1965

Electromagnetic pumps for liquid metals

Gutierrez, Alejandro U.

Monterey, California. Naval Postgraduate School

ELECTROMAGNETIC PUMPS FOR LIQUID METALS

ALEJANDRO U. GUTIERREZ
and
CLAIR E. HECKATHORN

ELECTROMAGNETIC PUMPS FOR LIQUID METALS

* * * * *

Alejandro U. Gutierrez

and

Clair E. Heckathorn

ELECTROMAGNETIC PUMPS FOR LIQUID METALS

by

Alejandro U. Gutierrez

Lieutenant Junior Grade, Chilean Navy

and

Clair E. Heckathorn

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN

ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

1 9 6 5

ELECTROMAGNETIC PUMPS FOR LIQUID METALS

by

Alejandro U. Gutierrez

and

Clair E. Heckathorn

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

from the

United States Naval Postgraduate School

ABSTRACT

This thesis is the result of a literary research on the subject of electromagnetic pumps for liquid metals. The research was conducted at the U. S. Naval Postgraduate School to educate the authors in the field of electromagnetic pumps and to fulfill requirements for a Master of Science Degree in Electrical Engineering.

This thesis which is a synopsis of information obtained from various technical publications is designed to give the reader information on the theory and design of electromagnetic pumps in general. Included are: (1) Description of operation of all types of conduction and induction pumps (2) The development of the DC conduction pump from the equivalent circuit. (3) Development of electrical efficiency (4) Analysis of armature reaction. (5) A comprehensive bibliography. The important results of work performed in the laboratory by various individuals has been included.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS

$\bar{B}$	Magnetic Flux Density
$\bar{F}$	Force
$\bar{H}$	Magnetic Flux Intensity
$\bar{E}$	Electric Field Strength
$\bar{J}$	Current Density
I	Current
N	Number of turns
V	Voltage
R	Resistance
X	Reactance
VAR	Reactive Volt-Ampere
P	Developed Pressure
Q	Volume Flow
W	Pump Power
$\mathcal{P}$	Leakage Permeance
$\mathcal{V}$	Stored Magnetic Energy
η_d	Duct Efficiency
η_e	Electrical Efficiency
a	Duct Height in the Y-direction
b	Duct Width in the X-direction
c	Duct Length in the Z-direction
s	Slip
t	Duct Wall Thickness
v	Velocity
i_1	Load Current

i_m	Magnetizing Current
f	Frequency of Power Supply
λ	Pole Pitch
μ	Magnetic Permeability
ρ	Electric Resistivity
τ	Ratio of Slot Width to Slot Pitch
ϕ	Flux

INTRODUCTION

The interaction between a magnetic field and an electrically conducting fluid was studied in the early 1800's when Michael Faraday attempted to measure the voltage induced in the Thames River by its motion through the earth's magnetic field. In 1821 he demonstrated electromagnetic rotation. In his experiment he demonstrated that the flow of an electric current would cause a magnet to revolve around a wire carrying this current and that a current carrying wire could be caused to rotate about a fixed magnet.

Although the basic principles of the electromagnetic pump have been known for about one and a half centuries, the advance in magnetohydrodynamic channel flow was not significant until Hartmann's theoretical investigations in 1937. He derived the fluid resistance law for laminar flow in a channel of conducting fluid in the presence of a uniform transverse magnetic field.

In the early 1930's Einstein and Szillard built an electromagnetic pump, however, its low efficiency precluded its use for existing requirements.

However with the advent of the atomic reactor came the need for an efficient, maintenance free, completely enclosed primary coolant loop. Liquid metals are an excellent heat transfer medium due to their heat conduction properties and metals with high boiling points are desirable since system pressure can be operated at a low level.

Pumping "hot" radioactive liquid metals, presents a problem since bearings and shaft wall seals can become a potential safety hazard if leaks occur or if seals and bearings require maintenance, not to mention the experse. Also the prospect of orbiting a space satellite using an

atomic reactor for power, led to the need for a maintenance free coolant pump which could be oriented in any aspect.

