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MAGNETOHYDRODYNAMICS TEST OF A ONE-SIXTH SCALE MODEL* OF A CTR RECIRCULATING LITHIUM BLANKET

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Summary

A one-sixth scale model of an element of a recirculating lithium blanket for a fusion reactor is tested experimentally. The model utilizes NaK 44 and is shown in Fig. 1. It is instrumented to measure flow, pressure drop and pumping power as a function of the applied magnetic field (0 to 4 T) and the pump current (0 to 300 amps dc). The flow is measured by an electromagnetic flow meter (the top set of electrodes) and by means of a buoyant capsule whose traverses are detected by the system of coils mounted on the lower part of the right leg of the loop. The pressure is measured by determining the liquid level in the head tanks located above the loop. In Table 1 are listed the important[1] fluid and magnetohydrodynamic parameters for the full-scale blanket,[2] a previous experiment[3] and the present model. In the present experiment a large increase has been made in the Hartmann number, one of the most significant parameters.

Table 1. Comparison of Dimensionless Parameters

Parameter	Full Scale[1]	Carlson[3]	1/6 Scale Model
Reynolds Number	350,000	17,000	22,000
Magnetic Reynolds Number	0.567	0.0409	0.0471
Hartmann Number	52,400	960	11,700
Wall to Channel Conductivity Ratio	0.008	0.048 to 0.098	0.0158

The experimental results indicate that the ratio of loop pressure drop and average fluid velocity increases as a quadratic function of the magnetic

field. The square term is dominant for the higher values of magnetic field and is predictable by simple laminar magnetohydrodynamic theory. For any given velocity and magnetic field the pressure drop in the field-flow aligned legs of the loop is much greater than it would be in ordinary hydrodynamic flow, but nevertheless is more than an order of magnitude less than the pressure drop encountered when the fluid flows across the magnetic field. The pumping power is measured as a function of magnetic field and fluid velocity. For fields greater than 1 T and velocities exceeding 1 cm/sec the pumping power varies as the square of the product of the fluid velocity and the magnetic field. The measured value of the proportionality factor agrees with predictions based on certain simplifying assumptions.

The extrapolation of these experimental results to a full scale recirculating lithium blanket indicates that no excessive pressures or pumping power is likely to result unless a drastic change in flow regime occurs as the MHD parameters are increased to those of the full scale device.

References

1. F. J. Young, Magnetohydrodynamic Blanket Scaling in a Toroidal Fusion Reactor, presented at the First Topical Meeting on Technology of Controlled Thermonuclear Fusion, San Diego, California, April 16-18, 1974.
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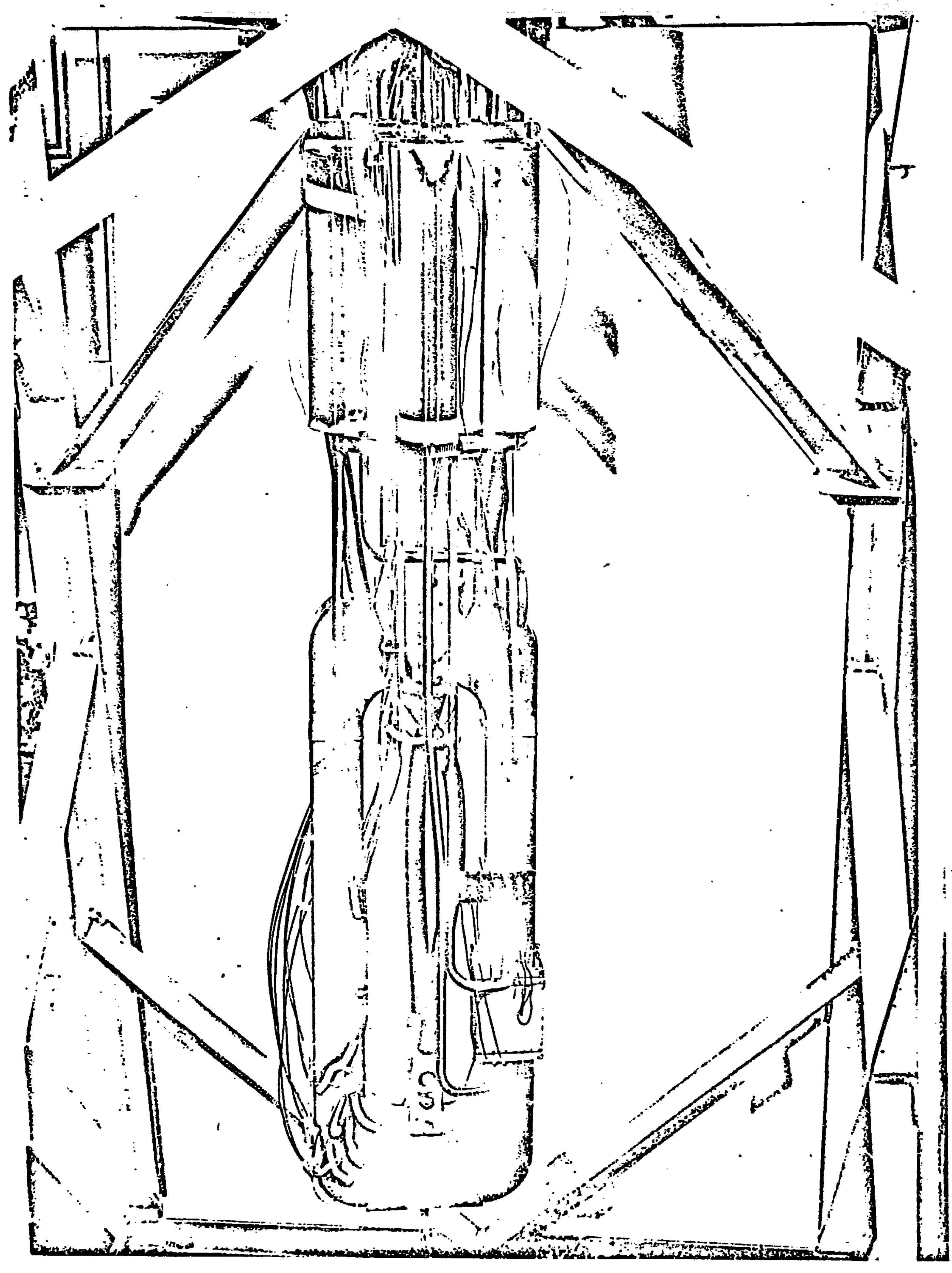

Fig. 1. One-sixth scale model of section of fusion reactor blanket.

