Annals of Nuclear Energy 87 (2016) 74–80

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Sodium flow measurement in large pipelines of sodium cooled fast breeder reactors with bypass type flow meters

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ARTICLE INFO

Article history:
Received 18 February 2015
Received in revised form 7 August 2015
Accepted 16 August 2015
Available online 3 September 2015

Keywords:
Sodium flow measurement
Bypass flow meter
Electromagnetic flow meter
Fast breeder reactor

ABSTRACT

Liquid sodium flow through the pipelines of sodium cooled fast breeder reactor circuits are measured using electromagnetic flow meters. Bypass type flow meter with a permanent magnet flow meter as sensor in the bypass line is selected for the flow measurement in the 800 NB main secondary pipe line of 500 MWe Prototype Fast Breeder Reactor (PFBR), which is at the advanced stage of construction at Kalpakkam. For increasing the sensitivity of bypass flow meters in future SFRs, alternative bypass geometry was considered. The performance enhancement of the proposed geometry was evaluated by experimental and numerical methods using scaled down models. From the studies it is observed that the new configuration increases the sensitivity of bypass flow meter system by around 70%. Using experimentally validated numerical tools the volumetric flow ratio for the bypass configurations is established for the operating range of Reynolds numbers.

1. Introduction

Sodium cooled fast breeder reactors (SFR) are envisaged in the second phase of Indian nuclear power program. Liquid sodium is used as the coolant in SFRs, due to its favorable nuclear properties, excellent heat transfer properties and compatibility with structural materials such as stainless steel. Sodium flow in primary and secondary circuits of the reactor needs to be measured to meet the operational, protective and safety functions. Choice of flow sensors required for the primary circuit of pool type SFRs is governed by their capability to withstand high temperature, nuclear radiation and chemically reactive environments. Secondary circuits and safety grade decay heat removal (SGDHR) circuits of 500MWe Prototype Fast Breeder Reactor (PFBR) (Chetal et al., 2006), need flow measurement in stainless steel pipes of diameter varying from 15 mm to 800 mm. Because of the good electrical conductivity of liquid sodium, electromagnetic methods are effectively used for measurement of sodium flow in both primary and secondary circuits of the reactor (Shercliff, 1962; Hemp and Versteeg, 1986). In PFBR, primary sodium flow is measured by eddy current flow meter (ECFM) (Sharma et al., 2010). Alnico-V based permanent magnet flow meters (PMFM) are used for the measurement of sodium flow through small pipelines up to 200 mm diameter. For large pipelines, PMFM become bulky, heavy and have installation problems. Different flow measurement techniques are considered for large sodium pipelines of SFRs as follows.

1.1. Large EM flow meter

Internationally, during the initial periods of SFR development, conventional permanent magnet flow meters and saddle coil type electromagnet flow meters were considered for flow measurement in small and large diameter pipes. Saddle coil type EM flow meter (Thatcher et al., 1980) of 355 mm diameter was used in prototype fast reactor (PFR) and Alnico-V permanent magnet flow meter (Devita, 1980) of 400 mm pipe diameter was developed for using in Fast Flux Test Facility (FFTF) reactor in US. But conventional EM flow meters for large pipelines become too bulky and heavy, inaccurate, low sensitive and occupy large space (Hans et al., 1979; Thatcher et al., 1980).

1.2. Eddy current flow meter

The local velocity of sodium in the large pipe cross section can be measured using eddy current type flow sensor introduced into the pipe. The volumetric flow rate can be estimated from the measured local velocity by proper calibration techniques. Eddy current flow meters can withstand high temperatures, but requires penetration in the main pipe. This method was developed by Inetratom, Germany for flow measurement in ducts of large nominal bore (Joachim Knak et al., 1980). The requirement of complex electronic

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http://dx.doi.org/10.1016/j.anucene.2015.08.018
0306-4549/

Nomenclature

a	proportionality constant for PMFM
B	magnetic flux density, T
b	proportionality constant for bypass flow measurement system
C	calibration constant for bypass flow meter
D	diameter of main line, m
d	inside diameter of bypass line, m
E	induced voltage, mV
F_m	volumetric flow ratio
k_m	resistance loss coefficient for friction in main line
k_{fri}	resistance loss coefficient for friction in bypass line
k_e	resistance loss coefficient at entry and exit of pipe
k_{be}	resistance loss coefficient due to bends in bypass pipe
k_{red}	resistance loss coefficient due to reducers
Q	volumetric flow rate in main line, m^3h^{-1}
q	volumetric flow rate in bypass line, m^3h^{-1}
V	mean velocity in main line, ms^{-1}
v	mean velocity in bypass line, ms^{-1}
Δp_{by}	pressure drop bypass line, Pa
Δp_m	total pressure drop in main line, Pa

circuits for the constant current source and for the temperature compensation makes the eddy current flow meters less attractive.