These needs paved the way for the rapid development of the electromagnetic pump which can be configured with no moving parts, thus no bearings or shafts, and the pump is essentially free of maintenance. However the law of "give and take" prevails as in most engineering situations; along with each gain come inherent losses as will be explained later.

Although this thesis deals with electromagnetic pumps designed to pump liquids, a new and rapidly expanding application has come to the fore, namely the pumping of gases, and the use of hot charged gas to generate electricity in magnetohydrodynamic (MHD) generators.

CHAPTER II

Basic Theory

The fundamental principle utilized in electromagnetic (E M) pumps is basically the same as the principle used in electrical motors. When a current carrying conductor is placed in a magnetic field, a force is exerted on the conductor. If the current density vector ($\bar{J}$) and the magnetic flux density ($\bar{B}$) are imagined to be in the plane of the head of a right hand screw, the direction of the force will be the advance of the screw when ($\bar{J}$) is rotated into ($\bar{B}$)

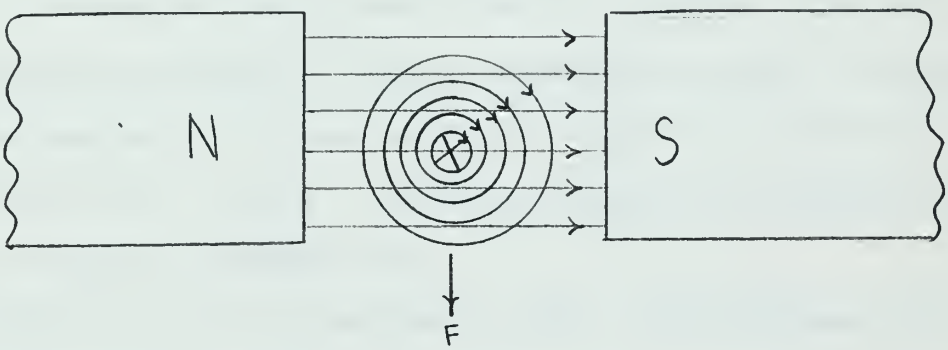


Figure 2-1 Fundamental Principle

In equation form: Force = (current) x (projected length, perpendicular to the magnetic flux density) x (magnetic flux density).

In Vectorial form: $\bar{F} = (I\bar{\ell}) \times \bar{B}$ (2-1)

where $\bar{F}$ is force in newtons

I is total current in amperes

$\bar{\ell}$ is length of conductor, perpendicular to magnetic field, in meters.

$\bar{B}$ is magnetic flux density in webers / square meter.

Consider the incremental force on a fluid particle.

$$dF_z = j_x B_z \, dx \, dy \, dz \qquad (2\text{-}2)$$

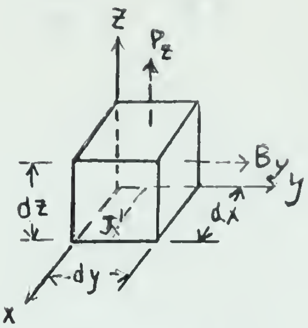


Figure 2-2 Differential Element

The microscopic element is shown in Fig. (2-2), where j_x is the current density in amperes per square meter in the x - direction. The basic assumptions here are that the fluid is constrained to flow in only the z - direction, and that the current density and magnetic flux density are constrained to the x - and y - directions respectively, neglecting such things as fringing, end-effects etc.

An electric field is established in the x - direction due to the resistivity of the fluid (conductor) and due to the motion of the conductor in the z - direction.

$[E_x]_\rho = j_x \rho$ where E_x is electric field in volts/ meter and ρ is resistivity of the fluid in ohms/meter.

