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Development of Large Compact PM Flowmeters for Fast Breeder Reactors

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Abstract

Sodium flow measurement in various loops of the reactor is of prime importance from the operational and safety point of view. Permanent Magnet Flow Meters (PMFM) and Eddy Current Flow Meters (ECFM) are used to measure the sodium flow in sodium cooled Fast Breeder Reactor Circuits. PM flowmeter is a non-invasive device, which works on the principle of generation of motional EMF by magnetic forces exerted on the charges in a moving conductor. The conventional PM flowmeters which uses ALNICO-5 magnets are found to be bulky, heavy and occupies more plant space and leads to other related mechanical problems. R&D activities were initiated in IGCAR to optimize the design of magnetic circuit and make the flowmeter compact for the future fast breeder reactors. Towards this, development of PM flowmeters with rare earth magnets and development of side wall flowmeters for pipe size 100NB and 200NB are taken up. Design, manufacturing and sodium testing of 100 NB samarium cobalt PM flowmeter, 100 NB side wall PM flowmeter and 200 NB samarium cobalt PM flowmeter were completed. Feasibility of manufacturing compact PM flowmeters suitable for high temperature sodium flow measurement with SmCo magnet assembly and a new concept of flow measurement with side wall flowmeter were demonstrated. This paper describes about the details of the R&D activities carried out for development of large compact PM flowmeters for future Fast Breeder Reactors.

Key words: Sodium flow measurement, Permanent Magnet Flow Meter, Fast Breeder Reactor, optimize the design, compact flowmeter, rare earth magnets, side wall flowmeter,

1. INTRODUCTION

Liquid sodium is used as the coolant in Fast Breeder Reactors (FBRs) due to its favourable nuclear properties and excellent heat transfer properties. Permanent Magnet Flow Meter (PMFM) is used to measure the sodium flow in the reactor Circuits. The principle of operation of the magnetic flowmeters is similar to that of a DC generator and is based on the Faraday's law of electromagnetic induction. Sodium flow measurement in various loops (15 NB to 800 NB) of the reactor is of prime importance from the operational and safety aspects. A magnetic flowmeter basically consists of a pipe made of a non-magnetic material mounted in the transverse magnetic field between the two poles of a permanent magnet structure. Electrical contacts (electrodes) positioned diametrically opposite each other are welded to the outer surface of the pipe, with their central axis oriented normal to the direction of the lines of magnetic field and flow. A small DC voltage is developed across the electrodes by the conductive liquid metal (sodium) as it flows through and cuts the magnetic field. The magnitude of DC voltage is directly proportional to the velocity of the liquid, and the polarity is determined by the direction of liquid flow. Principle of operation of flowmeter is given in Fig.1 [1].

The conventional PM flowmeters which uses ALNICO-5 magnets are found to be bulky, heavy and occupies more plant space and leads to other related mechanical problems. PM Flowmeters of size 100 NB and above are considered as large flowmeters. R&D activities were initiated to optimize the design of magnetic circuit and make the flowmeter compact for the future fast breeder reactors [2]. Towards this, development of PM flowmeters with rare earth magnets [3,4,5] and development of side wall flowmeters for pipe size 100NB and 200NB are taken up. Design, manufacturing and sodium testing of 100 NB samarium cobalt PM flowmeter, 100 NB side wall PM flowmeter and 200 NB samarium cobalt PM flowmeter were completed. Feasibility of manufacturing compact PM flowmeters suitable for high temperature sodium flow measurement with SmCo magnet assembly and a new concept of flow measurement with side wall flowmeter were demonstrated. This paper describes about the details of the design, manufacture and sodium testing of 100 NB SmCo PM Flowmeter, 100 NB sidewall PM flowmeter and 200 NB SmCo PM flowmeter for future Fast Breeder Reactors.