1.3. Side wall flow meter

Permanent magnet based side wall flow meter (SWFM) with Alnico-V magnet block is passive, non invasive and does not require any special welding or penetration in the pipe. The stability of Alnico-V permanent magnet with respect to time and temperature is studied in detail as a part of Alnico-V PMFM development (Rajan and Vijayakumar, 2014). SWFM is very compact and reliable but sensitivity is low and sensitivity estimation is difficult due to non uniform magnetic field in the flow meter duct.

1.4. Ultrasonic flow meter

Ultrasonic flow meter is a non invasive method for liquid sodium flow measurement. For higher temperature applications, suitable wave injectors are required. Requirement of wave injectors, special couplant during high temperature operation and the need of advanced signal processing electronics are the main drawbacks of ultrasonic flow meters.

1.5. Bypass type flow meter

The volumetric sodium flow in the large pipeline can be estimated using the measured volumetric sodium flow in the bypass line and the predetermined ratio of main flow to bypass flow. Bypass flow meters give fairly good accuracy and sensitivity for liquid sodium flow measurements in large pipe. The hydraulic characteristics of the bypass flow system can be calibrated by simulated hydraulic experiments. Alnico-V based PMFM is used as the sensor for the flow measurement in bypass circuit, which can be conveniently calibrated in sodium. Adequate study has been done on Alnico-V based flow meters and their manufacturing methods. Long term stability of Alnico-V permanent magnet in operating condition is well established and same is used in bypass flow meter (Rajan and Vijayakumar, 2014). However it is an invasive method of sodium flow measurement and the flow ratio of the system is variable with respect to the sodium velocity in the main line.

Considering the simplicity, large amount of experience with PMFM and the passive nature of operation bypass type flow meter is selected for flow measurement in the 800 NB main secondary sodium pipe line of PFBR from the available sodium flow measurement methods for large sodium pipe lines. Table 1 shows the pipe flow measurement methodology followed for existing Indian SFRs and the methodology proposed for reactors under design.

PMFM works on the principal of Faraday's law of electromagnetic induction. A PMFM basically consists of a pipe made of a non-magnetic material mounted in the transverse magnetic field between the two poles of a magnet structure. Electrodes positioned diametrically opposite to 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 D.C. voltage in the order of a few mV is developed across the electrodes by the conductive liquid metal (sodium) as it flows through and cuts the magnetic field. The magnitude of the D.C. voltage developed is directly proportional to the velocity of the liquid, magnetic flux density in the pipe cross section through which sodium is flowing and the internal diameter of the pipe. The polarity of the induced emf is determined by the direction of liquid flow. Fig. 1 shows the schematic of PMFM.

The overall sensitivity of the bypass flow meter system used in PFBR secondary system is 0.993 $\mu V/m^3/h$ of sodium flow in main line. This low value of the sensitivity is because the sensor measures only a portion of the sodium flowing through the main line. This makes the measurement difficult and the measurement of the lower flow rates uncertain. By modifying the hydraulic characteristics of the bypass line, the sodium velocity through the PMFM sensor can be increased, which will lead to a higher sensitivity for the estimation of sodium flow in the main line. The current article presents a design optimization for the bypass flow meter system using

Table 1
Pipe flow measurement methods in reactors.

Reactor	Pipe diameter in 15–100 mm range	Pipe diameter in 100–200 mm range	Pipe diameter in 200–800 mm range
FBTR*	Alnico-V based PMFM	Alnico-V based PMFM	No pipe above 200
PFBR#	Alnico-V based PMFM	Alnico-V based PMFM	Alnico-V based PMFM in bypass line of 25 NB
FBR1&2&	Alnico-V based PMFM	SmCo based PMFM, Side wall flow meter (SWFM), Ultrasonic flow meter with wave injector	Alnico-V based PMFM in bypass line Side wall flow meter (SWFM) Ultrasonic flow meter with wave injector

* In operation.
\# Under construction.
& In design.