Introduction

In a previous study, A. P. Fraas described and proposed the construction of a one-sixth scale model of an element of a recirculating lithium blanket for a fusion reactor.[1] The proposed scale model has been constructed and instrumented to measure flow, pressure drop and pumping power. The scale model experiment has been conducted over a range of parameters in accordance with said original goals.

It is the goal of this work to check experimentally the analysis[1] which indicates a CTR blanket can utilize a dc EM pump to induce forced circulation power. In addition, this scale model can be used for heat flow measurements. In particular, various pressure drops in the loop were measured as a function of the applied magnetic field and the pump current. Among these are the pump pressure rise and the pressure drops in the legs where the fluid streams along magnetic flux tubes. The required pump power input and efficiency were determined as a function of applied magnetic field and pump current.

Description of Apparatus

The one-sixth scale model consists of a rectangular loop made of stainless steel and filled with NaK 44. A photograph of the loop is shown in Figure 1. The vertical legs of the loop have a 2 in. square cross-section. The horizontal legs have a 2 x 3.2 in. cross-section. The straight sections of the vertical legs are 13.5 in. long and the overall height is 24 in. The overall width of the loop is 8.5 in. The walls of the loop are made of 0.065 in. thick in stainless steel. Trapezoidal-shaped copper electrodes are brazed to each side of the horizontal legs at both ends. Welding cables were bolted to the electrodes at the lower end, and the direct current used to pump the liquid metal was applied to these electrodes in all the tests that were performed.

Instrumentation

Electrical Measurements

The direct current used to pump the liquid metal is provided by a regulated solid state AC-DC converter with an output of 600 amp. The current was measured from the voltage drop across a series shunt.

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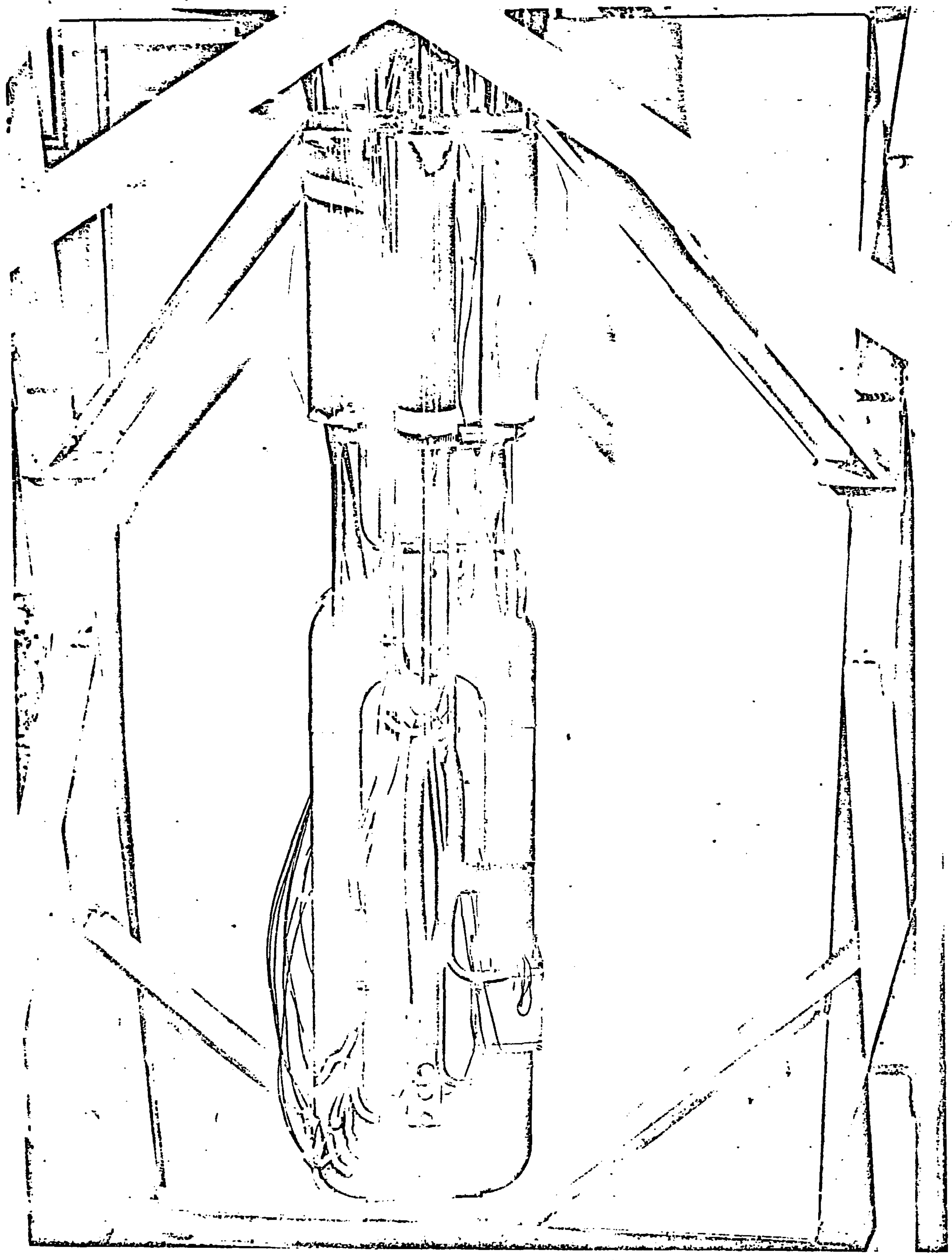


[illegible]

Voltage leads are attached to the loop wall at 22 points. Copper leads were soldered to short stainless steel ribbons and the ribbons were spot-welded to the loop wall. Voltage leads were located adjacent to each of the four electrodes and at 18 other locations. The voltage reading across the bottom pair of electrodes was used to calculate the pumping power, and the voltage reading across the top pair of electrodes was used in conjunction with the magnetic field strength to calculate the fluid velocity using the equation for an electromagnetic flowmeter.

Velocity Measurement by Eddy-Current Method

The fluid velocity was also measured by determining the transit time around the loop of a gas-filled stainless steel capsule that has a neutral buoyance in NaK 44.

This measurement was accomplished by the use of a differential transformer to detect the passage of the gas-filled capsule. A primary ac exciting coil was wound around the vertical leg of the loop. The ac frequency is adjusted to allow the ac fields to penetrate the fluid completely. The eddy currents induced in the fluid modify and tend to cancel the applied ac field from the primary coil. Two secondary coils comprising many turns are wound side by side under the primary coil. The hollow stainless steel capsule constitutes an electromagnetic void in the fluid where no eddy currents can be generated. Hence the capsule alters the ac fields existing in its vicinity. Thus when it approaches the first secondary coil, the voltage in that coil becomes altered before the voltage in the second coil changes. By connecting the voltage of the two secondary coils in opposition, a net voltage output is obtained each time the capsule passes by. The ac signal is rectified and applified to drive a counter.