$[E_x]_v = v_z B_y$

The total electric field in the x - direction is:

$$[E_x]_v = v_z B_y + j_x \rho \qquad (2\text{-}3)$$

In general, pressure (P) = Force per unit area. The pressure gradient can be found from equation (2-2)

$\frac{dF_z}{dA} = \frac{dF_z}{dydx} = j_x \; B_y \; dz = dP$, or the gradient is:

$$\frac{dP}{dz} = j_x B_y \qquad (2\text{-}4)$$

From figure (2-3) the pressure developed is:

$$\Delta P = \int_0^c j_x B_y \, d_z = j_x B_y \, C \qquad (2\text{-}5)$$

The volume flow is:

$$Q = v_f \, ab \qquad (2\text{-}6)$$

From equation (2-3) above, the voltage across b in Fig. 2-3, is found from the dot product.

$$V = (\bar{E} . \bar{b}) = (\rho_f \, j_x + v_f \, B_y) \, b \qquad (2\text{-}7)$$

Synchronous velocity (v_s) is defined as the fluid velocity at which the fluid current density becomes zero. Since

$$v_f = \frac{V + \rho_f \, j_x \, b}{B_y \, b} \qquad (2\text{-}8)$$

then $$v_s = \frac{V}{B_y \, b} \qquad (2\text{-}8a)$$

or slip $$s = \frac{v_s - v_f}{v_s} \qquad (2\text{-}9)$$

From equations 2-8 and 2-8a,

$$j_x = \frac{V - v_f \, B_y \, b}{b \rho_f} = \frac{v_s \, B_y \, b - v_f \, B_y \, b}{b \rho_f}$$