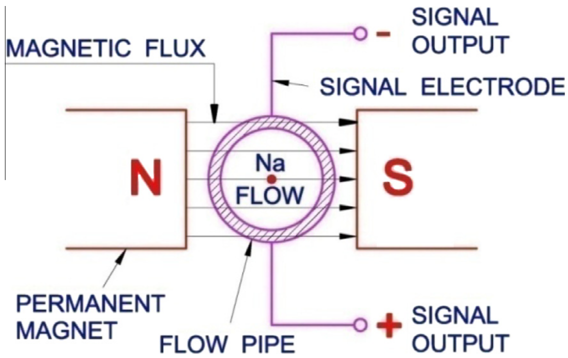

Fig. 1. Schematic showing the principal of permanent magnet flow meter.

numerical and experimental methods in order to enhance the measurement sensitivity of the bypass flow meter system.

2. Description and design considerations

The schematic of PFBR heat transport system indicating the location of secondary flow measurement is shown in Fig. 2. The sensor of the bypass flow meter is installed in a 25 NB Sch 40 bypass line of 800 NB main pipe line. The location selected for installation of bypass flow meter is at the main secondary pump suction line which is in vertical orientation. The bypass flow meter geometry in PFBR is shown in Fig. 3. Bypass flow upstream tapping of inner diameter 26.6 mm is taken from the center of main pipeline with 792.6 mm inside diameter. The downstream sodium flowing through the bypass line leaves at the center portion of the main line. This geometry is imparts negligible additional resistance to the sodium flow through the main line. Overall bypass circuit design ensures minimum pressure drop in the secondary line. The PMFM used in the bypass line is calibrated in sodium to an accuracy of ±2% by absolute constant volume method.

In the bypass flow meter configuration, when sodium flows through the main line, a definite portion of the flowing sodium will pass through the small diameter bypass line where the PMFM is installed. The volumetric flow ratio, F_m is defined as the ratio between volumetric flow rates through main line and the bypass line. The flow ratio F_m is decided by the flow resistances of the flow paths which are purely hydraulic characteristics of the flow path and hence it can be estimated fairly accurately by numerical studies or by hydraulic experiments in a convenient fluid medium. Conducting experiments for design validation in liquid sodium is difficult and costly; hydraulics characterization of sodium flow can be conducted in convenient fluid mediums like water. When a different fluid is used for the experimental studies the governing non dimensional numbers such as Reynolds number (Re) and Euler's number (Eu) has to be taken into consideration. The bypass sodium flow meter configuration for measurement of secondary sodium flow in PFBR was finalised after numerical studies. These numerical procedures were validated by hydraulic experiments in water medium with suitable scaled down models (Aggarwal et al., 2012).

3. Optimization of bypass circuit geometry for future FBRs

The induced voltage (E) in PMFM is directly proportional to the velocity of sodium flowing through the bypass line (v) which is proportional to the velocity of sodium flow through the main line (V). In PMFM

$$E = aBdv \tag{1}$$

$$v = \frac{E}{aBd}$$

where 'a' is the proportionality constant, 'B' is the strength of magnetic field and 'd' is the inside diameter of the PMFM.