The signal from the transformer was not influenced by the presence of the dc magnetic field.

Pressure Measurement

Pressure tap holes 1/8 in. in diameter are located at 12 positions in the loop wall. A 3/8 in. OD stainless steel tube is welded to the loop wall at each pressure tap and the tube is welded to a head tank located about

6 in. above the loop. The head tanks are 10 in. in height and have an OD of 2 in. Tubes are welded to the top of each head tank and connected to a common header so that fluid can overflow from any head tank to the others. The loop was initially filled to a level of 3 in. in the head tanks. When the fluid is circulating around the loop, a pressure gradient is established and the liquid level drops in the tanks on the low pressure side of the pump and rises on the high pressure side.

The liquid level in the head tanks is measured using a bridge circuit that employs inductance coils in two legs of the bridge and resistors in the other two legs. A schematic circuit diagram is shown in Fig. 2. A single layer coil is wound on the outside of each head tank and also on the outside of an empty tank that provides a fixed inductance in one leg of the circuit. An alternating current excites the coils in such a manner that the resulting magnetic field penetrates the stainless steel head tank wall easily but dies off rapidly in liquid NaK. As a head tank fills with NaK the inductance of the coil in the head tank decreases because the NaK excludes magnetic flux. Hence, it is possible to feed a constant value of alternating current to a head tank coil, measure the voltage and relate the voltage to the NaK level in the head tank. For this purpose a frequency of 5 Khz was found suitable. The current was passed through a head tank coil and the empty tank coil in series and the voltage was measured. The voltages measured during the tests were converted to NaK levels by comparing them to the voltage measured with known NaK levels in the head tanks and from special calibration head tanks with known levels of NaK.

Voltages measured with and without the presence of the dc magnetic field indicated that the measurements were not influenced by the dc magnetic field.

Scaling Considerations

A detailed study of the scaling of a recirculating lithium blanket[2] has been made. Excepting heat flow measurements, the important magnetofluid-mechanical parameters are:

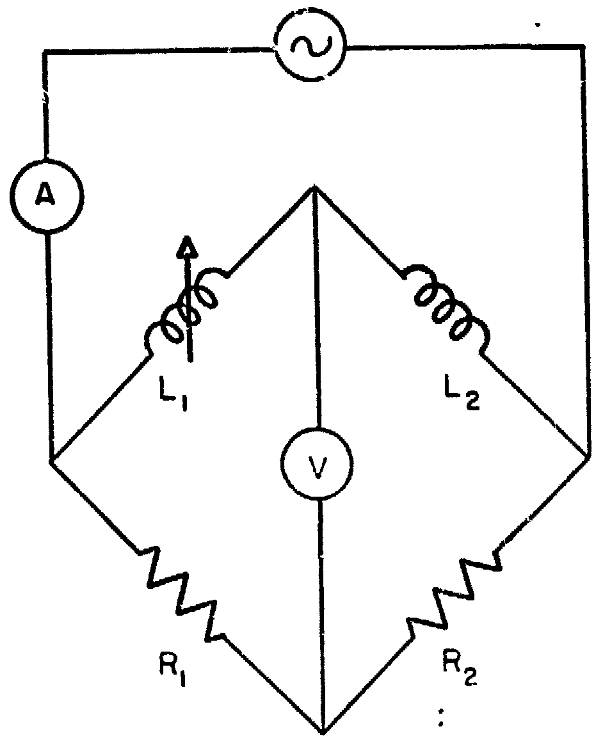


Fig. 2. Schematic circuit diagram of liquid level indicator.

1. The Reynolds number = Re = LV_o/ν which is a measure of the ratio of inertial to viscous force
2. The magnetic Reynolds number = Rm = $LV_o\sigma\mu_o$ which is a measure of the ratio of the magnetic convection to magnetic diffusion
3. The Hartmann number = M = $\frac{L}{2} B_o\sqrt{\sigma/\mu}$ which is a measure of the ratio of the electromagnetic to the viscous force and
4. The conductivity ratio = C = $2\sigma_w t_w/\sigma L$ where L is the cross channel dimension (in the direction paralleling the magnetic field), V_o the flow velocity, ν the kinematic viscosity, μ the viscosity, μ_o the magnetic permeability of free space, σ the fluid electrical conductivity, σ_w the wall electrical conductivity, t_w the thickness of the wall and B_o the applied magnetic induction. Table 1 compares the largest values of the parameters of the full scale lithium blanket and of those for an experiment carried out by Carlson[3] to those of the 1/6 scale model being investigated experimentally.

Table 1. Comparison of Dimensionless Parameters for Typical Cases.

	Full Scale	Carlson[3]	1/6 Scale Model
Re	350,000 (V_o = 0.361 m/s)	17,000 (V_o = 0.86 m/s)	22,000 (V_o = 0.18 m/s)
R_m	0.567	0.0409	0.0471
M	52,400 (B = 2T)	960 (B = 1T)	11,700 (B = 4T)
C	0.008	0.048 to 0.098	0.0158

As a rule of thumb turbulence does not occur if Re < 60 M. This is clearly the case for both the lithium loop and the experimental scale model. The Reynolds numbers need be scaled only well enough that both loops operate

Table 1. Comparison of Dimensionless Parameters for Typical Cases.

	Full Scale	Carlson[3]	1/5 Scale Model
Re	350,000 (V_o = 0.361 m/s)	17,000 (V_o = 0.86 m/s)	22,000 (V_o = 0.18 m/s
R_m	0.567	0.0409	0.0471
M	52,400 (B = 2T)	960 (B = 1T)	11,700 (V = 4T)
C	0.008	0.048 to 0.098	0.0153

