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FUJI ELECTROMAGNETIC FLOWMETERS FOR LIQUID SODIUM

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I. INTRODUCTION

One of the main national projects undertaken by the Japanese Government concerns improvement of the economy of atomic power generation and the effective utilization of atomic fuels. One aspect of this project is the development of fast breeder reactors which is now being handled mainly by Power Reactor and Neuclear Fuel Development Corporation. The coolant used in these fast breeder reactors is metallic sodium and there are various systems for measuring the flow of the sodium. This article will introduce the electromagnetic flowmeters developed by Fuji Electric for use with liquid sodium.

These flowmeters boast the following features. First, the principle is well-defined since the relation between output voltage and flow is almost linear. Second, construction is very simple. No foreign matter can get inside the flow tubes, there are no moving parts and there is no need to worry about stoppages in the tube containing the liquid sodium flow measuring points. Third, it is comparatively easy to use these flowmeters at high temperatures. These flowmeters have been successfully employed as the main flowmeters in fast reactors and in test loops for the development of sodium techniques. Research and development is now being carried out on " in-core " flowmeters to be used within the reactors. This work is extremely important in respect to highly efficient and safe operation of fast reactors as well as confirming design calculations.[1]

In 1968, Fuji Electric received a grant for research into the peaceful uses of atomic power. Trial research on in-core flowmeters for use inside the reactors was then instituted as one aspect of research concerning liquid sodium measuring instruments.

Also in 1968, a research commission was obtained from Power Reactor and Neuclear Fuel Development Corporation. For this research, deterioration tests were conducted to investigate the properties under high temperatures of permanent magnets used in in-core flowmeters. For this purpose, a detector was produced. This research and development into in-core flowmeters is still continuing at present. A total of 13 sodium loop flowmeters of various ratings between 2.5 l/min. and 100 l/min., the first of their kind in Japan, have been delivered to Power Reactor and Neuclear Fuel Development Corporation, as were the electromagnetic pumps described in another article.

II. PRINCIPLE OF THE ELECTROMAGNETIC FLOWMETERS

The principle of these flowmeters is based on the Faraday's induction law. In other words, an induced voltage perpendicular to both the direction of movement and the field direction arises in materials moving through magnetic fields.

Referring to *Fig. 1*, the induced voltage E which arises when sodium is flowing at an average speed of V (cm/sec) in a tube with an inside diameter D (cm) and a flux density B (gauss) can be expressed as follows:

$$E = KBDV \times 10^{-8} \text{ (v)} \quad \cdots\cdots (1)$$

The K in this equation is a correction factor which compensates for discrepancies in respect to the ideal output. It includes a correction factor for effects of the tube wall (K_1), a factor for the effects at the ends of the magnetic field (K_2), a factor for the influences of the magnet temperature characteristics and radiation (K_3) and a factor for thermal expansion of the tube (K_4); therefore:

$$K = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \quad \cdots\cdots (2)$$

If the output voltage E is measured from equation

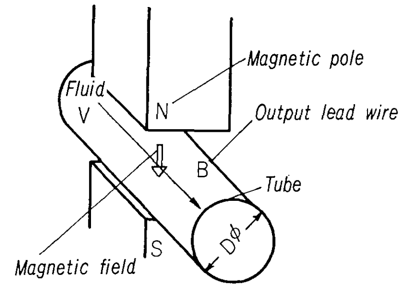


Fig. 1 **Principle of magnetic flowmeter**

(1) and B is known, then the flow rate V, which is actually the flow Q, can be obtained.

The electrical conductivity of the tube wall when compared to that of sodium can not be neglected. The output is short circuited by the tube wall and thus decreased. The correction factor for this, K_1 can be represented by the following equation:

$$K_1 = \frac{2\left(\frac{D}{D_0}\right)}{1+\left(\frac{D}{D_0}\right)^2+\frac{\rho_f}{\rho_m}\left\{1-\left(\frac{D}{D_0}\right)^2\right\}} \cdots\cdots\cdots (3)$$

Here, D_0 is the outer diameter of the tube and ρ_f and ρ_m are the specific resistances of the fluid and wall respectively. The factor K_2 is based on the limit in the axial direction of the magnetic field. It can be determined from the Michel correction curve.