Also, we know that in bypass flow meter system, V is proportional to v

$$v \propto V$$

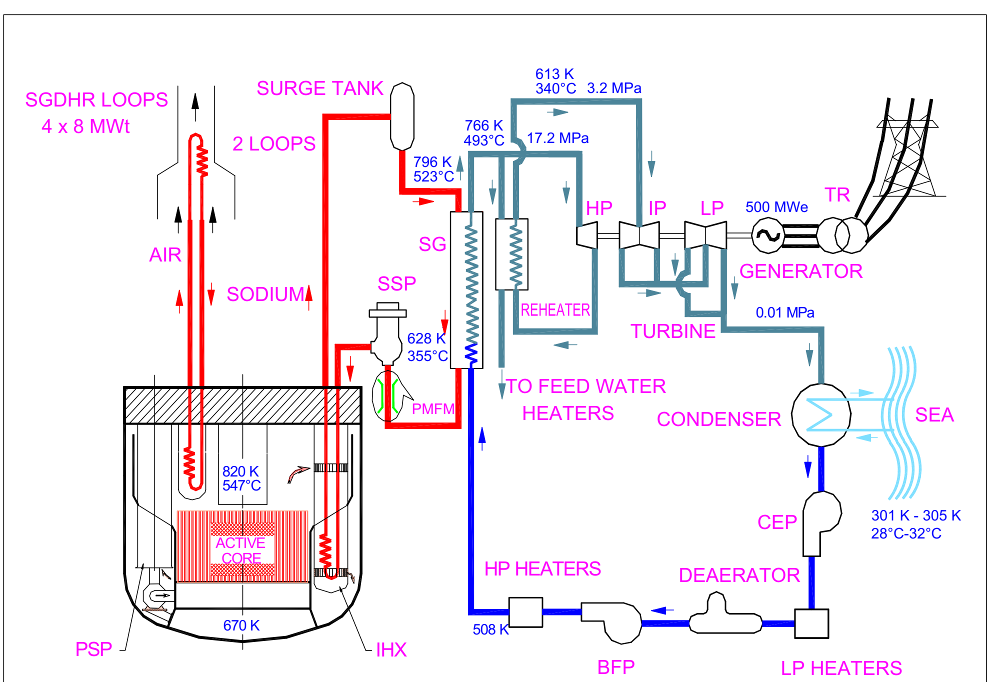

Fig. 2. Schematic of heat transport system for PFBR.

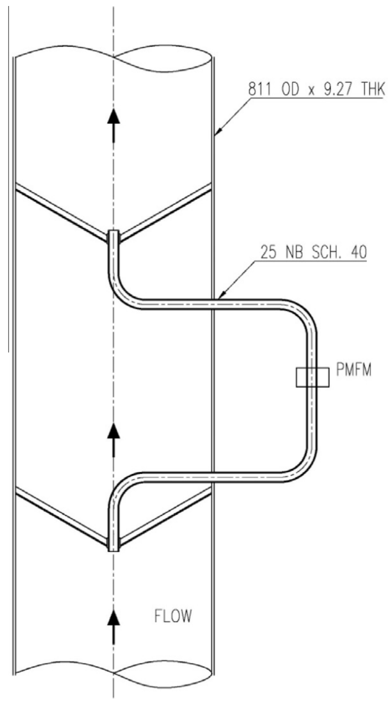

Fig. 3. Bypass flow meter geometry for PFBR secondary sodium flow measurement.

or

$$v = bV \tag{2}$$

$$V = \frac{1}{ab}\frac{E}{Bd}$$

The flow rate in main line is

$$Q = \frac{1}{ab}\frac{\pi}{4}\frac{D^2}{d}\frac{E}{B}$$

$$= \frac{1}{C}\frac{D^2}{d}\frac{E}{B} \quad \text{Where } C = \frac{4ab}{\pi}$$

And sensitivity of bypass flow meter system,

$$\frac{E}{Q} = C\frac{dB}{D^2} \tag{3}$$

For a given value of d and D, the sensitivity of the bypass flow meter can be increased by high value of C or B. With a given geometry of magnet assembly B is constant and C can be increased by an increase in sodium velocity through the PMFM by increasing b. The sensitivity and resolution of the bypass flow meter system will increase with the increase in fluid velocity through bypass line and associated increase in the induced voltage across the electrodes.

The velocity of sodium in bypass line depends upon the kinetic head of flowing sodium in main line and flow resistance of the parallel flow paths. The static pressure difference responsible for sodium flow in bypass line, ΔP_m is given by the relation below:

$$\Delta p_m = k_m \frac{\rho V^2}{2} \tag{4}$$

where k_m is the overall pressure loss coefficient for the main line

Pressure drop in Bypass line:

$$\Delta p_{by} = k_{by} \frac{\rho v^2}{2} \tag{5}$$

where k_{by} is the overall pressure loss coefficient for the bypass line, which is the sum of different components as given below:

$$k_{by} = k_{fr} + k_e + k_{be} + k_{red}$$

For the bypass flow system,

$$\Delta p_m = \Delta p_{by}$$

and from Eqs. (4) and (5)