in a laminar flow regime, i.e., with essentially no turbulence. The magnetic Reynolds number is not very easily scaled. For the full scale model it is 0.567 in the pump section, indicating a slight drag of the applied field caused by transverse fluid flow. In the 1/6 scale model very little drag is produced. For a first approximation it is permissible to ignore the scaling of the magnetic Reynolds number. The parameters of greatest importance are the Hartmann number and the wall-to-fluid conductivity ratio. The latter can be controlled by the proper choice of scale model wall material and thickness. In the 1/6 scale model the wall-to-channel conductance ratio is almost twice that existing in the full scale model. This means that for the experimental 1/6 scale model the wall shorts more electric current than desirable for proper scaling. Once the scale model liquid and scale factor (1/6) are picked, the Hartmann number of the scale model depends on the strength of the available magnet. Our magnet is rated at 6.5 Tesla rather than 4 Tesla. Had we permission to use it at its peak rating, a Hartmann number of about 19000 would have resulted. This gain was not considered worth the risk of the magnet. To scale properly the Hartmann number with the 1/6 scale model (assuming NaK 44) requires a 17.9 Tesla magnet, an almost impossible requirement in view of the magnet bore required. Hence, for the first experiment we attained a maximum Hartmann number of about 12,000 which nevertheless is more than an order of magnitude greater than previously attained by G. A. Carlson.[3] The conductivity parameter for the 1/6 scale model more closely approximates that of the full scale prototype than do previous experiments. None of the experiments mentioned reproduce the Reynolds or the magnetic Reynolds numbers desired. It is noteworthy that for the 1/6 scale model loop the proper magnetic Reynolds number can be attained if the fluid velocity is boosted to about 2.2 m/sec. Then the Reynolds number would increase to 265,000 which is close to the full scale value.

Results

Although data were taken with the NaK loop in various positions, time limits our discussion to the case where the loop was centered in the solenoid,

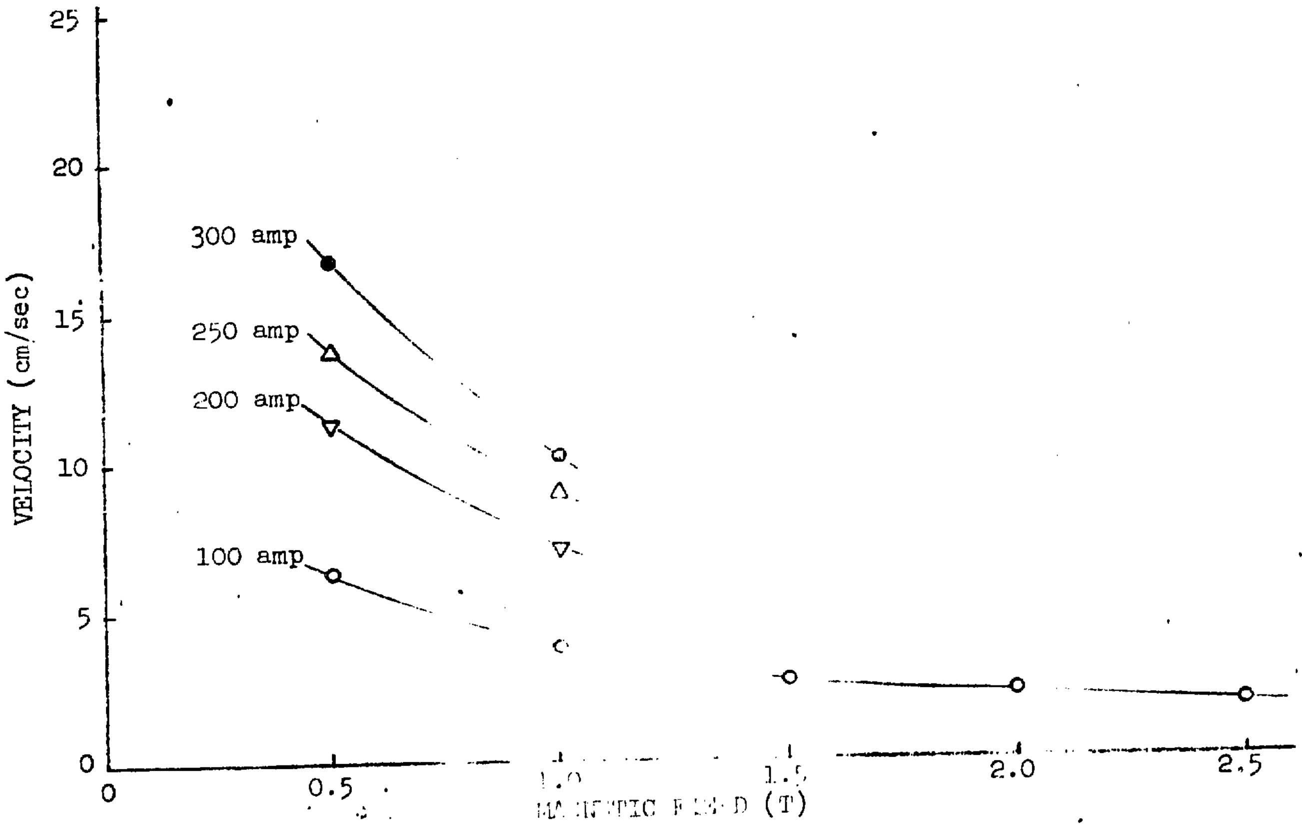


Fig. 3. Velocity vs. magnetic field for various pump currents with the loop centered. (4 pressure taps)