The main parts to realize this principle are 1) the exciting part 2) the tube and 3) the output lead wires. The tube is non-magnetic and the specific resistance is high to keep K_1 small. Austenite steel which is highly resistant to corrosion is used as the tube material, and the inside surface of the tube which is exposed to the sodium is specially treated. The lead wires are made of the same material as the tube and welded on in order to minimize thermo-electromotive force. The electromagnetic sodium flowmeter employs a dc exciter. In order to save on space occupied by the in-core flowmeter, a cylindrical type permanent magnet is used, but in the loop where there are no space limitations, the flowmeter employs either an electromagnet or permanent magnet which makes it possible to obtain the best magnetic distribution.

Since the output is a low dc voltage and the maximum temperature used is very high (600°C), it is essential to give sufficient consideration to thermo-electromotive force. However, since the output impedance is low, it is relatively easy to make measurements.

Because of eddy current in the sodium, the effective magnetic flux density becomes low and when the inner diameter is large, output characteristics are not linear. However, if the inner diameter is 25 cm or less, this effect becomes negligible. Even if the inner diameter is 25 cm or less, this effect becomes neglible. Even if the inner diameter of flowmeter is larger, the electrode can be shifted in respect to center of the field and it is sufficiently to fix the output characteristics by calibration.

III. IN-CORE FLOWMETERS

1. Model Test

The first step in the research concerning in-core flowmeters began in 1968 when Fuji Electric received a grant to study the peaceful uses of atomic power.

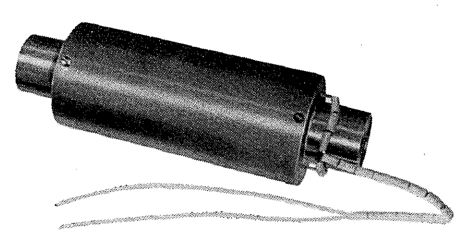


Fig. 2 In-core flowmeter

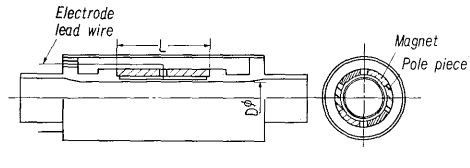


Fig. 3 Construction of magnetic flowmeter

A model flowmeter was produced and after calibration using liquid sodium by the flowmeter calibration section of Japan Atomic Energy Reserch Institute it underwent continuous short-term tests using the sodium testing equipment at Fuji Electric.

An exterior view of the flowmeter is shown in *Fig. 2,* and construction is as shown in *Fig. 3.* External dimensions are 60 ϕmm × 200 mm, orifice diameter is D=25 mm, and L/D=2.6. The exciting part consists of an anistrophic cast magnet made of Alnico V which has undergone aging treatment at 650°C as well as stabilizing treatment under three high temperature cycles, and a pure iron pole piece which has been chrome plated to prevent oxidation. After the magnetic circuit has been chrome plated to prevent oxidation. After the magnetic circuit has been formed, in order to reduce irreversible changes of the magnetic flux density due to variations of the temperature, the exiciting part underwent three heat treatments. To reduce the K_1 decribed previously, the tube is made of thin (1 mm) SUS 27. *Fig. 4* shows the flux density distribution in the axial direction from the air gap center line as measured at room temperature. An uniformity within ±2.5% deviations was obtained even for radial flux distribution in the plane including the electrode.