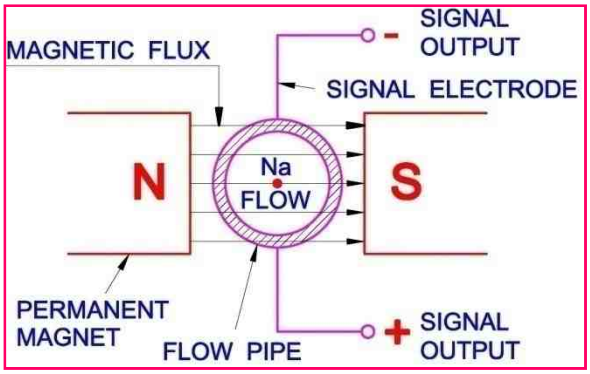

Fig.1: Magnetic flowmeter principle

2. COMPARISON OF ALNICO-5 AND SmCo MAGNET PROPERTIES [3]

Rare earth permanent magnet material like Samarium Cobalt (SmCo) is having higher coercivity and energy product than ALNICO-5. Table.1 gives the comparison of ALNICO-5 and SmCo magnetic properties.

Table 1: Comparison of ALNICO-5 and SmCo magnetic properties

Sl. No.	Details	ALNICO -5	SmCo 26
1	Remanance (Br) Gauss	12500	10500
2	Coercivity (Hc) Oersted	650	9000
3	Peak energy product (BH) max G.x Oe	5.25×10^6	26×10^6
4	Curie temperature ºC	870	825

3. TEMPERATURE STABILITY TEST OF SmCo MAGNET ASSEMBLY

Magnetic field of the magnet used in the PM flowmeter is mainly influenced by time, temperature and external field. To get a stable flux density at the operating temperature of the magnet in the air gap, it is necessary to do the temperature stabilization of the magnet assembly. This can be done by rapid heating and cooling cycles (RHC), gradual heating and cooling cycles (GHC) and endurance test at the operating temperature till a stable flux density value is obtained. Two Samarium Cobalt magnet assemblies were used for stability testing of the magnet. Long term stability of the magnet assembly at operating temperature was tested by keeping the magnet assembly in the furnace at 100℃ for 5000 hours and was observed that flux density remains steady [6]. Accelerated long term stability test at 200℃ for 10000 hours was also completed and found that no significant reduction in flux density. Stability of the magnet with time and temperature is found to be good. Since the presence of magnetic material nearby will disturb the magnetic field and in turn will affect the sensitivity, an exclusion zone is defined around the PM flowmeter so as to avoid presence of any magnetic material in that zone. Fig.2 gives the photographs of the Samarium Cobalt magnet assembly. Fig.3 gives the time vs flux density curve.

Fig.2: SmCo Magnet assembly

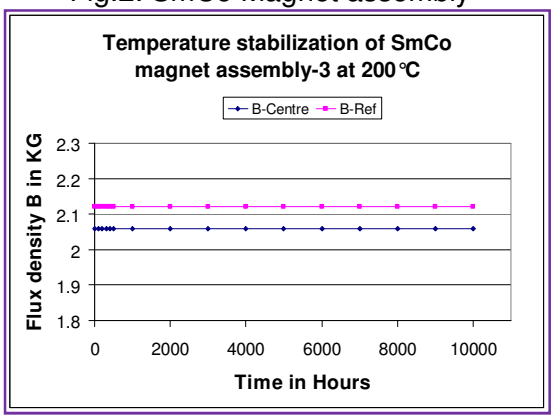

Fig.3: Time vs flux density curve

4. DEVELOPMENT OF 100 NB PM FLOWMETER WITH SmCo MAGNET ASSEMBLY

4.1 PM FLOWMETER DETAILS

a. Pipe size: Internal diameter : 102.3 mm
External diameter: 114.3 mm
Overall length : 1000 mm
b. Type : Single wall
c. Sodium Temperature : 550 °C
d. Internal pressure : 11 Bars
e. Flow range : 0-105 m^3 / h
f. Pairs of Electrode : 3
g. Principal Signal : 30 mV
(Signal level for Max. flow)
h. Mounting : Horizontal
i. Magnet temperature : 100 °C
j. Magnet material : Samarium Cobalt

4.2 DESIGN, MANUFACTURE AND TESTING DETAILS [7]

Samarium Cobalt material is selected for making the flowmeter magnet assembly due to its superior magnetic properties like high coercive force, high energy product and temperature stability. When the flowmeter is operating at a sodium temperature of 550˚C, magnet temperature will be around 100℃. Maximum operating temperature of Sm_2Co_{17} is 300℃ which gives good margin. Magnet assembly design was arrived based on the basic equations and manufacturing experience. Three dimensional model for 100 NB SmCo flowmeter made up with SmCo and soft iron was simulated in COMSOL 3.5a. Three dimensional model of 100 NB Samarium Cobalt magnet assembly flowmeter is shown Fig.4.

