Improved Flux-Concentration Type Electromagnetic Pump Based on Controlled Eddy Current

Improved Flux-Concentration Type Electromagnetic Pump Based on Controlled Eddy Currents

K. Bessho, S. Yamada, S. Nakano, and T. Yamazaki

***Abstract*-The electromagnetic pump proposed by the authors is concerned with the magnetic shielding effect of eddy currents in a conductive plate. In this paper we use FEM analysis to examine the shape of a copper plate for controlling eddy currents, and compare our findings with measured results. The proposed T-shaped plate improves shielding and reduces eddy-current losses compared with existing pumps. We also confirmed an improvement of the thrust force when used in a closed system for circulating a liquid alloy.**

I. Introduction

In the past we have studied the action of eddy currents flowing in a conductor in an ac magnetic field, and have developed an eddy current type coil for generating high ac magnetic fields which employs eddy currents to control the flow of magnetic flux [1,2]. This coil for high magnetic field generation employs the shielding effect of eddy currents in a conducting plate inserted between exciting coils to concentrate flux in a hole in the plate. Thereafter, this high field coil was adopted in a newly proposed electromagnetic pump for use in e.g. transporting liquid sodium metal in fast breeder reactors; this pump was named the flux-concentration type electromagnetic pump [3,4].

In conventional annular-linear electromagnetic pumps, an enlarged pump size necessarily means a larger magnetic circuit length, so that leakage flux is increased and the effective flux in the gap is reduced; consequently the thrust and the flow characteristics are degraded. However, a flux-concentration type electromagnetic pump employing theflux shielding effect of eddy currents can greatly reduce the amount of flux leakage from the magnetic circuit, and so can provide excellent performance characteristics compared with ordinary electromagnetic pumps. Thus an electromagnetic pump based on this principle can be constructed to pump large volumes of liquid.

In this paper we propose a method to further improve the characteristics of such flux-concentration type electromagnetic pumps, describe the results of numerical analysis of such a

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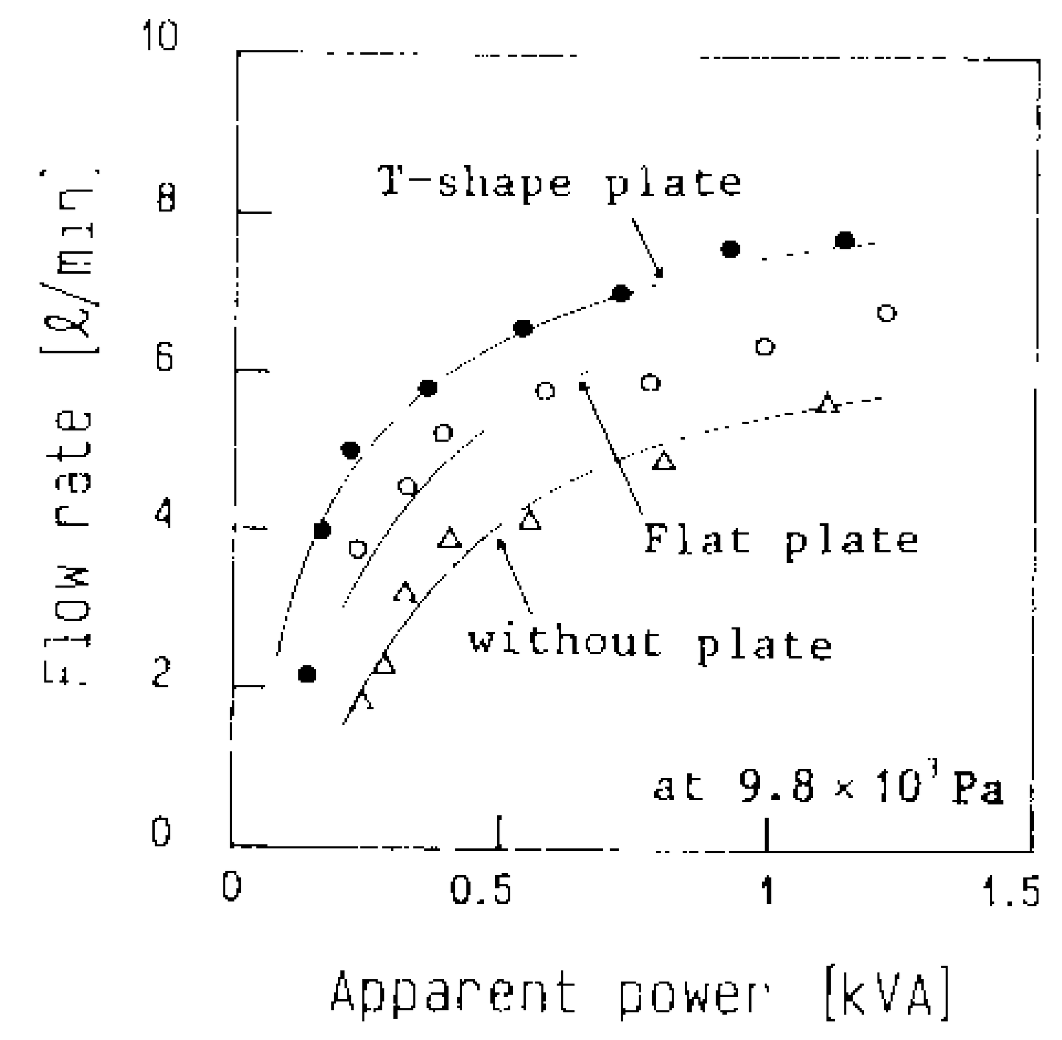

Fig. 13 Comparison of flow rates.

these experiments did not appear in the experiments using the copper pipe in Fig. 10, but is believed to be due to turbulence and other effects caused by an uneven traveling magnetic field in the circumferential direction, peculiar to pump behavior when using a liquid metal. The cause of this behavior and possible countermeasures are now being studied. These experimental results demonstrated that for a liquid metal, use of a T-shaped conductive plate increases the flow rate by 1.4 times over that possible when no conductive plate is used.

