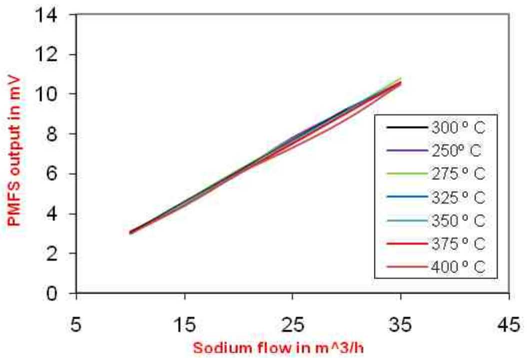

Figure 12- PPMFS -1 output at different temperatures

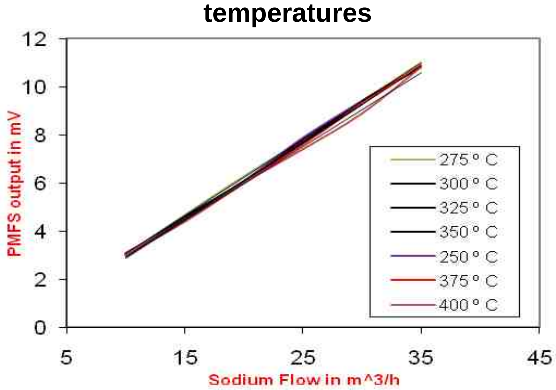

Figure 13- PPMFS - 2 output at different temperatures

Effect of temperature on sensitivity

It was observed that as the temperature increases slight deviation in sensitivity of both sensors. Temperature vs. sensitivity of both sensors was plotted for 35m3/h flow rate was shown in the fig.13. Maximum non-linearity of sensitivity with respect to temperature (250 ºC - 400 ºC) at a flow rate of 35m^3/h is found to be 2.9%

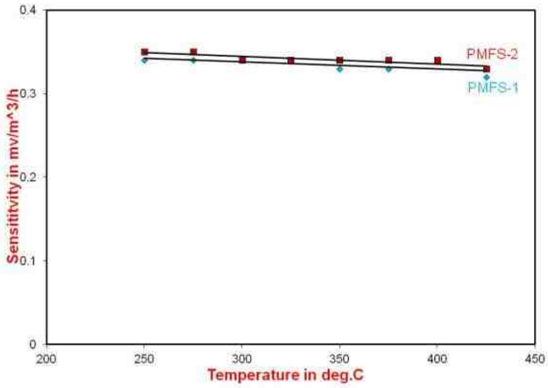

Figure 14 - Temperature vs. Sensitivity at 35m^3/h flow

9.0 CONCLUSION

A probe type PMFS towards the development of measurement of sodium flow in large diameter pipe lines was fabricated and calibrated in existing sodium loop in FRTG. Sensitivity of the PPMFS 1 & 2 was estimated to be 0.335 mV/m^3/h and 0.342 mV/m^3/h. The major advantage of this probe is, the output of the sensor is linear with respect to all flow i.e. from 10 m3/h to 35 m^3/h. The mV output generated by both the PPMFS was stable at all temperatures i.e. 250 º C - 400 º C. Hence flow can be measured without any temperature compensation as well as any complex electronics.

10.0 FUTURE WORKS

Since the performance of the PPMFS is satisfactory, it is proposed to fabricate three numbers of similar probes. Subsequently the probes will be calibrated in existing sodium loops in FRTG. The probes in triple arrangement will be used for measurement of sodium flow in large diameter pipes. In addition, feasibility studies towards velocity measurement using transit time technique and sodium void detection are being planned.

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