$$j_x = \frac{B_y \, v_s \, s}{\rho_f} \qquad (2\text{-}10)$$

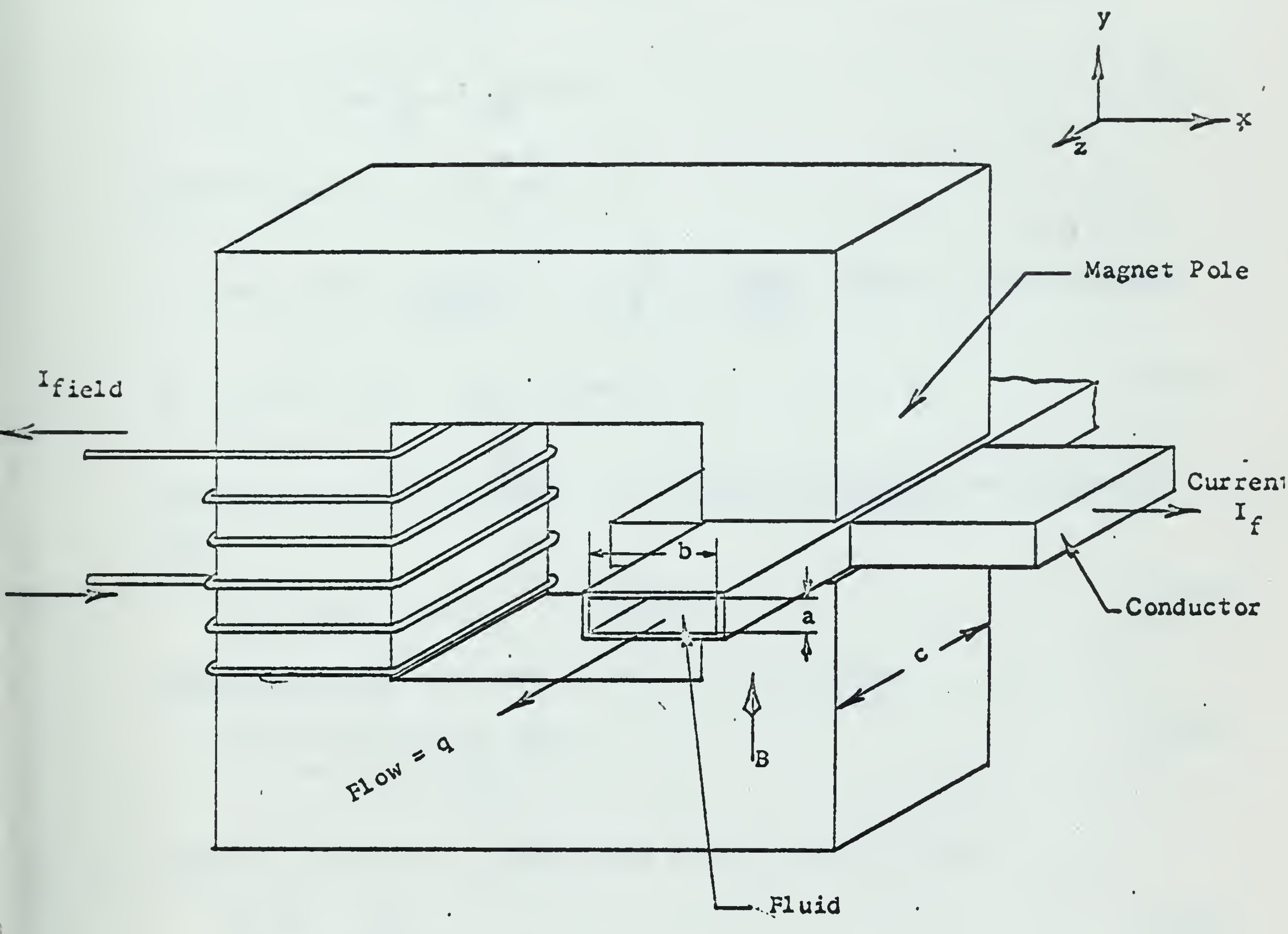
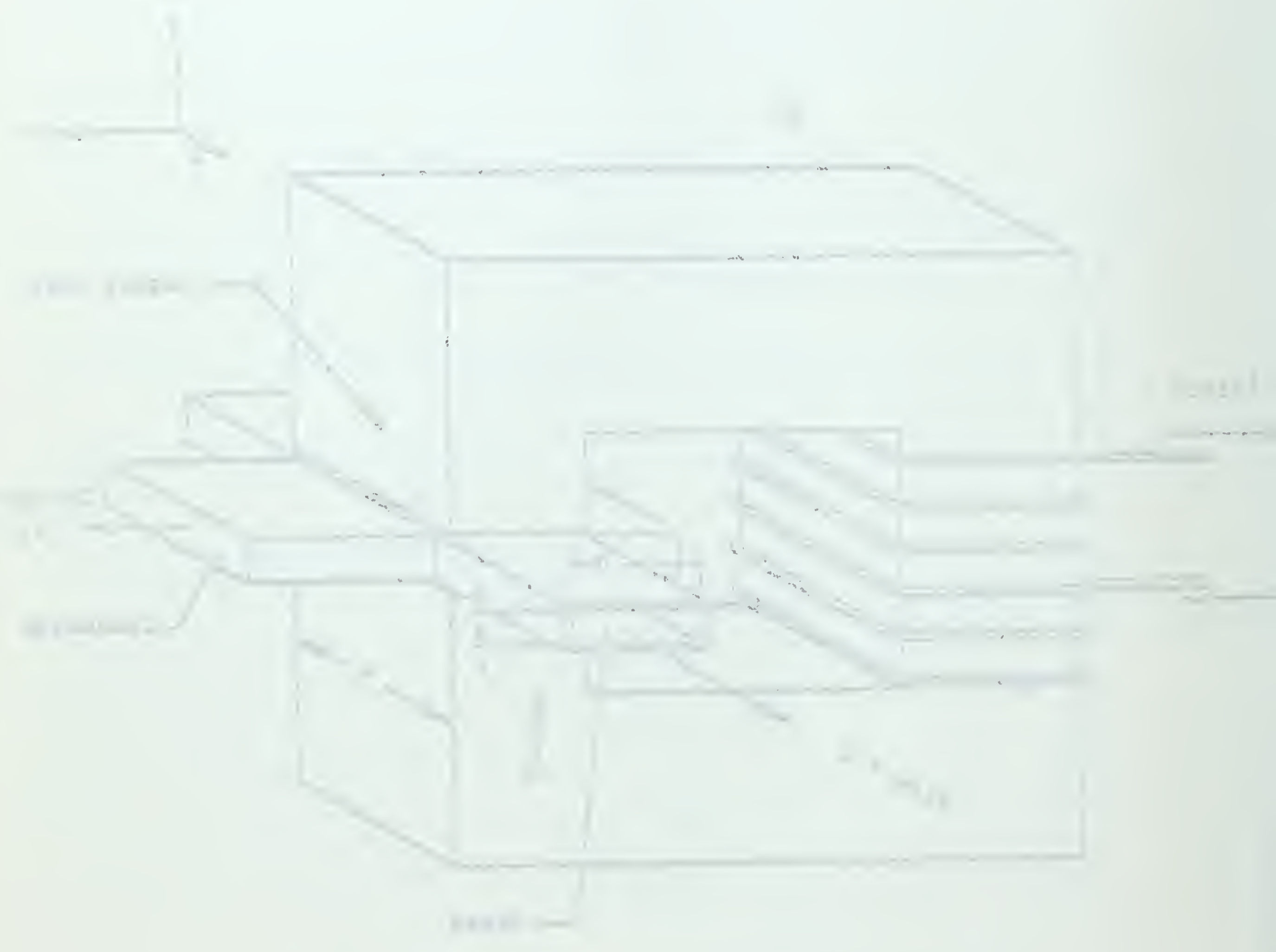