V. Conclusion

We have studied the shape of the conductive plate which is a key component in flux-concentration type electromagnetic pumps. In particular, we proposed the use of a conductive plate with a T-shape cross-section, in consideration of the distribution of eddy currents flowing in the plate. Using this plate, Joule losses were alleviated and leakage flux was reduced, for an increase in the effective flux in the gap. In addition, the plate was confirmed to have a beneficial effect on the thrust characteristics measured in mock-up tests using a copper pipe, as well as on the flow characteristics when using a liquid metal. Past experiments and analyses have shown that the thrust and flow characteristics vary greatly depending on the core, slot width and other parameters. Hereafter we intend to study optimal parameter values to improve the pumpcharacteristics, and to determine the optimal design of this pump.

We have completed trial fabrication of a flux-concentration type electromagnetic pump on a scale enabling practical use (capacity 400 ℓ/min) and are presently engaged in preparations for various tests in actual pumping of liquid sodium at 500°C; we shall report our results on a future occasion.

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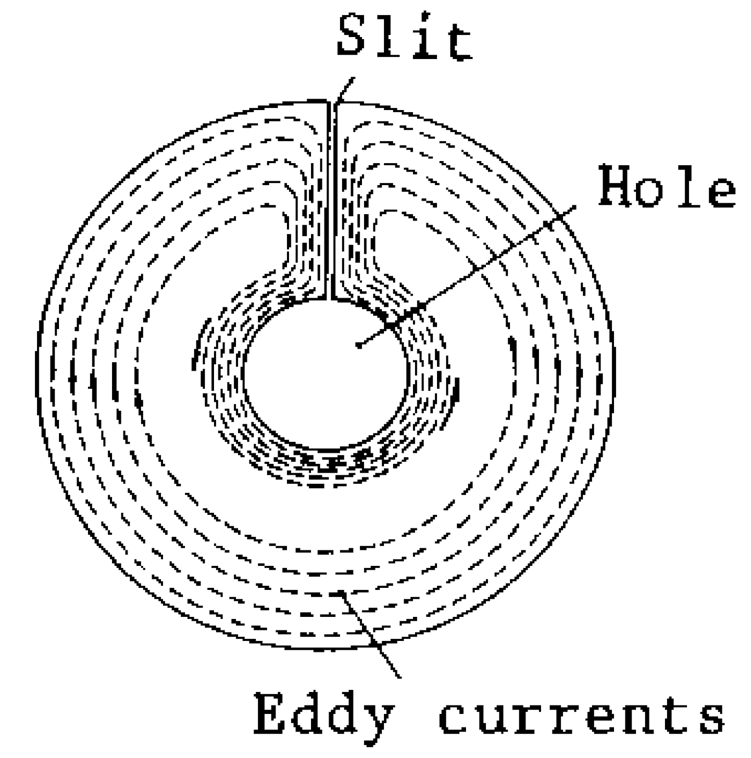

Fig. 5 Flow of eddy currents.

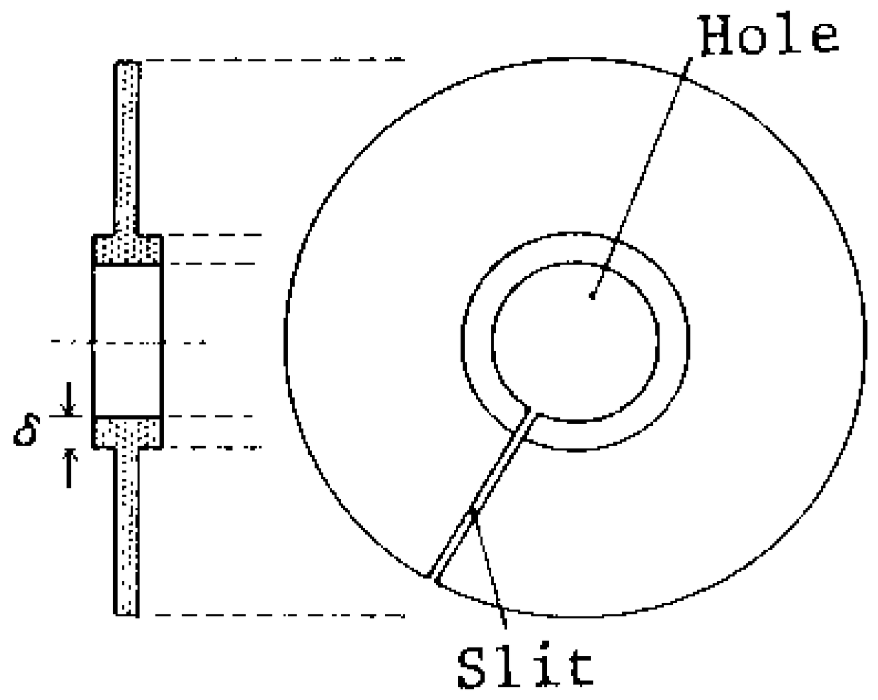

Fig. 6 The T-shaped plate.

for investigations of the effect of the conductive plate. These analysis results confirm that when a conductive plate is inserted, the flux-shielding effect causes the leakage flux which passes through the exciting coils in the slot to be concentrated in the gap between the tip of the outer core and the inner magnetic core.

