Nuclear Engineering and Design 275 (2014) 368–374

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Stabilization of magnet assemblies of permanent magnet sodium flowmeters used in fast breeder reactors

K.K. Rajan*, G. Vijayakumar

Fast Reactor Technology Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, TN, India

HIGHLIGHTS

- Stabilization procedure for ALNICO-5 permanent magnet material is evolved.
- Effect of time and temperature on ALNICO-5 assembly is determined.
- Suitability of ALNICO-5 flowmeters at high temperatures is established.
- Temperature coefficient of flux density is determined.

ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form 7 May 2014
Accepted 9 May 2014

ABSTRACT

Permanent magnet flow meters (PMFMs) are used to measure the sodium flow in sodium cooled Fast Breeder Reactor Circuits. Prototype fast breeder reactor (PFBR) which is under construction at Kalpakkam is a 500 MWe, sodium cooled, pool type reactor. Sodium flow measurement in various loops of the reactor is of prime importance from operational and safety point of view. To measure the flow of electrically conducting liquid sodium, in primary and secondary circuit pipe lines of PFBR, permanent magnet flow meters are used. PMFM 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. Flowmeters of different pipe sizes ranging from 10 mm to 200 mm pipe diameter are required for PFBR. Long term performance of the flowmeters mainly depends on stability of permanent magnets used in flowmeters to generate constant magnetic field in stainless steel (SS) pipes. This paper describes the effects of time and temperature on permanent magnet assemblies made of ALNICO-V used in PFBR flowmeters. The stabilization methodology for ALNICO-V permanent magnet assemblies is evolved and established. Loss of magnetic field strength with respect to time and temperatures is determined by experiments and found negligible.

1. Introduction

Electromagnetic flowmeters are used to measure the sodium flow in pipelines of experimental sodium facilities and Fast Breeder Reactor (FBR) Circuits (Turner, 1968; Affel et al., 1960). Electromagnetic flowmeters utilizes the electrical conductivity of liquid sodium and are based on the Faraday's law of electromagnetic induction. 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 or electromagnetic circuit. PMFM needs only electrical contact between electrodes and liquid sodium flowing in Stainless steel (SS) pipes. Electrical contact is achieved by electrodes welded to the SS pipe in which liquid sodium flows. Flowmeter voltage signal is measured across SS electrodes welded to SS pipe diametrically opposite to each other with their central axis oriented normal to the direction of the lines of magnetic field and liquid sodium flow. The magnitude of flowmeter voltage signal depends on magnetic flux density distribution and velocity profile distribution in flowmeter pipe (Vijay Sharma et al., 2012), and its polarity is determined by the direction of liquid flow. For axis symmetric velocity profile, transverse PMFM voltage signal is independent of velocity distribution/profile. This is true for any shape of duct or channel. SS pipe with circular cross section is chosen in sodium systems due to mechanical reasons. Theory for measuring the flow of electrically conducting fluids in pipes was first developed as early as 1962 (Shercliff, 1962). Author developed the two dimensional weight functions to represent the contribution of fluid velocity profile to flowmeter voltage signal developed across pipe cross sections of different shapes.

* Corresponding author. Tel.: +91 44 27480311/44 27480083; fax: +91 44 27480311.
E-mail addresses: kkrajan@igcar.gov.in, vijay_sharma@igcar.gov.in (K.K. Rajan).

http://dx.doi.org/10.1016/j.nucengdes.2014.05.018
0029-5493/

Nomenclature

PMFMs	permanent magnet flow meters
PMFM	permanent magnet flow meter
PFBR	prototype fast breeder reactor
MWe	Mega Watt (electrical)
EMF	electromotive force
LMFBR	liquid metal fast breeder reactor
FBTR	fast breeder test reactor
SWG	standard wire Gauge
MS	mild steel
NB	nominal bore
R_m	magnetic Reynolds number
μ	permeability of liquid metal
σ	electrical conductivity of liquid metal
v	velocity of liquid metal in pipe
d	inner diameter of SS pipe
T_c	Curie temperature
H_c	coercive force
B_r	residual induction
AT	Ampere-turns
B_m/H_m	permeance coefficient

The short circuiting effect of pipe wall conductivity on flowmeter voltage signal and effect of finite length of magnetic field were studied by Hemp and Versteeg, 1986). Electromagnetic flowmeters used to measure the flow of liquid metals encounters the problem of magnetic field distortion at high magnetic Reynolds number (R_m) due to currents induced in liquid metals (Mahmud et al., 1982).

$$R_m = \mu \times \sigma \times v \times d$$

Schematic of a typical permanent magnet flowmeter is shown in Fig. 1.