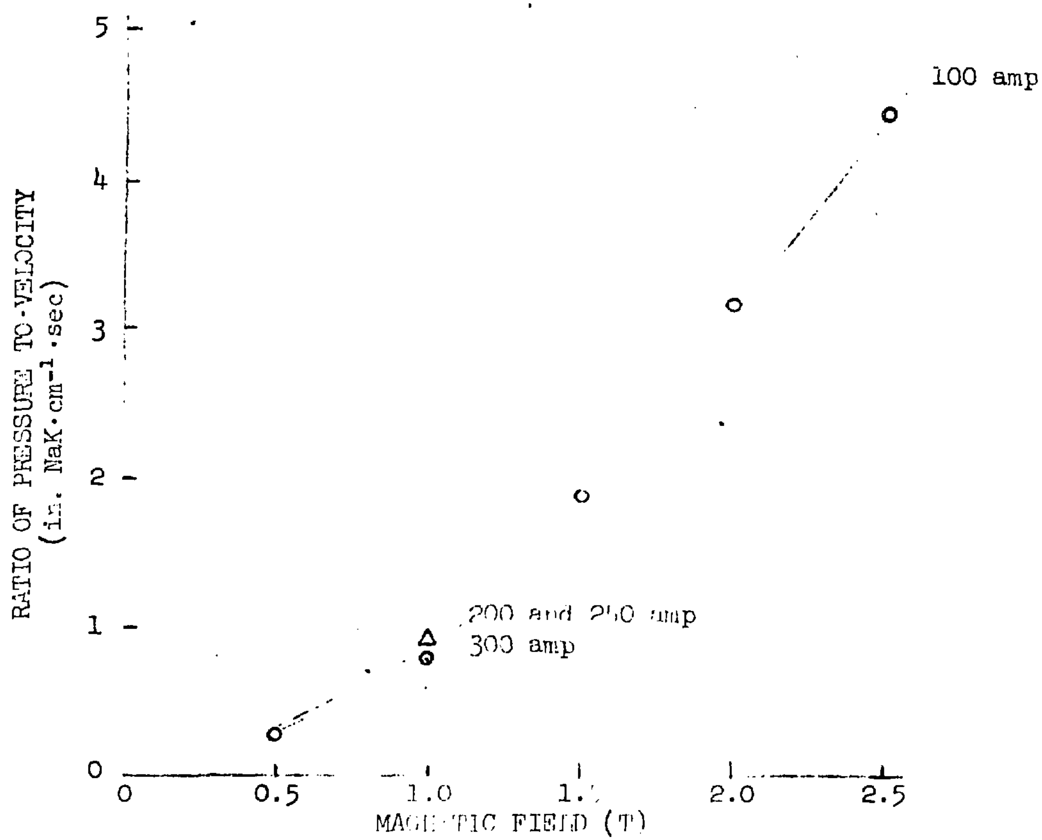


Fig. 4. Plot of pressure-velocity ratio vs. the applied magnetic field for various currents when the loop was centered with 3 pressure taps.

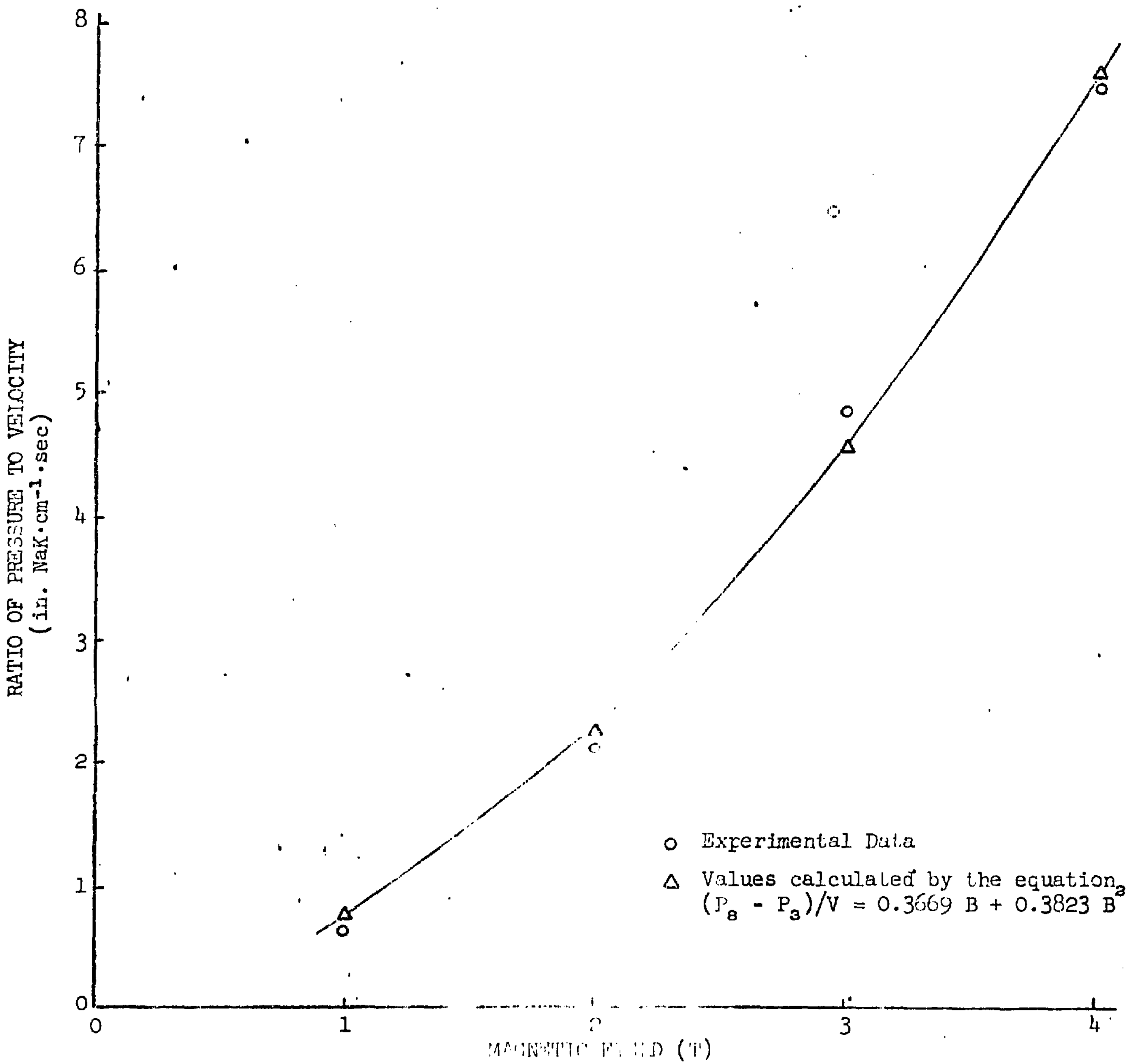


Fig. 5 . Comparison of experimental data and an empirical equation for the pressure-velocity ratio as a function of the magnetic field for the centered loop with three pressure taps and a pump current of 50 amp.