A schematic illustration of the flow of eddy currents in the conductive plate is shown in Fig. 5. The presence of the slit causes the eddy currents, flowing in the direction opposite the exciting current, to be concentrated around the hole of the plate, so that the current density in this region becomes very high and local overheating gives rise to increased Joule losses. To alleviate this, we employed the conductive plate (with a T-shape cross-section) shown in Fig. 6. Here the required thickness, δ, is determined by the penetration depth (here 8.4 mm at 60 Hz) of the material of the conductive plate (copper); hence a thickness of 10 mm or so is adequate.

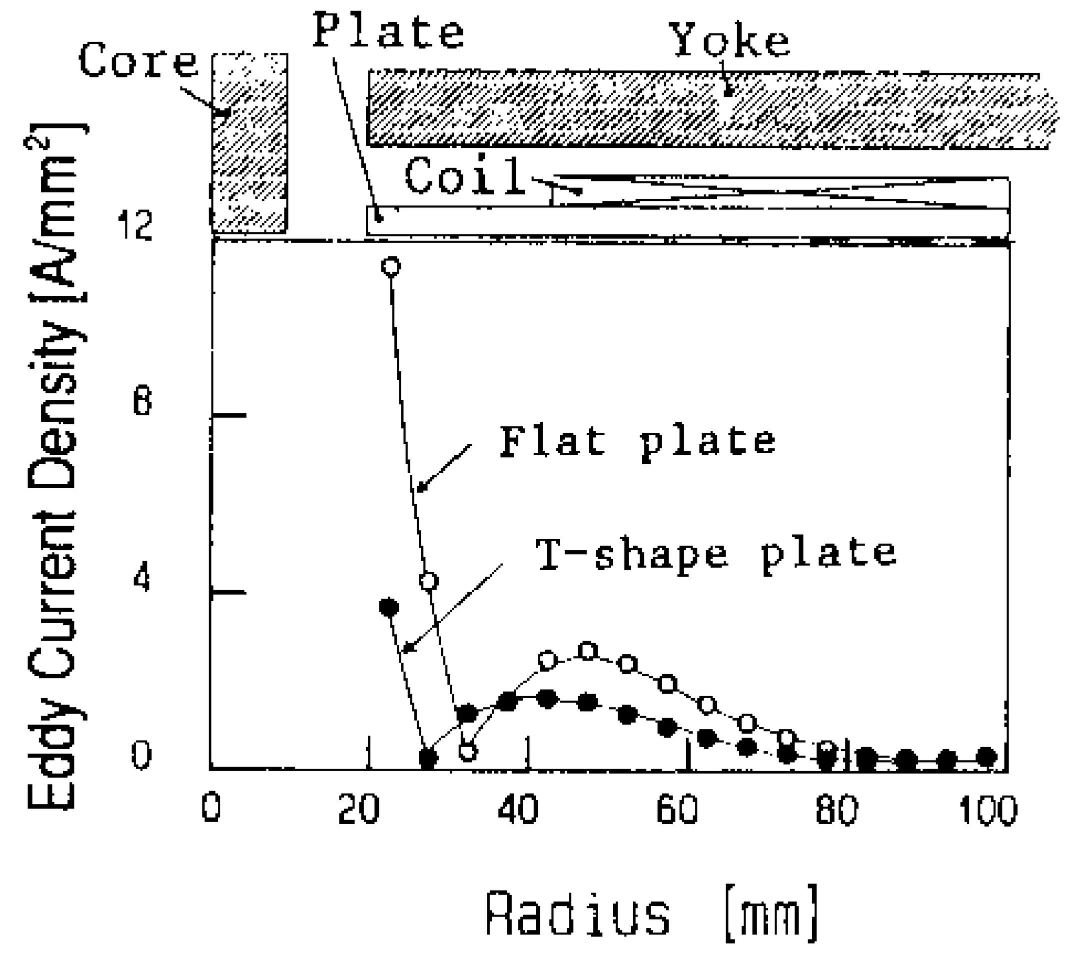

Fig. 7 Distribution of the eddy current density.

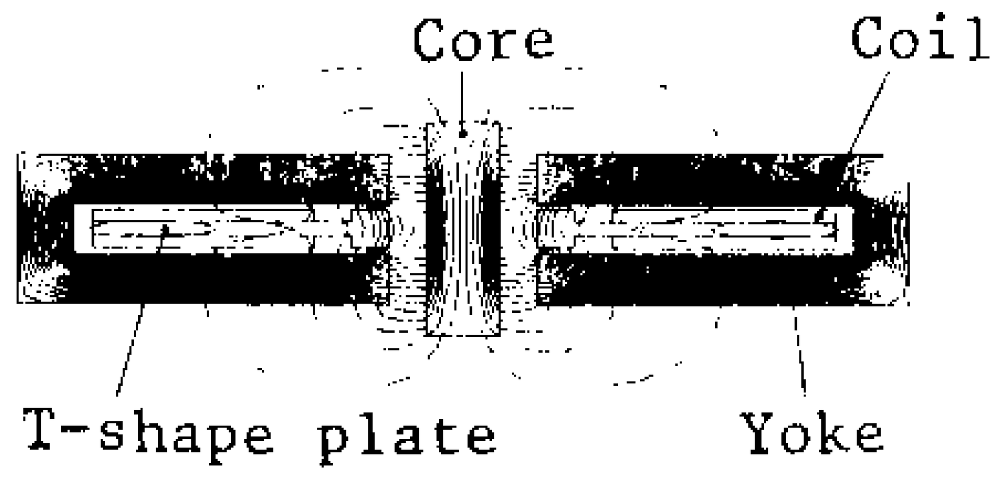

Fig. 8 Flux distribution (calculated by FEM analysis).