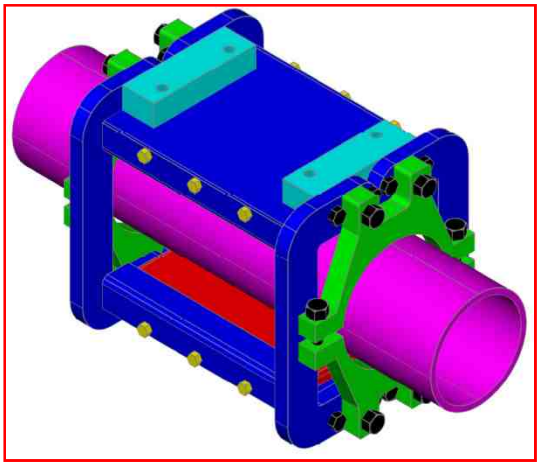

Fig.4: Three dimensional model of 100 NB PMFM

Fig.5: 100 NB PMFM after manufacture

Based on this design, detailed fabrication and assembly drawing and technical specification was prepared.

Magnetic assembly is of double magnetic circuit. Magnets are integral part of pole face. Rectangular blocks of 50 x 50 x 12.5 mm size, magnetically oriented along 12.5 mm, are selected for the flowmeter magnet assembly. 24 blocks have been used for making the assembly. Pole face length, pole face width and air gap are fixed as 225, 166 and 141 mm respectively. Three pairs of electrodes are welded to the stainless steel pipe. Photograph of 100 NB PM flowmeter after manufacture is given in Fig.5. Temperature stabilization of the magnet assembly was carried out by conducting rapid and gradual heating and cooling cycles at 150°C until a steady flux density value is obtained at the reference point. Flux density at different planes in the air gap was measured and average flux density value found to be 0.11 Wb/m^2. This flowmeter was installed in a sodium facility and sodium testing was completed at three different temperatures of 250, 350 & 450°C and at five different flow rates. The sensitivity evaluation was carried out by volumetric method. Flow trace during sodium draining is given in Fig.6 and average flow vs PMFM output is given in Fig.7. It was found that all the electrode pairs of the flowmeter are giving uniform millivolt outputs. The estimated sensitivity of the flowmeter based on sensitivity evaluation was found to be 0.285 $mV/m^3/h$ and accuracy of flowmeter is well within 2%.

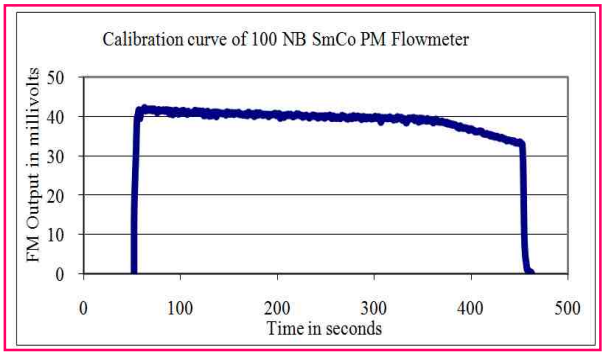

Fig.6: Flow trace

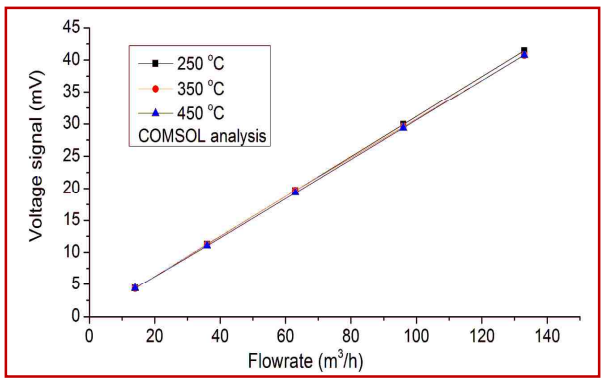

Fig:7: Average flow vs PMFM output

4.3 COMPARISON OF 100 NB ALNICO-5 AND SmCo PMFM

Comparison of 100 NB ALNICO-5 and SmCo PMFM is given in Table 2. It was observed that overall weight reduction of the flowmeter was found to be 55% and at the same time increase in sensitivity was 102%.