$$\frac{P}{V} = 0.5\ B + 0.4\ B^2 \text{ for } I = 100 \text{ amps}$$

$$\frac{P}{V} = 0.37\ B + 0.38\ B^2 \text{ for } I = 50 \text{ amps}$$

$$\frac{P}{V} = 0.01\ B + 0.4\ B^2 \text{ (simple theoretical prediction)}$$

Fig. 6

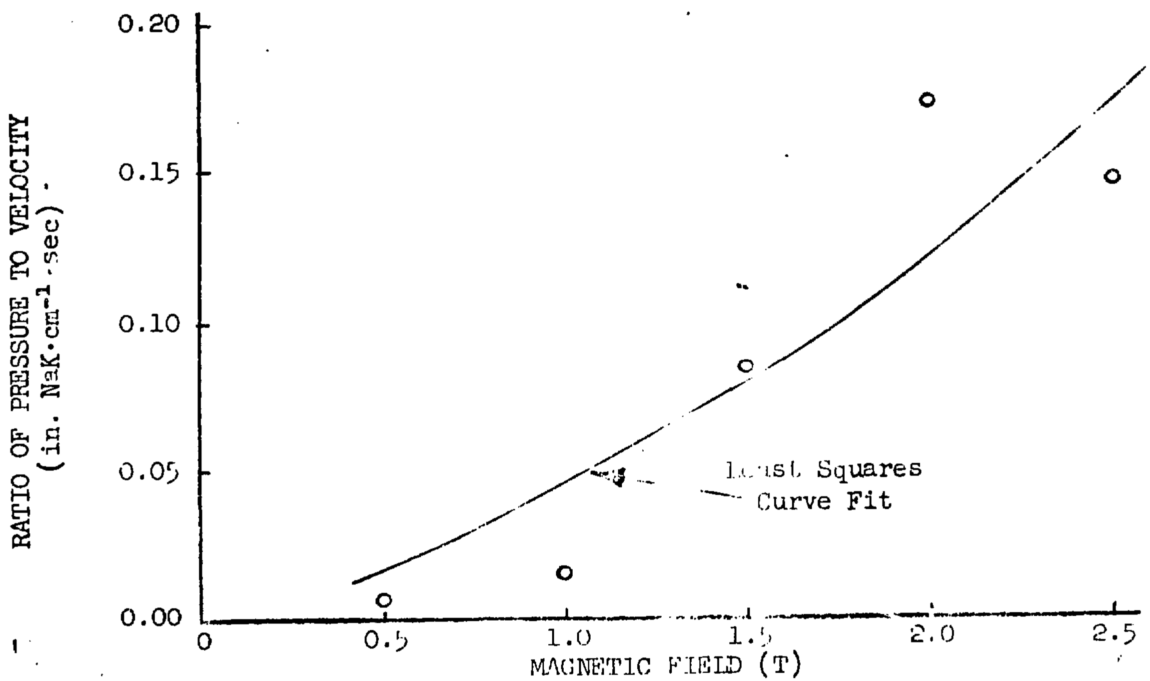


Fig. 7. The pressure-velocity ratio in the discharge leg vs. applied magnetic field for a pump current of 100 amp. (The circles are the experimental data.)

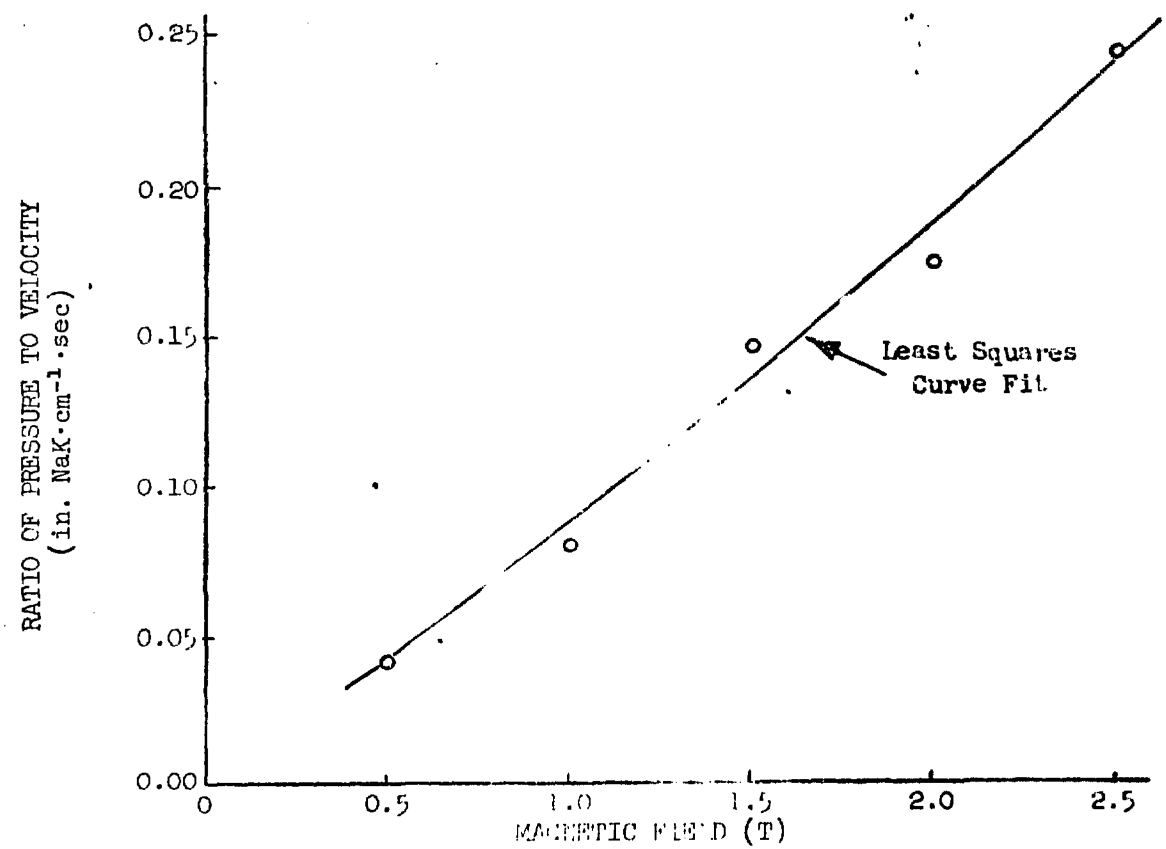


Fig. 8. Pressure-velocity ratio in the suction leg vs. applied magnetic field for a pump current of 100 amp. (The circles are experimental data.)

hence immersed in a uniform magnetic field. The discussion is divided into three categories; (1) velocity measurements relating velocity to pump current and axial magnetic field, (2) the ratio of pressure to velocity related to pump current and axial magnetic field and (3) pumping power related to velocity and magnetic field. The ratio of pressure to velocity is extrapolated as a function of magnetic field in order to obtain a rough idea of the functional role of M, the Hartmann number. This allows a prediction of the pressure drop to be expected in the full scale prototype. A similar attempt is made to predict the pumping power as a function of magnetic field or Hartmann number for a fixed velocity.

Velocity Measurements

In Fig. 3 we have plotted mean velocity versus the applied magnetic field for several values of pump current. By the method of least squares the mean velocity can be expressed as a function of current and magnetic induction. For any given value of induction the mean velocity varies almost linearly with the applied current.

Pressure to Velocity Ratio Measurements

The loop pressure to velocity ratio for various pumping currents is plotted as a function of induction in Fig. 4. The head tanks were not large enough to allow this curve to be extended to 4 Tesla. The pump current was reduced to 50 amps and the pressure-to-velocity ratio was obtained for inductions up to 4 Tesla. The variation was found to be quadratic in nature as may be seen in Fig. 5 and 6. The coefficient of the linear term is much larger than simple MHD theory preducts.