Figure 2-3 Conduction EM Pump



$$I = j_x ac$$

$$R = \frac{\rho_f \; b}{ac}$$

The I^2R loss in the fluid is:

$$W_f = (jac)^2 \left(\frac{\rho_f \; b)}{ac}\right. = j^2 \rho_f \text{ (abc) or from equation (2-9)}$$

$$W_f = \frac{B^2 \; v_s^2 \; s^2}{\rho_f} \text{ (abc)} \qquad (2\text{-}11)$$

The I^2R loss in the duct wall is:

$$Wd = \frac{V^2}{R} = \frac{V^2 \; (2tc)}{\rho_d \; b} = \left(\frac{V^2}{b}\right) \frac{(2tcb)}{\rho_d} \quad \text{where } t = \text{wall thickness}$$

or $$W_d = B_y^2 \; v_s^2 \quad \frac{2t}{ap_d} \quad \text{(abc)} \qquad (2\text{-}12)$$

The power output of the pump is the product of pressure and volumetric flow

$$W_o = \triangle PQ = B_y j_x \quad v_f \text{(abc)} \qquad (2\text{-}13)$$

Substituting eqs. 2-9 and 2-10 into eq. (2-13) gives

$$W_o = \frac{B^2 \; v_s^2 \; (1-s) \; (abc)}{\rho_f} \qquad (2\text{-}14)$$

The duct efficiency N_d, neglecting viscous losses, is now

$$N_d = \frac{W_o}{W_o + W_f + W_d} \qquad (2\text{-}15)$$

Substitution of equations (2-11), (2-12), and (2-14) into equation (2-15) results in a simplified form.

$$N_d = \frac{1 - s}{1 + D/s} \qquad (2\text{-}16)$$

where $$D = \frac{2t}{a} \frac{\rho_f}{\rho_d} \qquad (2\text{-}17)$$

Differentiating equation (2-16) with respect to slip and setting the derivative equal to zero gives the slip (S_m) at which maximum duct efficiency (N_d max) occurs.

$$S_m = D\left(\sqrt{1 + \frac{1}{D}} - 1\right) \qquad (2\text{-}18)$$

$$N_d \max = 1 - 2\,S_m \qquad (2\text{-}19)$$

Equations (2-16) and (2-19) are plotted in Figure 2-4). This figure shows that duct efficiency can be increased by decreasing the parameter D, i.e., reducing wall thickness, and/or fluid resistivity, or increasing duct resistivity. For any given parameter D there is a value of slip which will give a maximum duct efficiency shown by the dashed line in Figure (2-4). For example, sodium fluid and stainless steel ducts have a resistivity ratio $\frac{\rho_f}{\rho_d} \lesssim .25$ so that duct efficiencies of over 50% can be obtained in quite narrow channels, a = .5", for example, and duct thickness of 1/16" to 1/8".