Invasive and non invasive type flowmeters have been used in FBRs. Invasive flowmeters such as eddy current flowmeters and probe type permanent magnet flowmeters have been used (Hans et al., 1979) in primary sodium circuits. Saddle coil flowmeters were used in PFR (Thatcher et al., 1970; Thatcher, 1980) and JOYO (Araki et al., 1980). Permanent magnet flowmeters which are of non-invasive type were used in BN-350, BN-600, FFTF, Phenix, Super-Phenix, SNR-300, KNK and FBTR (Hans et al., 1979). Constant magnetic flux density in flowmeter pipe can be generated with an electromagnet or permanent magnet assembly, but permanent magnets are preferred in flowmeters for liquid sodium flow measurement. Main advantage of permanent magnet over electromagnet are its high reliability, passive nature, less maintenance, high stability achieved by proper stabilization, wide range of linearity and is economically competitive. It also does not require

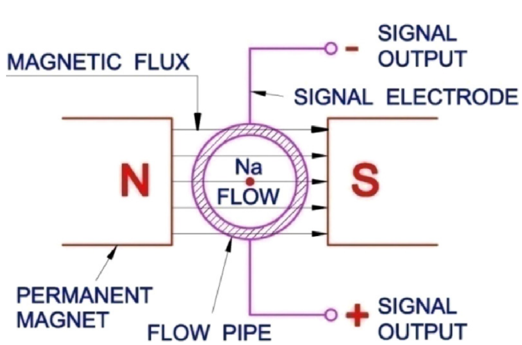

Fig. 1. Schematic of permanent magnetic flow meter.

power supply, there are no operating power costs, no heat dissipation, less possibility of field interruption, no insulation required, is immune to problem of moisture and electrical short circuit, has low weight, low volume and higher degree of self sufficiency. Disadvantages of permanent magnet flowmeters are mainly the difficulties to regulate field, to clean the magnets and stability of the field over period of time under hostile operating environment. Permanent magnet flowmeters with stable magnetic field over the life of a Fast Breeder Reactor can be designed and manufactured with proper stabilization of magnet assembly. Non-wetting of pipe and presence of chromium oxide layer on pipe surface affects the voltage signal of flow meter. Removal of oxide layer and complete wetting is achieved by purification of sodium and by initial few hours of high temperature operation above 250 °C. Hence dependencies of the potential difference by wetting and oxidation between channel and fluid are negligible at steady state operation. Permanent magnet flowmeters are used over a wide range of liquid sodium velocities. Shift in the resultant magnetic field in the downward direction at high velocities is taken care by providing magnetic pole face of length greater than two to three times of SS pipe diameter.

Choice of permanent magnets used in PMFMs for liquid metal flow measurement in FBRs, depends on temperature and radiation level at flowmeter locations (Parker and Studders, 1962; Peter Cambel, 1994). Among the permanent magnet materials available in Indian markets, Cast ALNICO-V is chosen for PFBR flowmeters due to its compatibility with sodium, the feasibility of casting to required shape, anisotropic property which enhances the magnetic property at desired direction and availability at reasonable cost. Apart from factors given above ALNICO-V shows good magnetic properties like high remanance, coercive force, Curie point and high temperature stability.

Primary and secondary circuits of PFBR require flow measurement in pipes of sizes ranging from 10 mm to 200 mm for different auxiliary circuits. In sodium circuits, SS pipes carrying sodium at around 550 °C are thermally insulated, hence maximum magnet temperature during operation of flowmeter is less than 100 °C. In the specific case of failed fuel location module of PFBR, magnet assembly of the flowmeter is located in the cover gas space of reactor pool and the estimated temperature is around 465 °C during reactor operation.

Calibration of the flowmeter depends on factors such as sodium resistivity, pipe material resistivity, pipe and magnet dimensions and magnet temperature during operation. These factors are accounted during design and calibration. Long term performance of the flowmeters mainly depend on stability of permanent magnets used to generate constant magnetic field in stainless steel (SS) pipes. In the present work, an effective electrical and thermal stabilization procedure is developed for stabilizing the magnet assemblies used for PM flowmeters. Further the stability behavior of indigenously manufactured permanent magnet assemblies (ALNICO-V), which operates around the knee point of the demagnetization curve is studied experimentally over long periods of time at high temperatures. Rate of loss of magnetic field strength at high temperatures is determined with experiments and compared with reported values in literature.

2. Magnet assemblies used for different PM flowmeters in PFBR

Magnets used for flowmeters are anisotropic in nature and the anisotropy is achieved by grain orientation during casting. Visual inspection and Liquid Penetrant examination are conducted for detecting crack or surface defect in the assembly. Ultrasonic examination of the magnet assembly is conducted for detecting internal porosity. During casting stage, magnet sample is drawn