Table 2: Comparison of ALNICO-5 and SmCo 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 $mV/m^3/h$

5. DEVELOPMENT OF 100 NB SIDE WALL PM FLOWMETER (SWFM)

5.1 FLOWMETER DETAILS

a. Pipe size: Internal diameter : 102.3 mm
External diameter: 114.3 mm
Overall length : 400 mm
b. Type : Single wall
c. Sodium Temperature : 550 °C
d. Internal pressure : 11 Bars

e. Flow range : 0-105 m^3 / h
f. Pairs of Electrode : 2
g. Principal Signal : 10 mV
(Signal level for Max. flow)
h. Mounting : Horizontal
i. Magnet temperature : 100 °C
j. Magnet material : ALNICO-5

5.2 DESIGN, MANUFACTURE AND TESTING DETAILS [8]

In permanent magnet based SWFM, a permanent magnet block is mounted on one side of the large pipe, the magnetic field penetrates through the pipe and interacts with the flowing sodium and induces a motional voltage proportional to the flow. This is a compact, cost effective, reliable and accurate method for flow measurement in large pipelines of FBR circuits. SWFM is suitable for pipelines of 100 mm and above. In the present work, one SWFM, in which a permanent magnet block mounted on one side of SS pipe of 100 mm diameter is designed, fabricated and analyzed. The SWFM consists of a single ALNICO-5 magnet block of size 200×140×35 mm. One side of the magnet block (200×35 side) is cast to have a curved surface matching to the pipe outer diameter profile and mounted on the 100 NB pipe with thermal insulation of 5 mm thickness between the magnet and the pipe. The magnet is clamped on the pipeline with SS bolts and nuts. Mineral insulated SS sheathed, SS conductor of size 4 mm is used as electrode. The SS core conductor of size 1.2 mm diameter is welded outside the SS pipe on either side of the magnet block at an angle of 60 and 120 degrees, in line with the centre of the magnet block. Three dimensional FEM modeling of SWFM is done in COMSOL 3.5a software. Three dimensional model of SWFM is shown in Fig.8. Photograph of SWFM is shown in Fig.9.

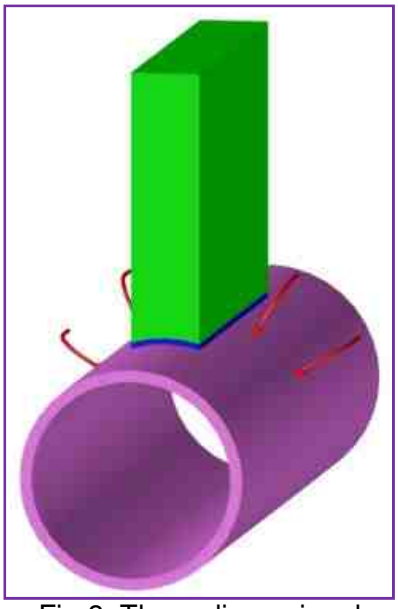

Fig.8: Three dimensional model of SWFM

Fig.9: Photograph of SWFM

This flowmeter was installed in a sodium facility and sodium testing was completed at three different temperatures of 250, 350 & 450°C and at five different flow rates. The sensitivity evaluation was carried out by volumetric method. It was found that both the electrode pairs of the flowmeter are giving measurable millivolt outputs. The estimated sensitivity of the flowmeter based on sensitivity evaluation was found to be 0.059 mV/m^3/h and accuracy of flowmeter is well within 2%. The feasibility of use of this type of flowmeter for large pipelines of FBRs was demonstrated. Flow trace during sodium draining is given in Fig.10 and flow rate vs SWFM output is given in Fig.11.