$$k_m \frac{\rho V^2}{2} = k_{by} \frac{\rho v^2}{2}$$

$$v = V\sqrt{\frac{k_m}{k_{by}}} \tag{6}$$

For a given velocity V in the main line, the fluid velocity in bypass line depends on the numerical values k_m and k_{by}. To get a lower $F_{m,}$ the resistance k_m should be increased and/or resistance k_{by} should be decreased. The value of k_m is not recommended to be increased because it will increase the pressure drop in main line. Hence, the value of k_{by} should be reduced to get higher sodium velocity in bypass line. The liquid sodium velocity in the bypass line at normal operating condition is limited to around 12 m/s by considering erosion and flow induced vibration and set as upper constraint of velocity for optimization process. The optimization study is conducted to minimize the flow resistance in the bypass line and keeping the sodium velocity through the PMFM section in the allowable limit. In order to reduce the flow resistance inside the bypass line, the size of the bypass line is increased while keeping the diameter of the PMFM section unchanged. Only standard pipe sizes are considered for the optimization study due the convenience of manufacturing the bypass line. From the design calculations conducted with different possible pipe sizes, it is found that with 35.1 mm inside diameter for the bypass line with 26.6 mm inside diameter for PMFM section is the best suited solution. The schematic of the new bypass flow meter configuration is shown in Fig. 4. The flow ratio F_m was established by numerical studies over a wide range of Re.

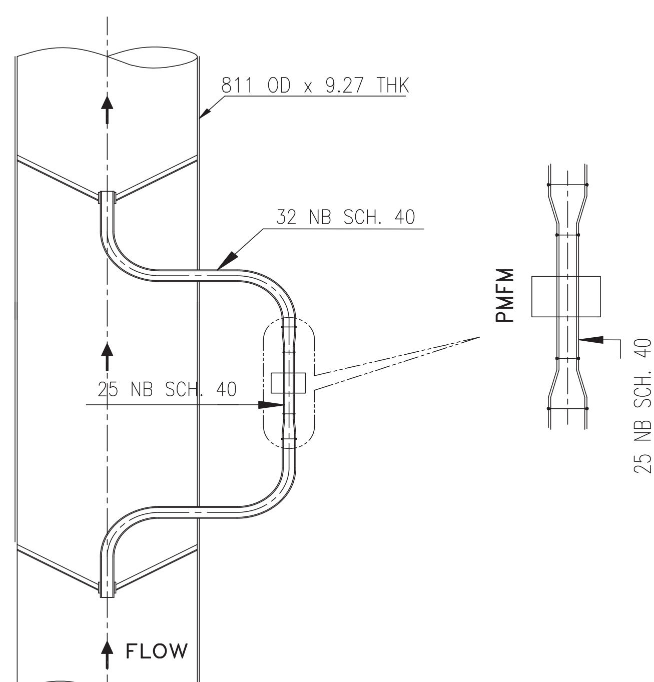

Fig. 4. Proposed optimized bypass configuration for future reactors.

4. Experimental validation of numerical procedure

The numerical procedure used to evaluate the F_m was validated with hydraulic experiments in water medium using scaled down model of bypass flow meter configuration. The fluid passing through the bypass line is depending on the kinetic head of the fluid passing through the main line and the hydraulic resistance of the main line and bypass line. The influence of hydraulic resistance of the main line is comparatively less on the mass flow rate of fluid through the bypass line with respect to the other two components. Hence the fluid velocity in the main line is selected as the similarity criteria when experiments are conducted with scaled down models. Full scale water experiments with velocity/Re similitude demands very large test facilities and flow velocities. Hence to reduce the cost and complexity of experiments, the main line diameter of the model for the experimental validation is scaled down to 254.5 mm from 792.6 mm by keeping the bypass line geometry unchanged. This reduces the water flow requirements considerably and makes the experiments economical. The Schematic of the model used for experimental validation of the new proposed bypass flow meter configuration is shown in Fig. 5. Numerical analysis was performed for this scaled down model with water. A commercial navier stock solver is used for the analysis using 180° sector model of the bypass flow meter. Sufficient free length of the main pipe is provided in the numerical model as well as scaled down model for experimental study to develop the flow at the bypass tapping locations as in the reactor system. The size of mesh is finalised after conducting a mesh dependence study. Velocity inlet and pressure outlet boundary condition with standard wall functions were used to solve the problem. From the numerical analysis, it has been observed that the sodium velocity at PMFM section in the scaled down model of modified geometry is 71.0% more than that with the scaled down PFBR geometry. The velocity vectors and pressure profile for the model of the optimized geometry is shown in Figs. 6 and 7. The maximum fluid velocity is at EM flow sensor location and the magnitude of velocity is 12.2 ms^{-1}. The drop in the static pressure of flowing