The pressure drop-to-velocity ratio was measured in the leg where the fluid flowed along the magnetic field lines on the discharge and suction sides of the electromagnetic pump. Comparison of the results shown in Figs. 7 and 8 indicates a smaller ratio in the discharge leg. The pressure drops are two orders of magnitude greater than would be expected in ordinary, fully developed, laminar flow. Thus it seems that a magnetoviscous profile persists in the vertical legs and is characterized by pressure drops which

Discharge Leg

$$\frac{P}{V} = 0.03\ B + 0.016\ B^2$$

Suction Leg

$$\frac{P}{V} = 0.08\ B + 0.007\ B^2$$

Fig. 9

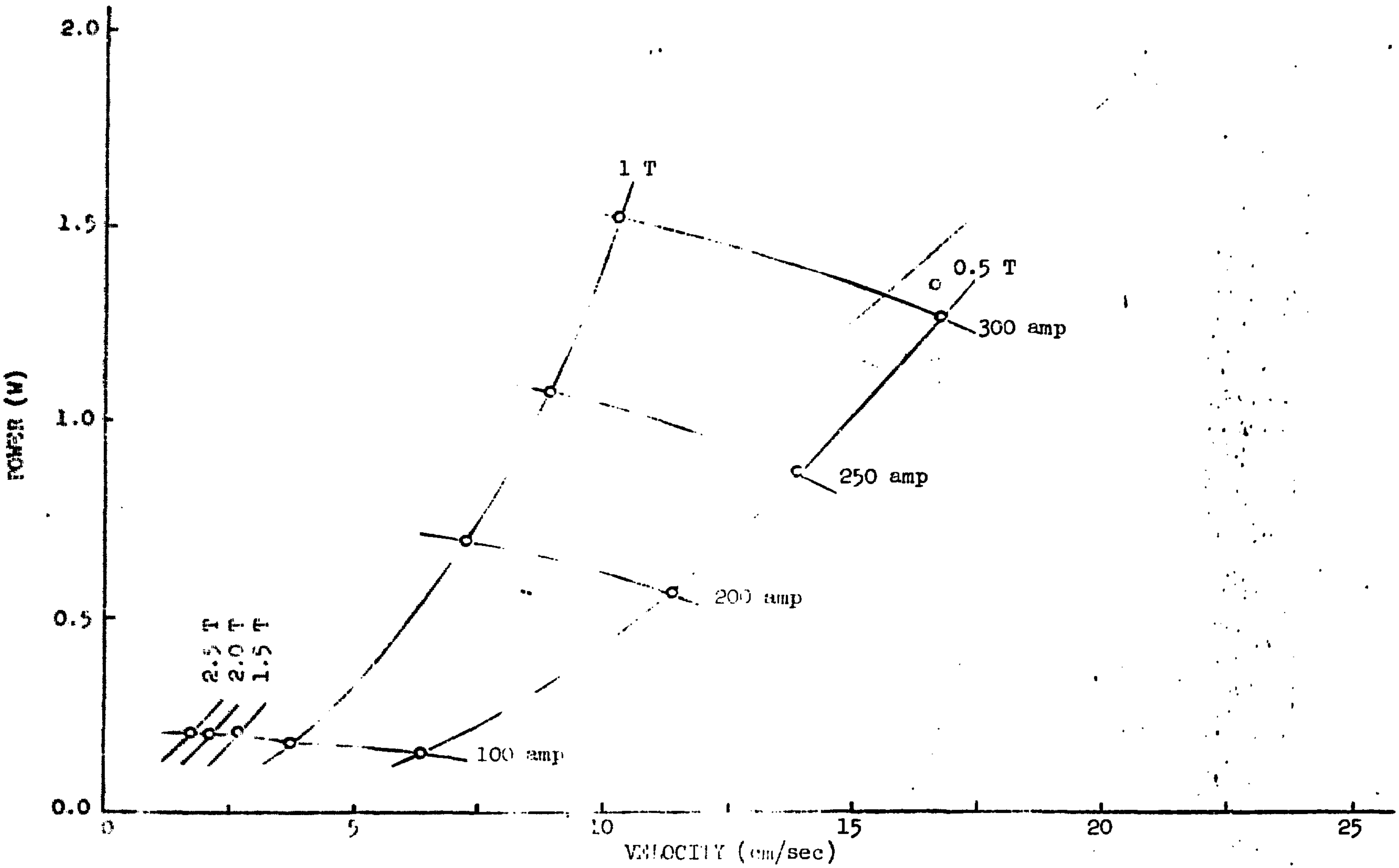


Fig. 10. Plot of pumping power for the centered loop when four pressure taps were monitored.

$$POWER = VB\,[-0.012 + 0.004V + (-0.007 + 0.012V)\,B]$$

Fig. 11

are small compared to those existing in regions where the fluid crosses magnetic field lines. The results indicate that the vertical legs behave as entrance and exit regions in which fully developed flow does not exist. Fig. 9 shows the least squares fit for the pressure-to-velocity ratio in the discharge and suction legs as a function of induction.