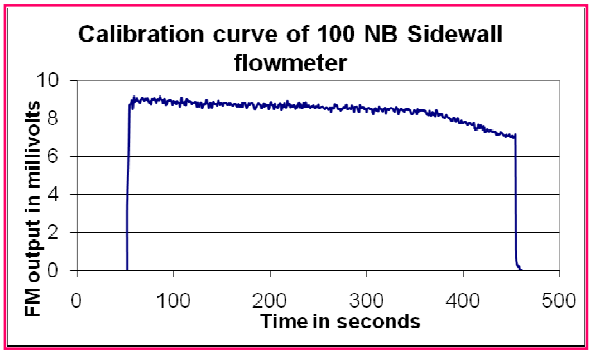

Fig.10: Flow trace

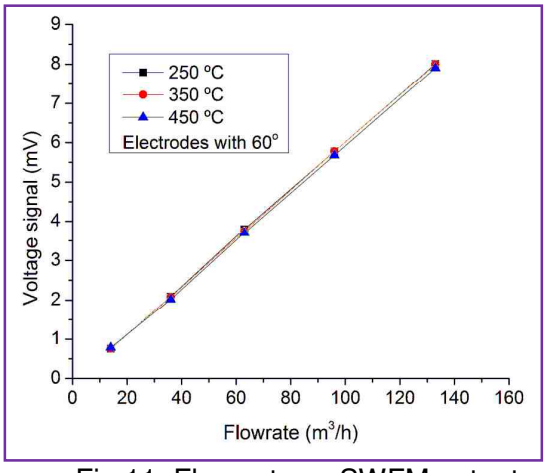

Fig.11: Flow rate vs SWFM output

6. DEVELOPMENT OF 200 NB SmCo BASED PM FLOWMETER

6.1 PM FLOWMETER DETAILS

a. Pipe size: External diameter : 219.1 mm
Internal diameter : 202.74 mm
Overall length : 1100 mm
b. Type : Single wall
c. Sodium Temperature : 550 °C
d. Magnet temperature : 100 °C
e. Magnet material : Samarium Cobalt
f. Internal pressure : 11 bars
g. Flow range : 0- 600 m^3 / h
h. Pairs of Electrode : 3
i. Principal Signal : 60 mV
(Signal level for Max. flow)
j. Mounting : Horizontal

6.2 DESIGN, MANUFACTURE AND TESTING DETAILS [7]

One of the difficulties faced with 200 NB flowmeters with ALNICO-5 magnet assembly is their relatively large weight and size. The higher weight led to various handling difficulties, excessive load on piping and difficulties in supporting the flowmeter. As part of R & D on sodium flow measurement, different possibilities for making the flowmeter compact and of low weight were attempted. Samarium Cobalt material is selected for making the flowmeter magnet assembly. Magnet assembly design was arrived based on the basic equations and manufacturing experience. Three dimensional finite element modelling (FEM) using Comsol 3.5a was done to establish the flux density distribution in SS piping. Three dimensional model of SmCo PMFM is shown in Fig.12. SmCo permanent magnets were simulated using their demagnetising curve and mild steel blocks were simulated using BH curve of soft iron. Based on this design, detailed fabrication and assembly drawing and technical specification was prepared. Magnetic assembly is of double magnetic circuit. Magnets are integral part of pole face. Rectangular blocks of 50 x 50 x 12.5 mm size, magnetically oriented along 12.5 mm, are selected for the flowmeter magnet assembly. 108 blocks have been used for making the assembly. Pole face length, pole face width and air gap are fixed as 512, 317 and 240 mm respectively. Three pairs of electrodes are welded to the stainless steel pipe. Temperature stabilization of the magnet assembly was carried out by

conducting rapid and gradual heating and cooling cycles at 150°C until a steady flux density value is obtained at the reference point. Weight of the 200 NB SmCo flowmeter was found to be 183 kg. Flux density at different planes in the air gap was measured and average flux density value found to be 0.07 Wb/m^2. Photograph of 200 NB SmCo PMFM is given in Fig.13