Fig. 7 compares the distributions of the eddy current density in a T-shaped conductive plate and in a flat conductive plate. The current density in the T-shaped plate near the hole is 1/3 that in the flat plate, confirming that Joule losses are reduced. Fig. 8 shows the flux distribution resulting from use of a T-shaped plate. Compared with the flat conductive plate of Fig. 3(b), the T-shaped plate allows less flux leakage, so that the effective flux in the gap is increased. One possible reason for this is that the T-shaped plate causes eddy currents concentrated around the hole to be distributed in the axial direction along the pipe, resulting in less flux leakage.

Fig. 9 is a cross-sectional diagram of a flux-concentration type electromagnetic pump model which was trial-fabricated as part of this work. It consists of six of the above-described unit elements, aligned in series. We determined the thrust characteristics of the pump with and without a conductive plate, and for plates of different shapes. The thrust was measured by inserting a copper pipe in the gap in place of liquid metal,

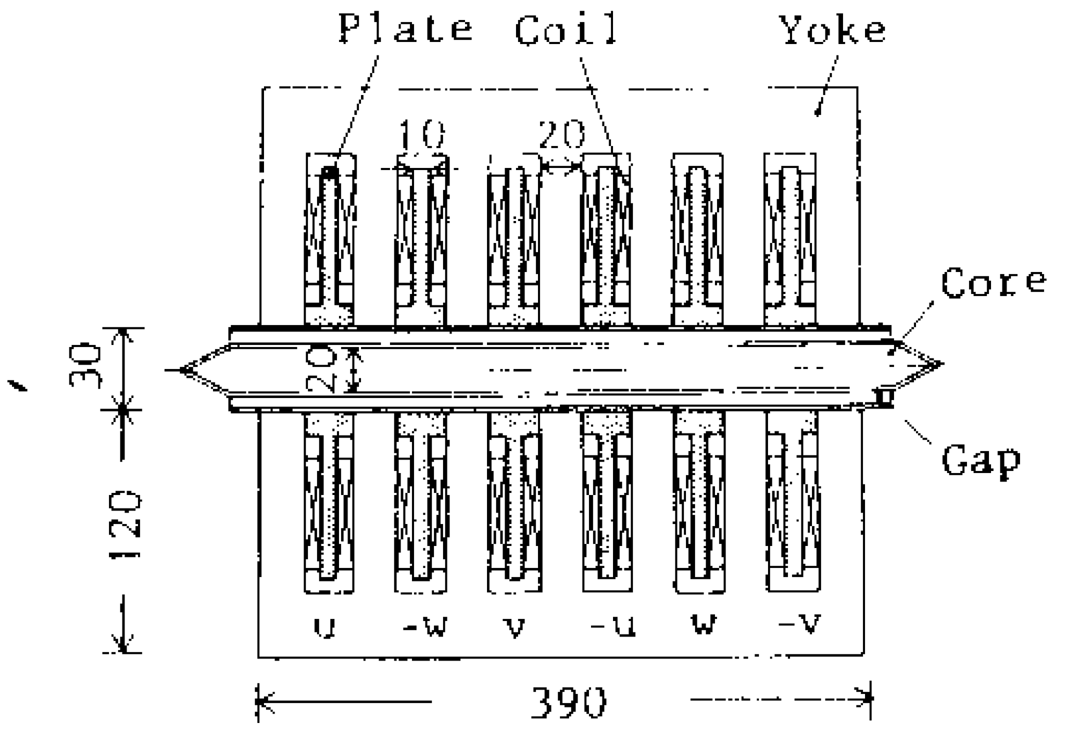

Fig. 9 Cross-section of a flux-concentration type electromagnetic pump.