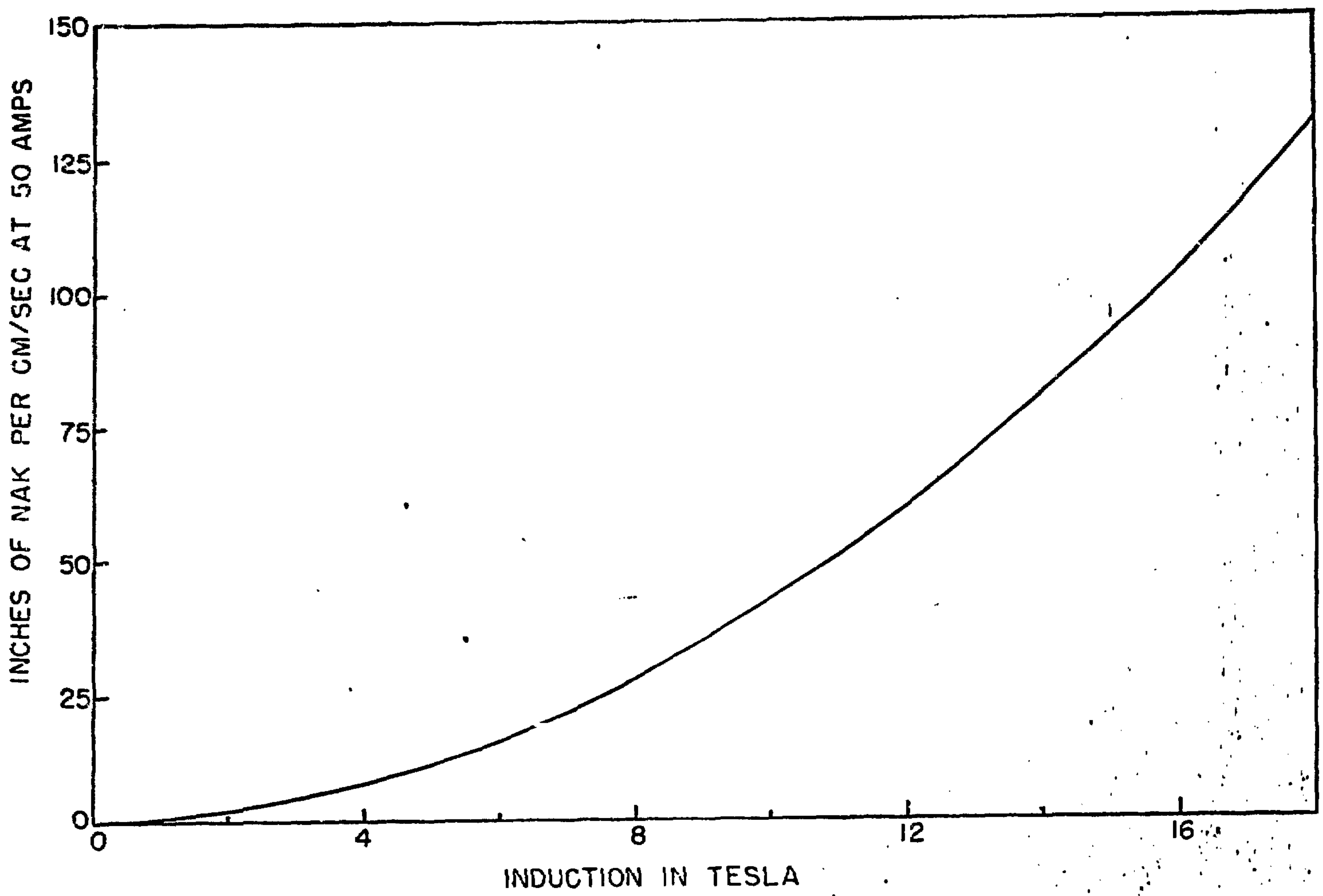
Pumping Power

The pumping power versus mean fluid velocity for various values of magnetic induction and pump current are shown in Fig. 10. The equation describing this plot is given in Fig. 11. It was observed that the pump efficiency never dropped below 50% and at times exceeded 70%. This is due to the fact that the pump is entirely immersed in the magnetic field thereby eliminating pump exit and entrance fringing current effects.

Conclusions and Recommendations for Future Work

It is possible to make pressure drop, velocity, pump power and efficiency measurements at the high values of characteristic parameters found in the proposed CTR blanket. However, the pressure measuring head tanks must be increased in size over those of the initial test unit as the pump current (fluid flow rate) and Hartmann number are increased to values characteric of a full scale reactor. By increasing the diameter and length of the head tanks, pressure drops more than one order of magnitude greater can be measured. For more severe conditions another pressure drop measuring method should be sought because the head tanks would become too large.

The pressure drops in the vertical flow, field-aligned suction and discharge legs of the race track are about one order of magnitude less than the pressure drops in the legs where fluid flows perpendicular to the magnetic flux tubes. The pressure drops in the suction and discharge legs are not the same, indicating the possibility that each leg has its own characteristic velocity profile. The pressure drops in the discharge and suction legs were only roughly measured in this experiment. Much more



Fi . 12. Plot of pre re-ve ratio versus induction.

$$P_{Li} = P_{NaK} \cdot \frac{C_{Li}}{C_{NaK}} \cdot \frac{X_{Li}}{X_{NaK}} \cdot \frac{a^2{}_{NaK}}{a^2{}_{Li}} \cdot \frac{\mu_{Li}}{\mu_{NaK}} \cdot \frac{V_{Li}}{V_{NaK}}$$

which reduces to

$$P_{Li} = 116.7 \times \frac{8}{15} \times \frac{6}{1} \times \frac{1}{36} \times \frac{0.2275}{0.541} \times 36 = 157 \text{ inches of NaK}$$

Fig. 13

$$\text{POWER} = 4ab\ L\ C\ B^2\ V^2 = 0.011\ B^2\ V^2 \quad \text{(Fraas)}$$

$$\text{POWER} = K\ V^2 B^2 \quad \text{(This experiment)}$$

where $0.008 \leq K \leq 0.12$

Fig. 14

accurate results can be obtained by differential pressure measurements between discharge and suction legs. Such a measurement should be made to determine definitively the existence of different velocity profiles in the suction and discharge legs.

Fig. 12 exhibits a plot of the ratio of pressure to velocity versus induction for a pump current of 50 amp. It can be shown that about 17 Tesla is needed in order to achieve magnetohydrodynamic similarity between the 1/6 scale model tested here and the full size CTR blanket. The pressure at 17 Tesla and 50 amp is equal to 117 times the fluid velocity, where the pressure is reckoned in inches of NaK and the velocity in cm/sec. In order to predict the pressure drop in the full sized lithium loop being excited by an 1800 amp pump current, the pressure drops are scaled in accordance with Carlson's approximation.[3] This is shown in Fig. 13. In this scaling the pump current density has been held constant and the pressure resulting is of small concern in the design of a full scale blanket. The value obtained above for the pressure drop in a full scale lithium blanket should be checked experimentally in a loop which is completely magnetohydrodynamically similar to the full scale loop. Such an experiment would not require the extrapolation of the experimental data and the attendant possibility of error owing to a different flow regime which might be present.

Accoring to Fraas[1] the pumping power can be approximately predicted by the formula given in Fig. 14. The expressions obtained in this experimental approach the prediction of Ref. 1 when B >> 1 T and V >>/cm/sec. Hence, it is concluded that the power prediction of Fraas has been verified experimentally by this experiment and is true under all the conditions of this experiment set forth in Table I. Thus, the pumping power predicted for a full scale 1000 MW(e) thermonuclear reactor[1] should be valid provided that no new flow regime is encountered as the Reynolds, magnetic Reynolds, Hartmann and wall conductance are changed.

In summary, this experiment done at Hartmann numbers up to 12,000 indicates that no excessive pressures or pumping power is likely to be encountered in the CTR blanket design of Ref. 1.

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