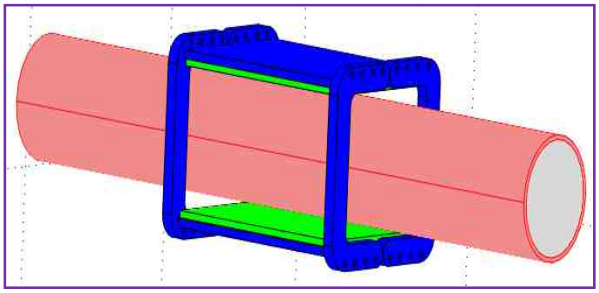

Fig.12: Three dimensional model of 200 NB PMFM

Fig.13: Photograph of 200 NB PMFM

Sodium testing of 200 NB SmCo PM flowmeter was completed with three different sodium flows and sodium temperatures. Readings acquired during sensitivity evaluation were processed and sensitivities obtained at different sodium temperatures and flows were tabulated. Sensitivity of this flowmeter was evaluated by constant volume method. Accuracy of the sensitivity evaluation is well within ±2%. It was found that all the electrode pairs of the flowmeter are giving uniform millivolt outputs. Average sensitivity based on sensitivity evaluation was found to be 0.0898 mV/m^3/h. Weight and sensitivity of the 200 NB SmCo flowmeter is found to be 183 Kg and 0.0898 mV/m^3/h respectively. Flow trace during sodium draining is given in Fig.14 and flow rate vs flowmeter output is given in Fig.15.

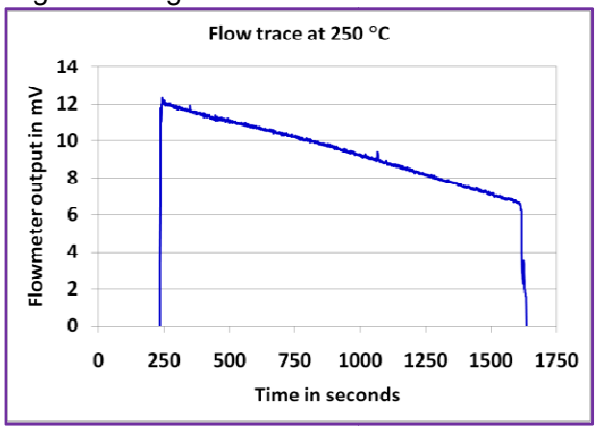

Fig.14: Flow trace

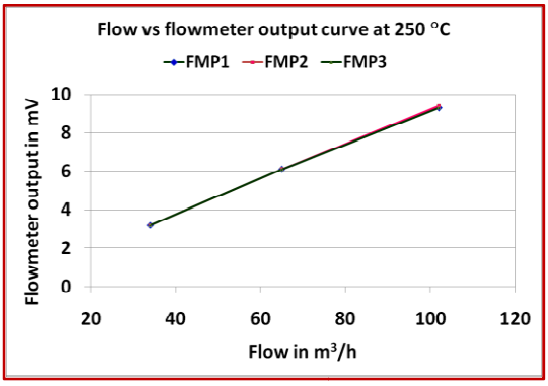

Fig.15: Flow rate vs SWFM output

6.3 COMPARISON OF ALNICO-5 AND SmCo PM FLOWMETER

Comparison of 200 NB ALNICO-5 and SmCo PMFM is given in Table 3. The sensitivity of the 200 NB SmCo flowmeter is 40% higher and the overall weight is 37% lesser than that of ALNICO-5 based 200 NB flowmeter.

Table 3: Comparison of ALNICO-5 and SmCo PMFM

Property	ALNICO-5 PMFM	Sm_2Co_{17} PMFM
B_{avg} at center of SS pipe	0.04 T	0.07 T
Magnet Temperature	<100 ºC	<100 ºC
Weight	290 kg	183 kg
Sensitivity	0.064 mV/m^3/h	0.0898 mV/m^3/h

7. CONCLUSION

The large size PM flowmeters which uses ALNICO-5 magnets are found to be bulky, heavy and occupies more plant space. R&D activities were initiated to optimize the design of magnetic circuit and make the flowmeter compact for the future fast breeder reactors. Design, manufacturing and sodium testing of 100 NB samarium cobalt PM flowmeter, 100 NB side wall PM flowmeter and 200 NB samarium cobalt PM flowmeter were completed. It was observed that overall weight reduction of the 100 NB SmCo PM flowmeter was found to be 55% and at the same time increase in sensitivity was 102%. The estimated sensitivity of the 100 NB side wall type flowmeter based on sodium calibration was found to be 0.059 $mV/m^3/h$. The sensitivity of the 200 NB SmCo flowmeter is 40% higher and the overall weight is 37% lesser than that of ALNICO-5 based 200 NB flowmeter. Hence the feasibility of using compact flowmeter for large pipelines of FBRs was demonstrated.

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