Flow calibrations are based on the volumetic

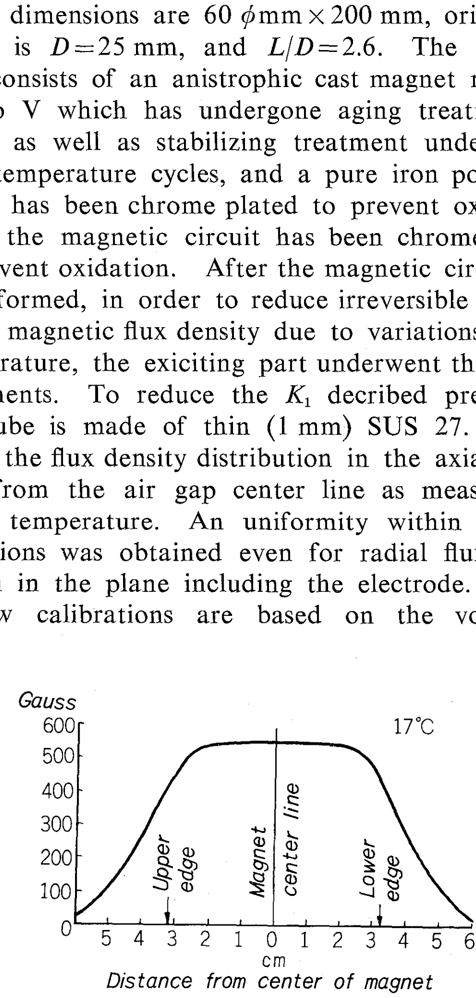


Fig. 4 Measured center line air gap flux density

Table 1 **Output Correction Factors**

Sodium Tempera-ture (°C)	Measured output correction factor K_m			Calculated output correction factor $K_c=K_1K_2K_3K_4$					Ratio
	Flowmeter I	Flowmeter II	Average	K_1	K_2	K_3	K_4	Kc	K_m/Kc
250	0.912	0.899	0.905	0.984	0.981	0.953	0.996	0.913	0.992
350	0.873	0.875	0.874	0.982	0.981	0.931	0.994	0.891	0.981
450	0.850	0.830	0.840	0.972	0.981	0.896	0.992	0.854	0.984