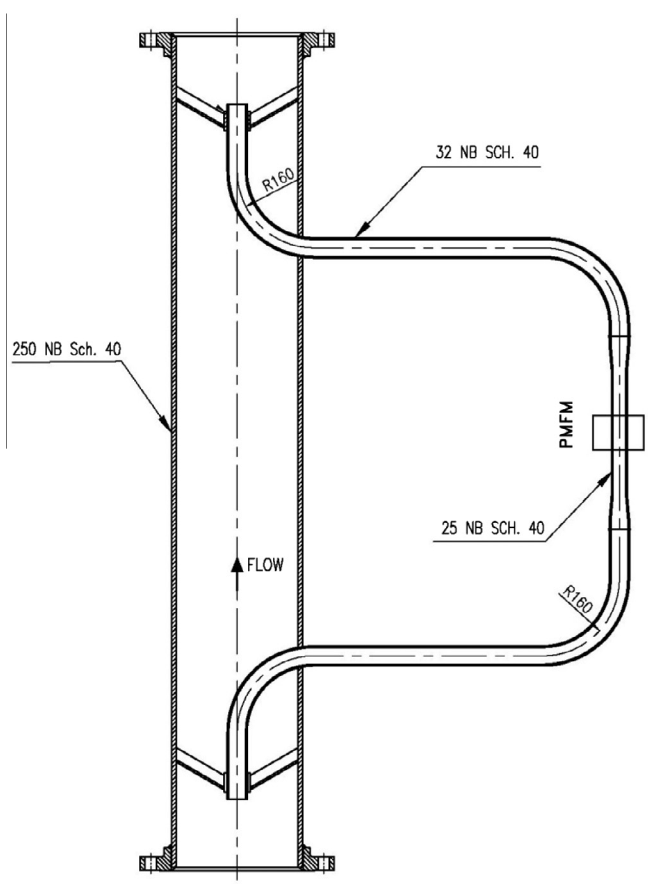

Fig. 5. Model for optimized bypass loop for Experimental and numerical studies.

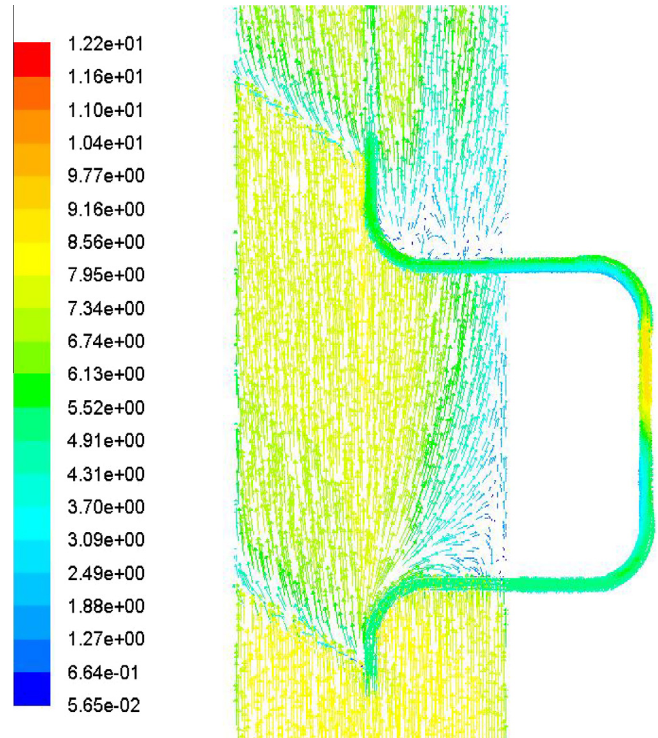

Fig. 6. Schematic of velocity vector profile in optimized bypass geometry (m/s).