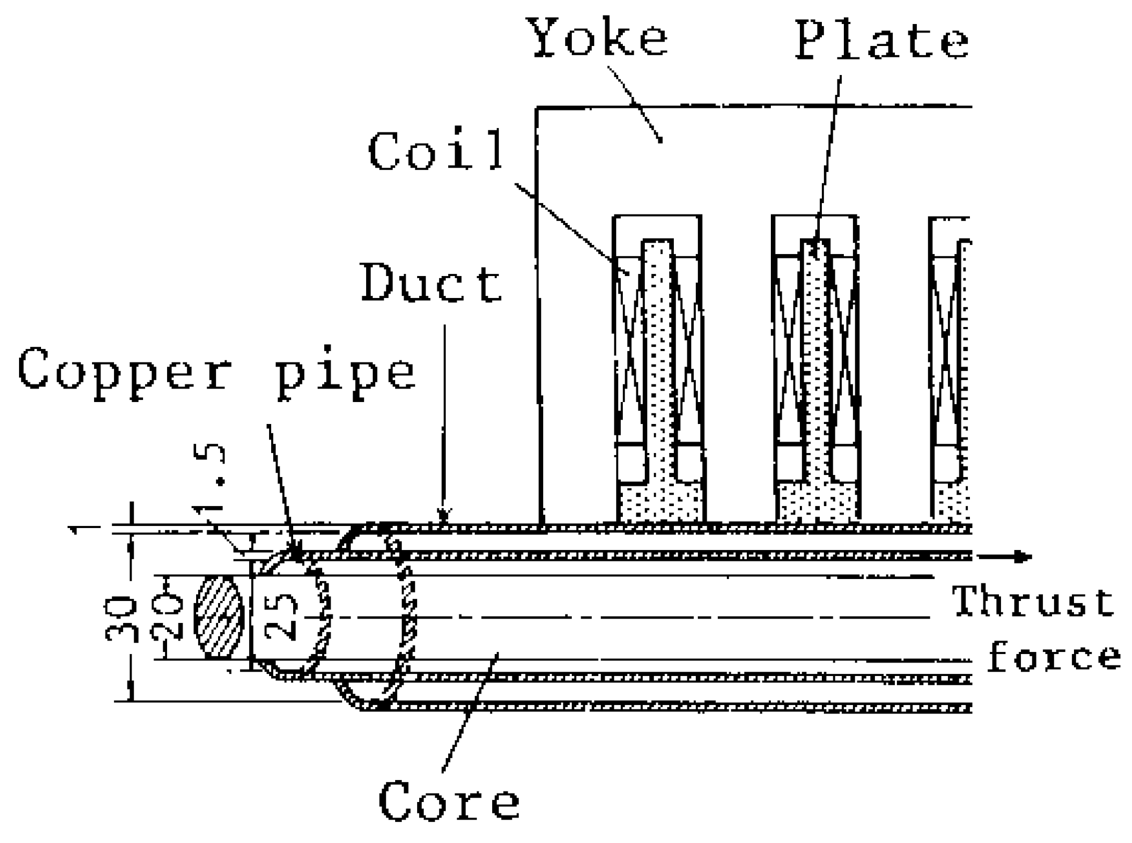

Fig. 10 Configuration used in measuring thrust force.

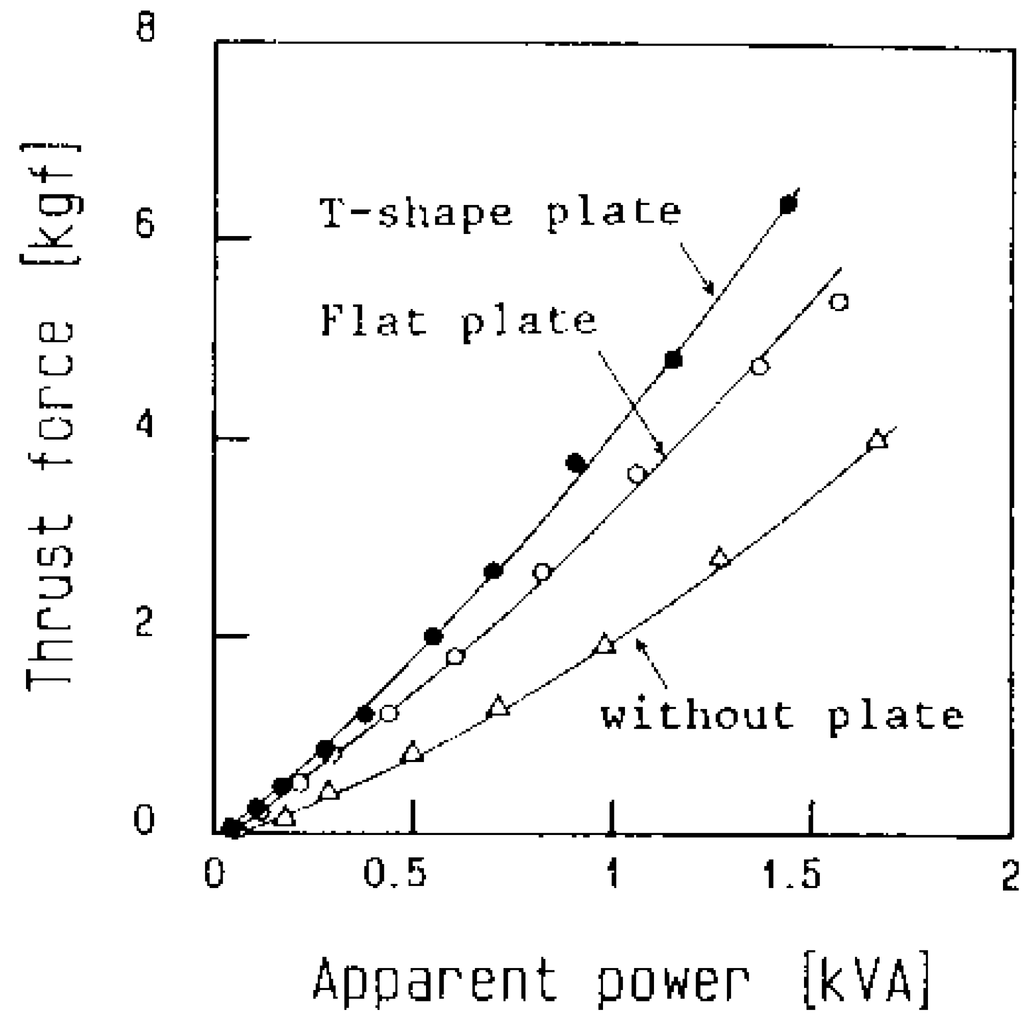

Fig. 11 Comparison of thrust force.