Electrical efficiency - The electrical efficiency includes the I^2R loss of the fluid, duct, and windings. The assumptions of the previous section still hold in addition to the following:

1. Space harmonics (AC pumps) and time harmonics in the exciting MMF are neglected.

2. Fluid and duct wall currents are assumed to be compensated by pump winding currents. (DC pumps)

3. Leakage reactance of the fluid and duct are neglected.

4. The excitation windings are symmetrically distributed along the Z - axis.

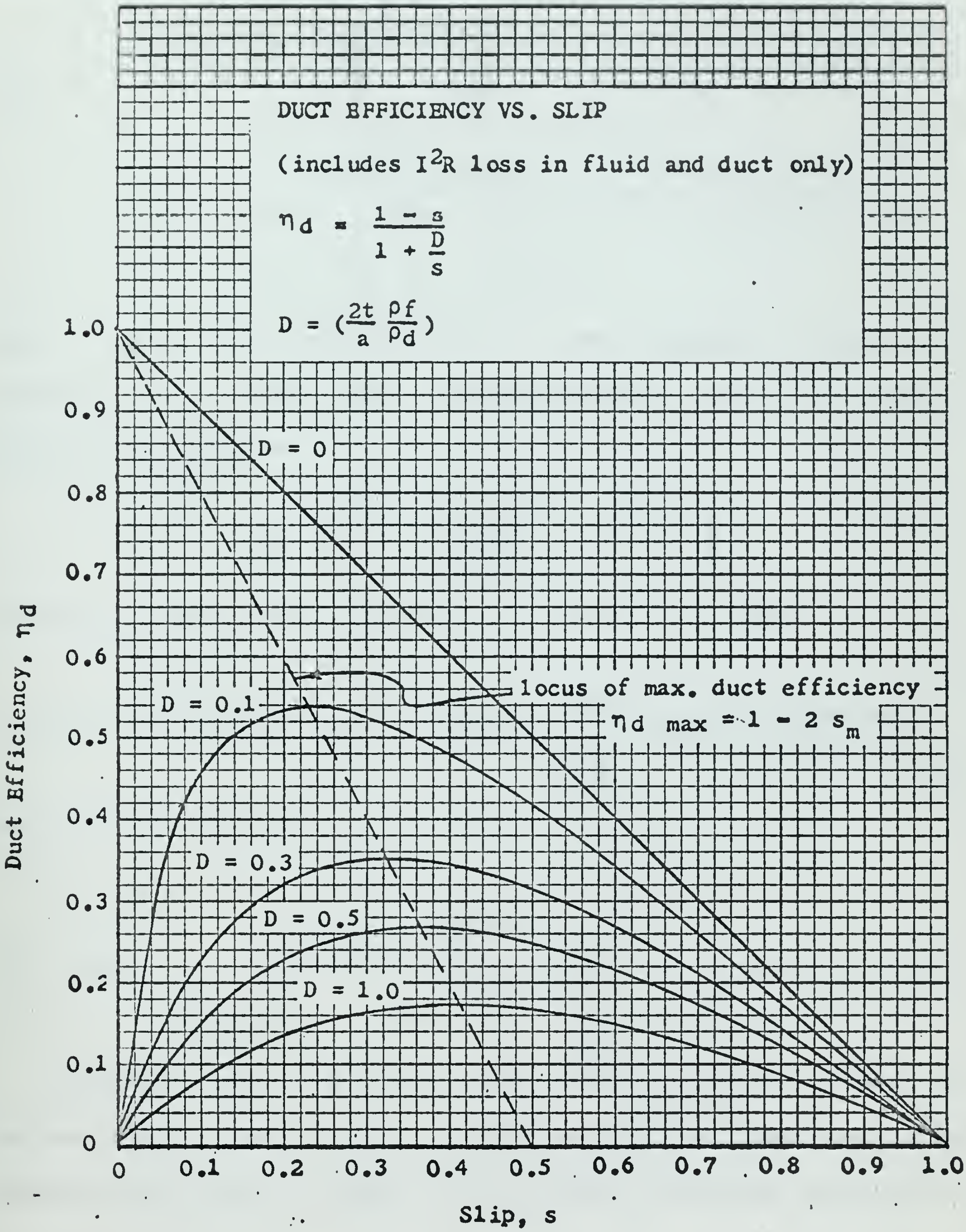


Figure 2-4 Duct Efficiency Vs. Slip

The current is the resultant of two components, the magnetizing current (i_m) which produces the flux density, and the load current (i_1) which compensates fluid and duct wall currents.