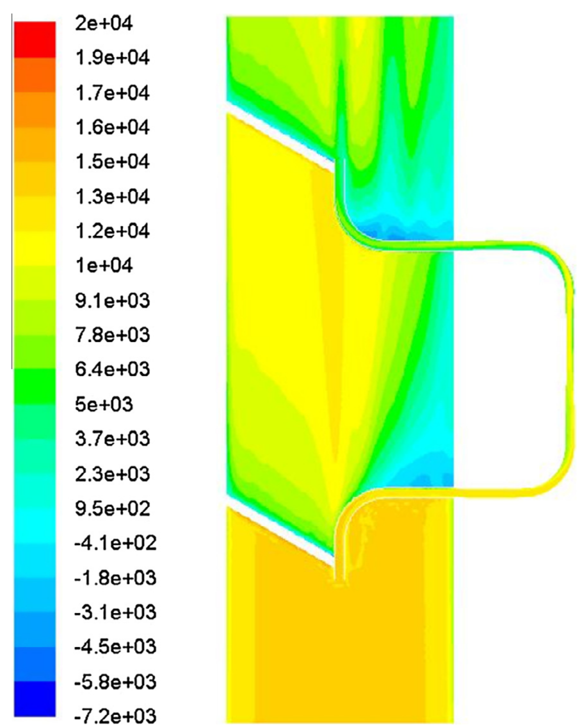

Fig. 7. Schematic of pressure contour profile in optimized bypass geometry (Pa).

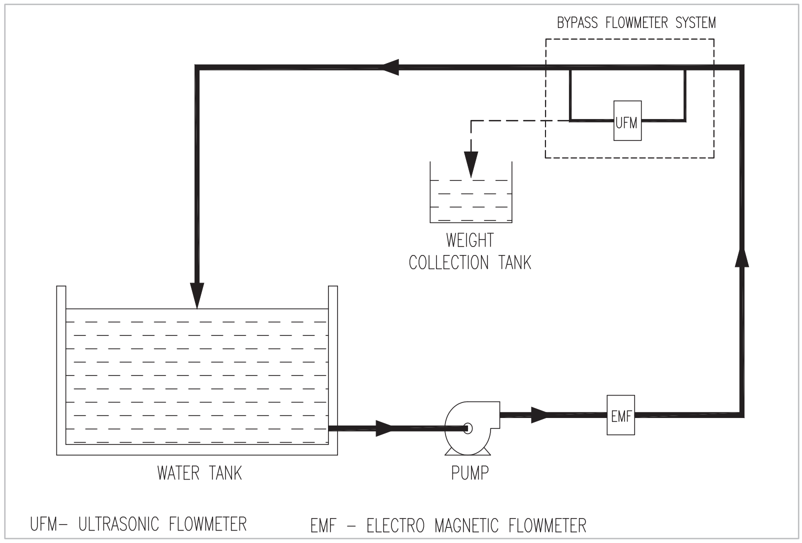

Fig. 8. Schematic of the water loop used for the experimental studies.

sodium between the suction and delivery points of the bypass line is 3.3 kPa only.

To validate the numerical results, experiments were conducted with the model of the bypass flow meter configuration used in PFBR and the proposed modified configuration for future FBRs. The schematic of the hydraulic test loop where the experiments were conducted is shown in Fig. 8. Straight pipe lengths more than 15 times and 10 times of the main pipe diameter were provided at the upstream and downstream of the bypass locations. A centrifugal pump was used to circulate the water in the closed test loop with a very large reservoir. The temperature of the circulating water was made unchanged during the testing. The volumetric flow rate of water through main line is measured by an EM flow meter with an accuracy of ±0.15% of the measured value. The volumetric flow rate of water through bypass line is measured with an ultrasonic flow meter which is calibrated in situ by absolute weight collection method with an uncertainty of ±0.75%. From these individual uncertainties of the measurement, and the various geometrical uncertainties of experimental system the uncertainty in the estimation of F_m is calculated as ±1.5% of the reading. The result obtained from the numerical calculations is compared with the experimental results and the same is shown in Fig. 9. The mean deviation between experimentally obtained volumetric flow rate in bypass line with numerically evaluated trend line is +2.15% with maximum deviation as +2.3%. The bypass flow estimation with numerical analysis is fairly matching with the experimental value. Thus, the experimental studies validated the numerical procedure for evaluating F_m of bypass flow meter configuration in PFBR and future SFRs. The experimentally obtained F_m cannot be applied directly on the actual system as the flow apportionment between main line and bypass line is a function of the size of main pipe and fluid properties.