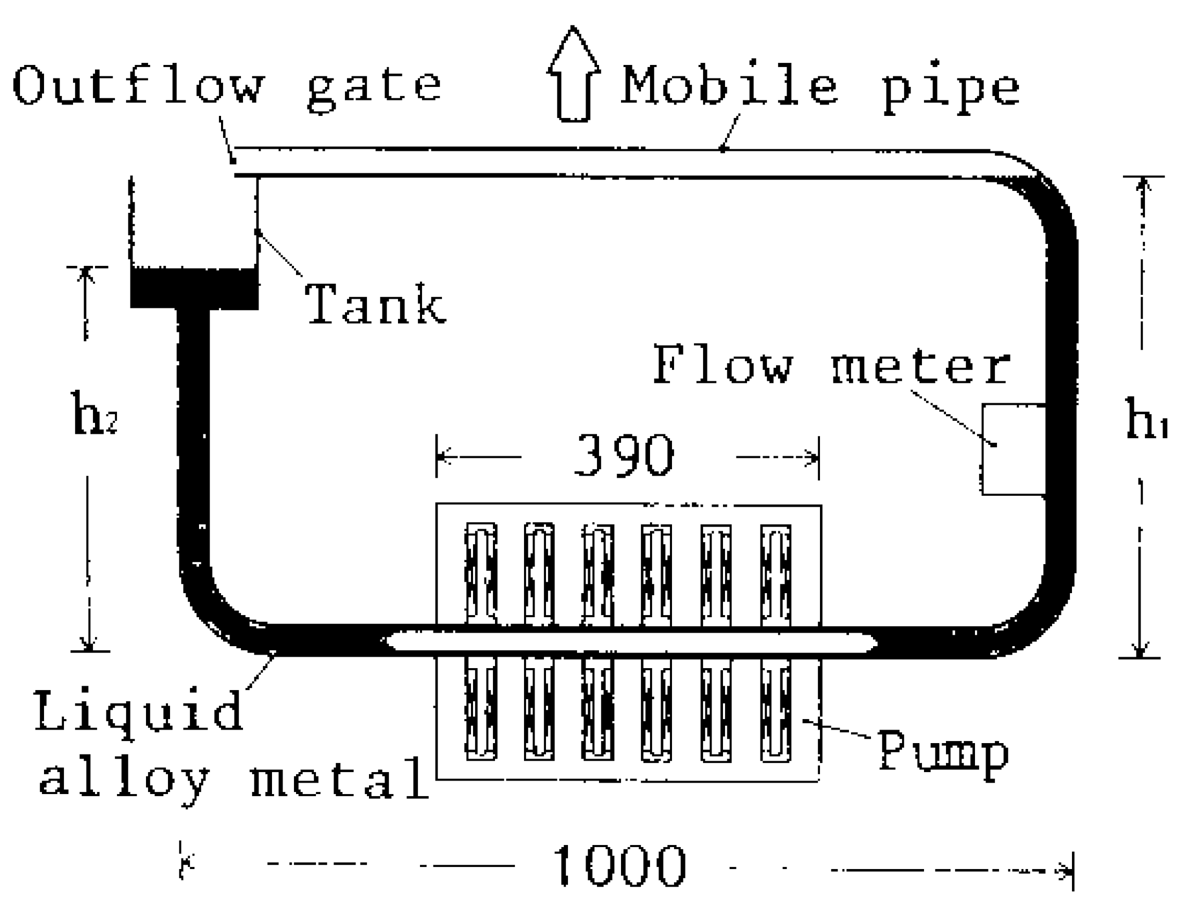

Fig. 12 Circulating system used in measuring flow rates.

and measuring the force acting on the pipe by using a load cell (Fig. 10). Fig. 11 shows the thrust force as a function of the apparent input power. In experiments a 60 Hz three-phase power supply was used, applying voltage within the range in which magnetic saturation effects did not appear. As a result, the thrust was increased by 1.7 times using the flat plates, and by 2.1 times using the T-shaped plates, over the thrust resulting when no plates were inserted. The apparent input power is a quantity often used to express the scale of an ac apparatus.

IV. Flow Characteristics of the Electromagnetic Pump

In order to measure the electromagnetic pump characteristics when using it to transfer liquid metal, we constructed the experimental apparatus shown in Fig. 12. The liquid metal was pumped through a circulating system into which the electromagnetic pump was inserted. As shown in the figure, the height, h_1, of the outflow gate was varied, changing the difference in the heights of the two fluid levels (h_1-h_2) to set the pressure. The flow rate was computed from the fluid velocity, measured using an ultrasonic flow meter mounted on the pipe, and the pipe cross-sectional area, assuming turbulence-free flow. The liquid metal was an alloy (U alloy 47) with a melting point of 46.7°C, a conductivity at room temperature of 2.3×10^6 S/m and a specific gravity of 8.8 (values taken from the producer's catalog).