$$i_m = \frac{\pi \quad g}{k_1 \quad u \quad \lambda} B \qquad (2\text{-}20)$$

and

$$i_1 = \frac{a}{k_1} \left(1 - \frac{D}{s}\right) i_f \qquad (2\text{-}21)$$

$$i_1 = \sqrt{i_m^{\,2} + i_1^{\,2}}$$ therefore the winding loss is

$$W_1 = r_1 \left(i_m^{\,2} + i_1^{\,2}\right) bc \qquad (2\text{-}22)$$

where r_1 is the pump winding resistance in the x-z plane. By substituting equations (2-10), (2-20), and (2-21) into equation (2-22) the following expression is obtained:

$$W_1 = r_1 \frac{(B)^2}{(k)^2} \left[\left(\frac{\pi g}{\lambda u}\right)^2 - \left(\frac{a_s v_s}{(\rho_f)^2}\right)^2 \left(1 + \frac{D}{s}\right)^2 \right] bc \qquad (2\text{-}23)$$

Neglecting viscous losses, electrical efficiency, N_e becomes

$$N_e = \frac{W_o}{W_o + W_f + W_d + W_1} = \frac{s(1-s)}{(s+D) + \frac{a\, r_1}{k_1{}^2 \rho_f} \left[(s+D)^2 + \left(\frac{\pi g \rho_f}{\mu \lambda a v_s}\right) \right]} \qquad (2\text{-}24)$$

Using the relationships

$2f = v_s$ and $v_f = (1-s)\, v_s$

$$N_e = \frac{s(1-s)}{(s+D) + \frac{a r_1}{k_1{}^2 \rho_f} \left[(s+D)^2 + \left(\frac{2\pi f_g \rho_f}{\mu a v_f^{\,2}}\right)^2 (1-s)^4 \right]} \qquad (2\text{-}25)$$

In General Electric's research work, nominal values were assumed for the variables in equation 2-25, and the electrical efficiency was plotted against slip as shown in Figure 2-5. Electrical efficiency is shown to