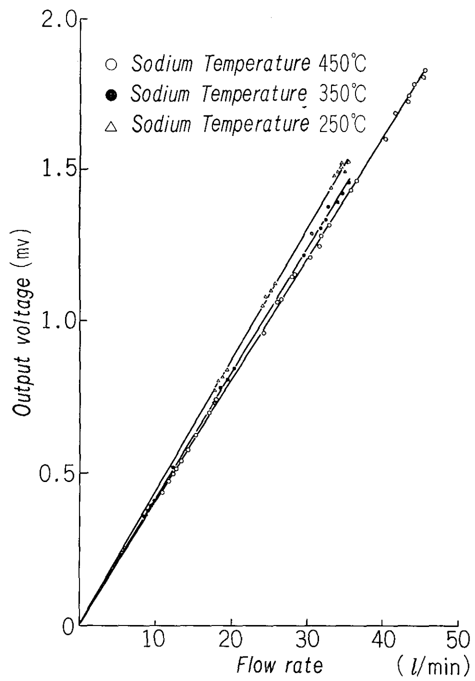


Fig. 5 Calibration characteristics of flowmeter

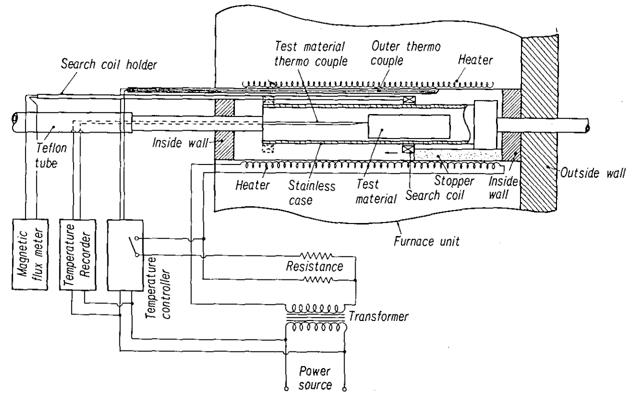


Fig. 6 Magnet testing equipment

method and details of the flow cablibration equipment and method is described in the previous paper[(2)]. The liquid sodium is forced by gas pressure or drops freely from the measuring tank and calibration is made by comparing the time taken for a standard volume to fall and the average output during this time. Typical results are shown in *Fig. 5*. The output characteristics are linear. The difference between the zero point output when the sodium remains static, and the various electromotive outputs occurring when the tube is filled with argon gas is less than 10 μv which is sufficiently low. This means that the attachment of the electrode leads is satisfactory. A comparison of the measured values and calculated values of the correction factor K is shown in *Table 1.* The difference in the two values is only about 2%. As the calculated values of K_3, measured values of residual flux density of a rod shaped magnet are used. After continuous operation for 130 hours at 520°C, no changes in output were noted during calibration at 500°C.

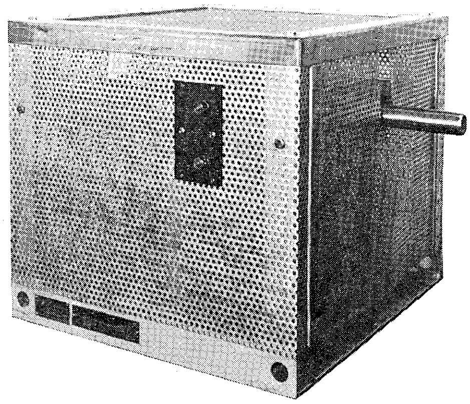
2. Permanent Magnet Heat Deterioration Tests

In order to decide the choice of magnetic materials with low deterioration and establish treatment methods, changes in residual magnetic flux density at 600°C using a rod shaped magnet were observed for 1000 hours. After aging treatment at 600, 650 and 700°C, magnets made of Alnico V and Alnico VIII with permeance factors of $P=8$, 12 and 16 were cooled from 650°C to room temperature and then subjected to heat deterioration tests. *Fig. 6* is an outline of the test equipment. The test material was placed in a furnace filled with nitrogen and containing a search coil for measuring flux. The interlinking flux density was measured with a flux meter. Test results revealed that the lowest value of the deterioration factor was 3.5% for Alnico V treated at 700°C. The deterioration factor for Alnico VIII aged at 650°C was 7%. The residual magnetic flux for Alnico V aged for long periods is remarkably low. At 700°C, it was half the value at 650°C, but in Alnico VIII there were almost no changes. The rod shaped magnet and the cylindrical magnet described in section 1 were subjected to the same type of deterioration tests but accurate data could not be obtained because of rust in the yoke.

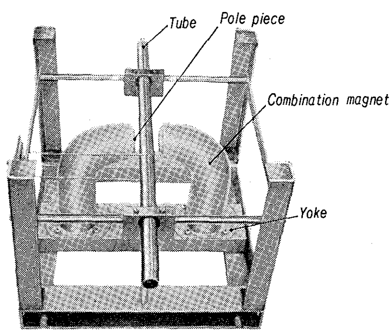
At the same times as these test models of fuel channel flowmeters of the sodium immersion type filled with argon gas were manufactured.