Fig. 13 shows the flow characteristic as a function of apparent input power when the pressure was held constant at 9.8×10^3 Pa = 0.1 kgf/cm^2. The saturation behavior observed in

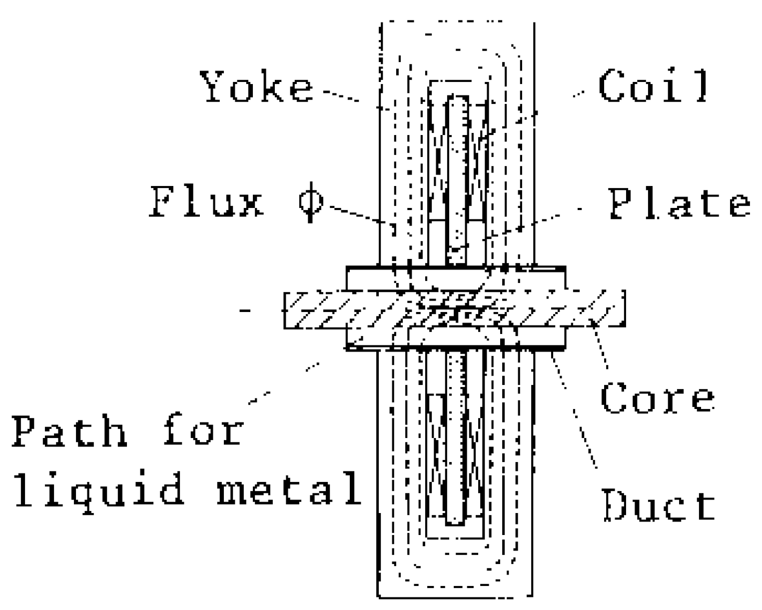

Fig. 1 A single unit of a flux-concentration type electromagnetic pump.

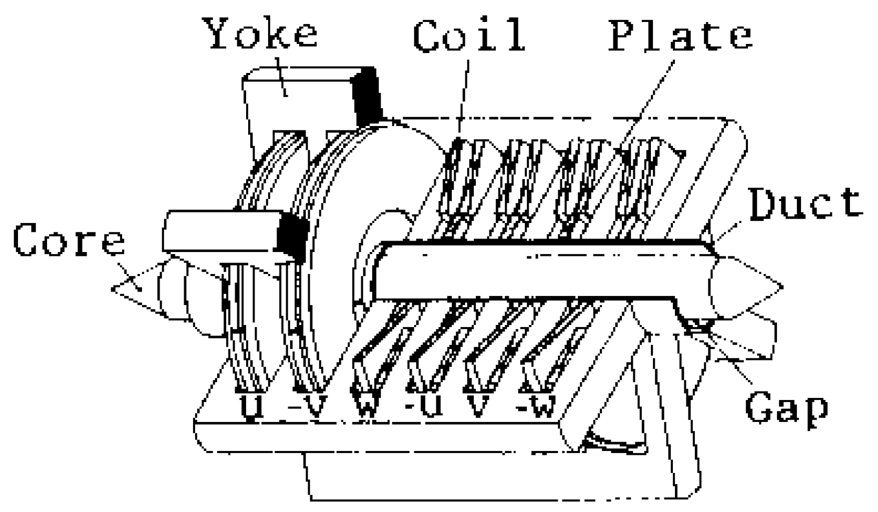

Fig. 2 A flux-concentration type electromagnetic pump.

pump, and, report the results of experimental studies of a trial-fabricated model pump.

II. Construction of the Flux-Concentration Type Electromagnetic Pump

Fig. 1 shows the construction and the flow of flux in a unit element (unit device) composing a flux-concentration type electromagnetic pump. A laminated eddy-current type coil [1,2] is surrounded by an external core; near the center of the coil is a duct, and at the center of the latter is an internal core, forming the magnetic circuit. The space between the duct and the internal core is the gap through which the liquid metal flows. A series of such unit devices are aligned to form a traveling magnetic field in the gap, and a multiphase power supply is used to excite the coils of the devices so that together they act as a flux-concentration type electromagnetic pump [3,4]. Fig. 2 shows an electromagnetic pump configured from six unit devices arranged in a row, and excited by a three-phase power supply. This flux-concentration type electromagnetic pump differs from the usual annular-linear electromagnetic pump in that conducting plates with slits in the radial direction for eddy currents are inserted between the exciting coils.