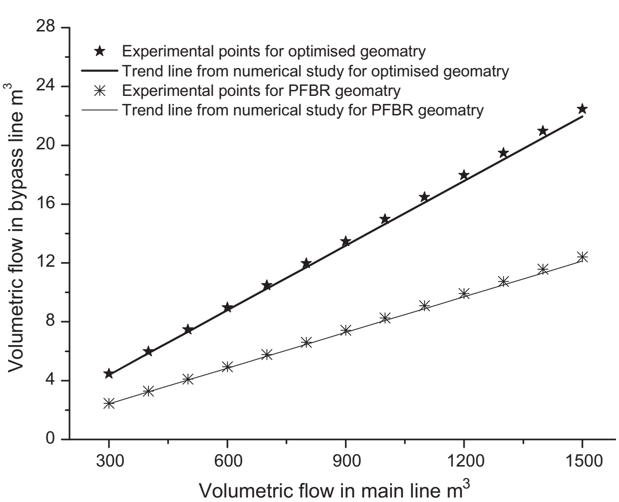

Fig. 9. Comparison of volumetric flow rates obtained by numerical calculations and experimental studies for present configuration in PFBR and optimized configuration.

5. Numerical estimation of flow multiplication factor

The flow ratio, F_m for the full size bypass flow meter configurations were evaluated numerically for a range of Re using the validated numerical procedure. The variation of F_m for the present bypass flow meter configuration used in PFBR and the optimized bypass flow meter configuration are given in Fig. 10. The characteristic equation obtained from this study for flow meter configuration used in PFBR is given as Eq. (7) and the same for optimized flow bypass flow meter configuration is given in Eq. (8)

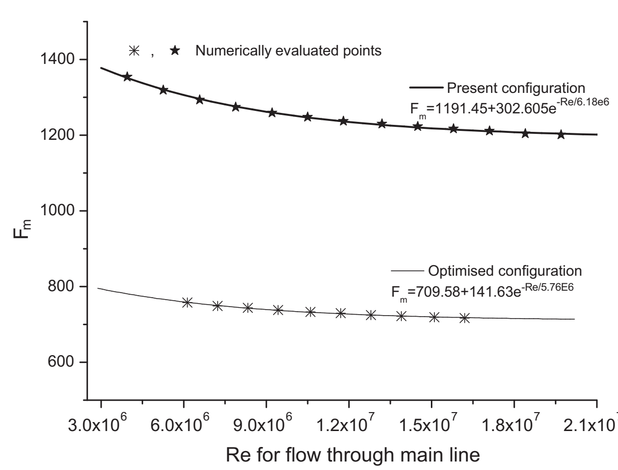

Fig. 10. Variation of F_m with respect to Re.

$$F_m = 1191.45 + 302.6e^{-\mathrm{Re}/6.18E6} \text{ for } 3.0\times10^6 < Re < 3.0\times10^7 \quad (7)$$

$$F_m = 709.58 + 141.63e^{-\mathrm{Re}\ /5.76E6} \text{ for } 3.0\times10^6 < Re < 3.0\times10^7 \quad (8)$$

The volumetric flow rate obtained through the bypass line of optimized geometry is 70% higher than the existing PFBR bypass geometry. This increased volumetric flow rate gives an increased velocity of sodium at the PMFM section and an increase in the sensitivity of the bypass flow measurement system by the same percentage. Sensitivity of the optimized bypass flow meter configuration is improved to 1.688 $\mu V/m^3/h$. The uncertainty in the flow ratio derived by numerical methods which is validated by experiments is estimated as ±1.5% of the reading based on statistical methods with 99.7% confidence level. The overall accuracy achieved in PFBR secondary flow measurement is ±2.5% which is adequate from process and safety considerations. The uncertainty of the estimated sodium flow through main line using the PMFM sensor installed in the bypass line is estimated as 2.39% which is slightly better than the PFBR configuration.

6. Conclusion

Bypass type permanent magnet flow meter is used for sodium flow measurements in secondary loop of PFBR. An optimization study was conducted to increase the sensitivity and resolution of the bypass flow meter by changing the bypass configuration. From the study, it is observed that the increase of inside diameter of bypass line from 26.6 mm to 35.1 mm by keeping the PMFM section size same will increase the sensitivity of the flow meter by 70%. With the increase in inside diameter of bypass line the flow resistance of bypass line reduces and more fluid will pass through it. This reduces the value of F_m and consequently the influence of geometrical tolerances on the level of uncertainty for bypass flow meter system will decrease. The numerical procedure used for the evaluation of F_m was validated by experiments with scaled down models of the bypass flow meter configuration in water medium. The variation of F_m with respect to Re was established for a wide range of Re using the validated numerical procedure. The increase in the sensitivity of the bypass flow meter system will enhance the control of secondary sodium flow and hence increase the convenience of the reactor operators.

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