IV. FLOWMETERS FOR SODIUM PROCESS

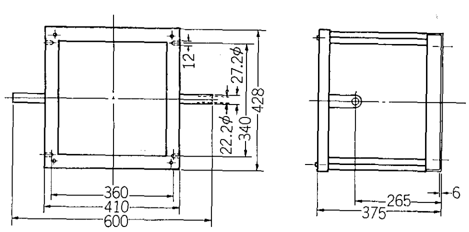
Figs. 7 (*a*), (*b*) and (*c*) show an external view, with protective cover removed and external dimensions respectively of a 100 *l*/min flowmeter with inner diameter of 22.2 m. The detectors are completely the same for ratings of 7.5, 15, 20, 75, 100 *l*/min. The output is connected to an amplifier or voltage divider circuit which converts all rated outputs to a standard signal of 10 mv and transmits this signal



(a) External view



(b) View with protective case removed



(c) External dimensions

Fig. 7 100 l/min flowmeter for liquid sodium loop

***Table 2* Specifications of Flowmeter**

Model	FTM-SLA 223
System principle	Permanent magnet type electromagnetic induction
Fluid used	Liquid sodium
Permissible fluid temperature (°C)	600
Permssible pressure (kg/cm^2)	5
Inner diameter (mm)	22.2
Center line air gap fliux densily (gauss)	3000
Air gap (mm)	40
Pole face (mm)	40 ϕ
Output sensitivity (mv/l·min)	0.25
External dimensions	See *Fig. 7*
Weight (kg)	55

to a receiving instruments. The specifications of this type of flowmeter are shown in *Table 2*.

As can be seen from *Fig. 7* (*b*), the flowmeter contains a high capability permanent magnet rationally arranged in a stout construction which provides high reliability. In order to minimize the leakage flux, the magnet is placed in the vicinity of the air gap. To obtain the most effective magnetic properties, Alnico V permanent magnet was divided into 6 parts and placed in an arc-shaped stainless steel case. This case was fixed firmly to the yoke with a bolt cast in the magnet itself. The pole piece was attached in the same manner. Since the extruded steel pipe comes into direct contact with the liquid sodium, it must be processed as little as possible. It is provided with a support so that output characteristics will not alter due to slide of the tube caused by thermal expansion. A coat of silver paint is applied to the entire surface, (especially the magnet) to reduce thermal radiation.

From the seven calibrations of flowmeters at sodium temperatures of 400°C mentioned previously, the average value of the correction factor was found to be $\overline{K_m}=0.862$. The standard deviation was $S=0.0216$ and the 95% reliability range of the average value of the correction coefficient was $\overline{K_m}\pm 0.0216$. From equation (3), $K_1=0.942$: from the Michel curve, $K_2=0.925$ and $K_3=1$ for a magnet temperature rise of 20～30°C. With such results, the planned correction factor $K_c=0.870$. The planned value is within 95% of the measured value. However, when other inner diameters are used, the same relations can not be applied. The output characteristics are linear.

An external view of the small diameter-flowmeter (diameter 15 mm and 13.3 mm) is shown in *Fig. 8*. Details other same as equipment mentioned above. Rated flow is 2.5, 3, and 15 l/min.

Fig. 8 Electromagnetic flowmeter for liquid sodium (15 l/min)

V. CONCLUSION

(1) The main results of Fuji Electric's research and development concerning in-core flowmeters have been introduced in this article. Since the condi-

tions under which the flowmeters are used are extremely severe, there are many problems which must be solved including finding a method to produce a magnet with excellent thermal stability, estimating the functional limits of the flowmeter, dealing with the influence of radiation and providing the best means of mounting.

(2) Fuji Electric has completed a rationally constructed, highly reliable, small inner diameter flowmeter for use in sodium loop which has shown excellent results.

Lastly, the authors wish to take this opportunity to offer sincere thanks to Power Reactor and Nuclear Fuel Development Corporation for their valuable guidance in developing these meters, to Japan Atomic Energy Reserch Institute and Kawasaki Heavy Industries for their help in calibrating and testing these meters and finally to Mitsubishi Steel for aiding in the manufacture of the magnets.

References :

(1) Popper et al.: The Design and Performance of a 1200°F magnetic flowmeter for in-core application in Sodium-cooled reactor, IEEE Trans. Feb. (1967)

(2) Kazuo Furukawa et al.: Manufacture and test results of a liquid sodium calibration loop, JAERI-memo-2973 (1968)