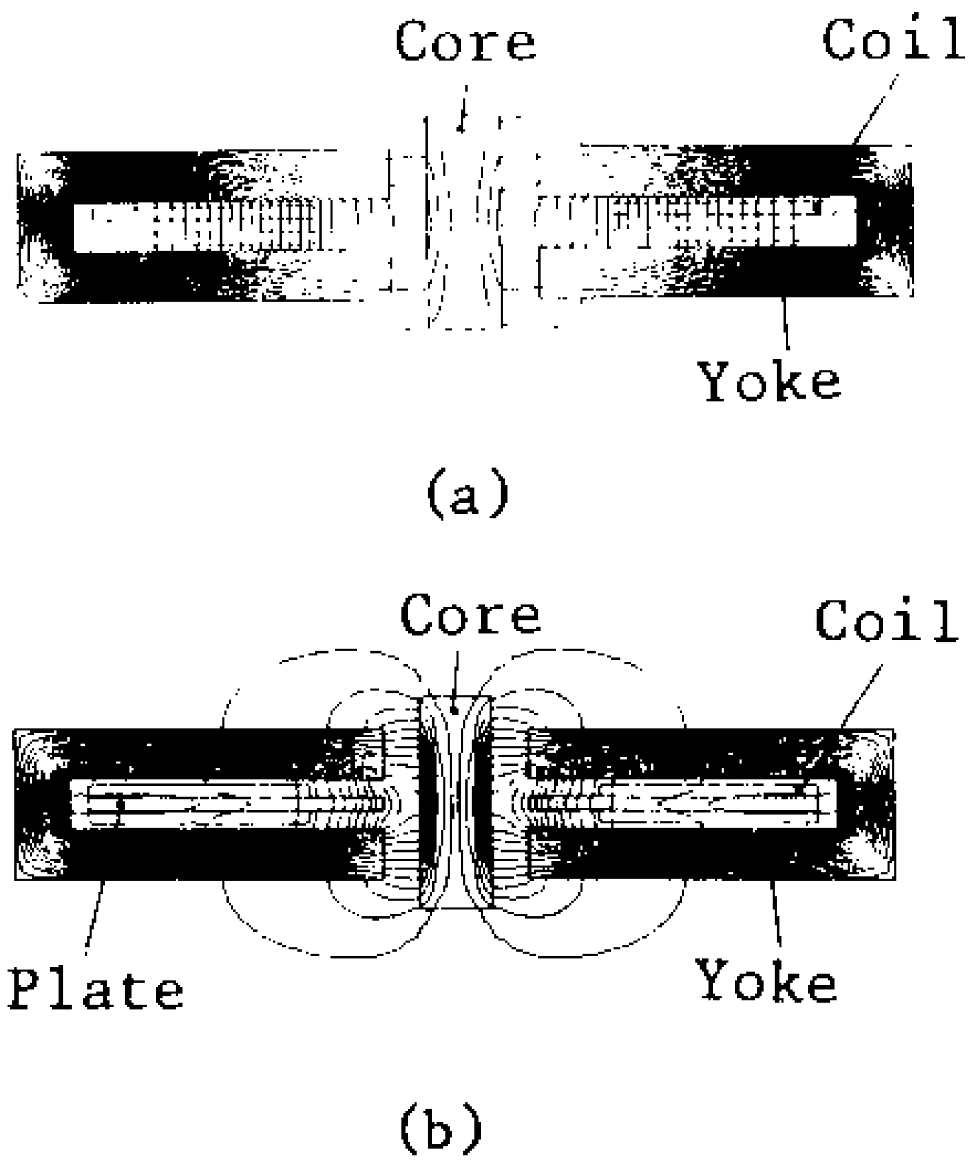

Fig. 3 Flux distributions (calculated by FEM analysis). (a) Without a conducting plate; (b) with a conducting plate.

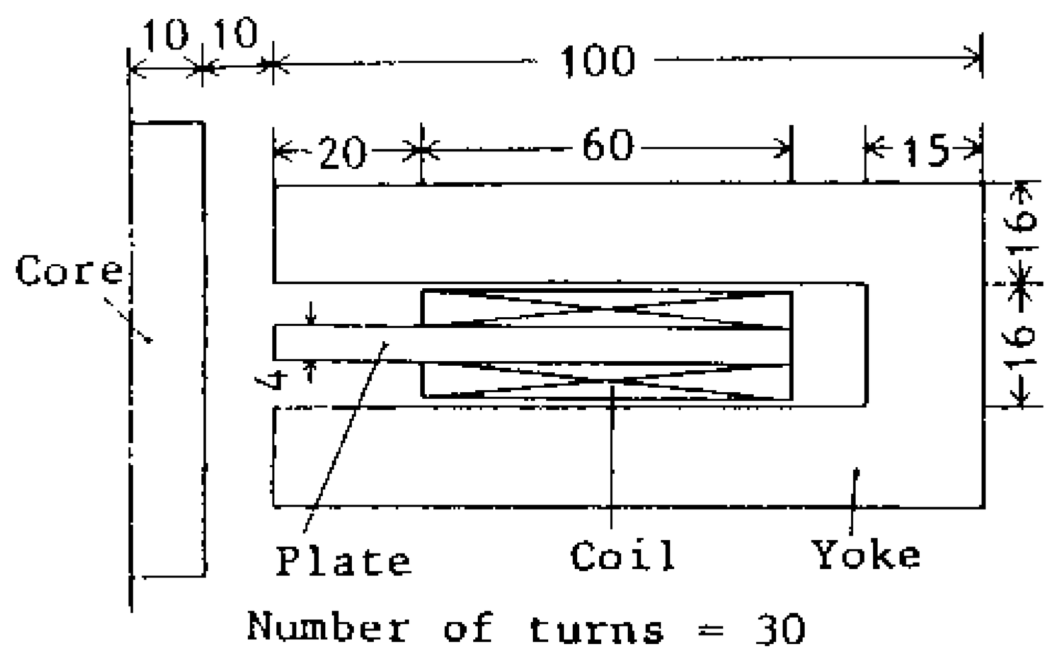

Fig. 4 Construction and dimensions of the experimental model.

III. Study of the Conductive Plates for Eddy Currents

Fig. 3 shows the change in flux distribution caused by the insertion of a conducting plate, as calculated by finite element analyses using the model shown in Fig. 4. This analysis was performed for single phase excitation of a single unit device (consisting of two exciting coils and one conductive plate), several of which constitute the flux-concentration type electromagnetic pump. While somewhat different from the operation of an actual electromagnetic pump, it is sufficient