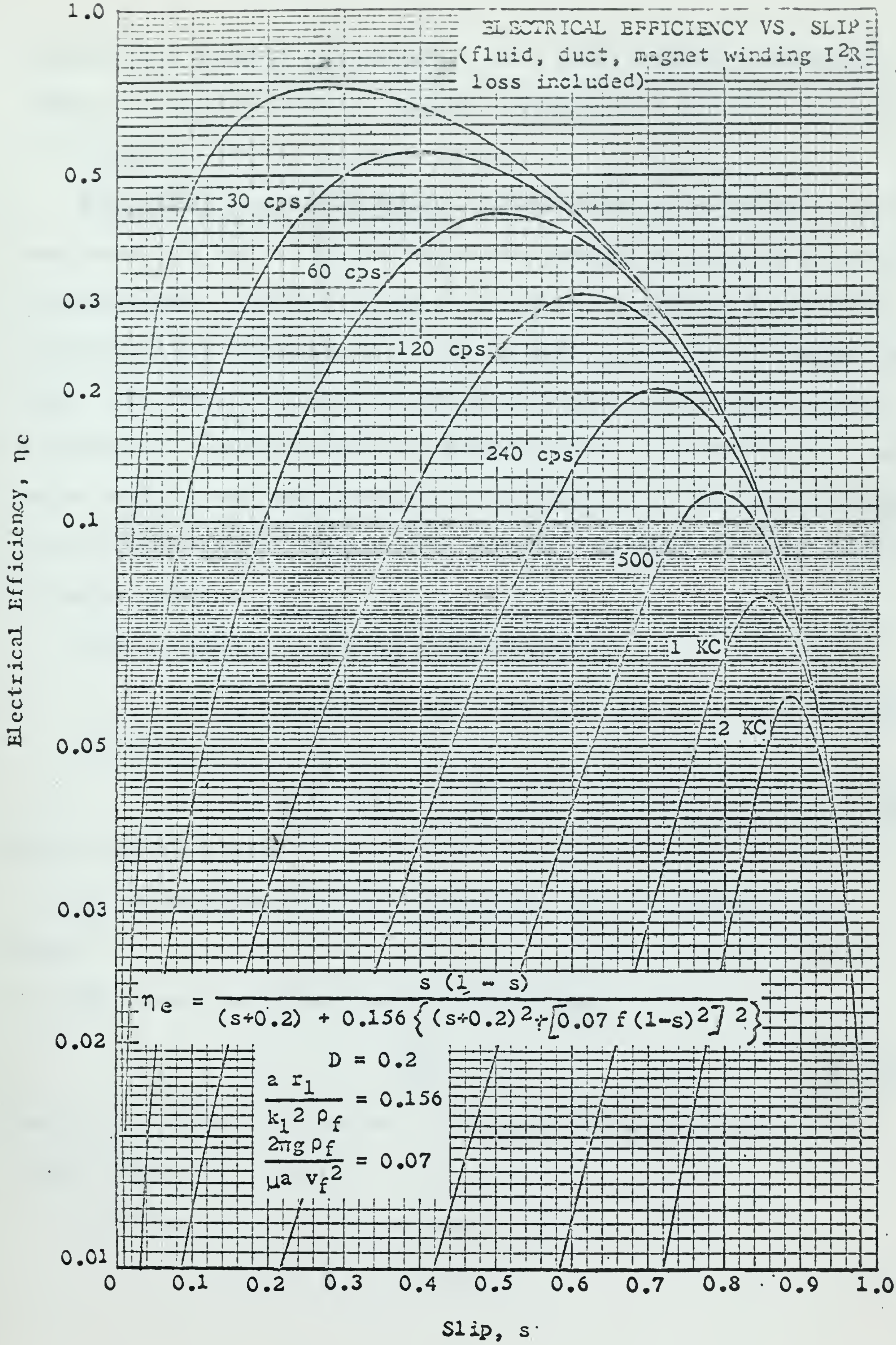


Figure 2-5 Electrical Efficiency Vs. Slip

decrease with increase in frequency. For a given frequency, electrical efficiency increased with an increase in slip up to a maximum, then falls off rapidly for further increases of slip.

Power Factor and Stored Energy - Energy stored in the magnetic fields associated with the air gap is larger than normally encountered in motors and generators. This fact is due to the large air gaps and the high resistivity of the liquid metals in the gap which cause greater leakage flux paths. The result is that A. C. EM pumps frequently have power factors less than 50%. Power is therefore transferred at the expense of high current, and to maximize the power transfer, it is necessary to add impedance matching, capacitive loads, which in turn further complicates and adds weight to the power supply.

In an inductive circuit the stored energy is

$$\mathcal{U} = \tfrac{1}{2} L I^2 \qquad (2\text{-}26)$$

The reactive power is

$$VAR = I^2 x = I^2 (2\pi f L) = 4\pi f \mathcal{U} \qquad (2\text{-}27)$$

where I is rms current.

The energy is stored in the duct region and in the winding flux paths.

The energy stored in the duct region ($\mathcal{U}_d$)

$$\mathcal{U}_d = \tfrac{1}{2} \frac{B^2}{\mu} gbc \qquad (2\text{-}28)$$

where g is the gap width and μ is the magnetic permeability of the region between the stators.

The energy stored in the windings ($\mathcal{U}_e$) is

$$\mathcal{U}_e = \tfrac{1}{2} i_1{}^2 \rho bc \qquad (2\text{-}29)$$

Where $i_1^2 = i_m^2 + i_1^2$, and ($\mathcal{P}$) is the leakage permeance per unit length in X-Z plane, and is the sum of the permeances of the slots plus the end turns.

The total energy is the sum of equations (2-29) and (2-30)

$$\mathcal{V} = \frac{1}{2} \frac{B^2}{\mu} \quad g\ b\ c + \frac{1}{2}\ i_1^2 \quad Rbc$$

Substituting for i_1, and using $\mathcal{P} = k_1 \frac{\mu\ d\ s}{3\tau}$ - where $k_1 > 1$ accounts for additional leakage flux paths, ds is slot depth, and τ is the ratio of slot width to slot pitch, the ratio of output to stored energy becomes:

$$\frac{W_o}{\mathcal{V}} = \frac{\mu\ V_s^2\ S\ (1-S)\ \lambda}{2g\ \rho_f\ \left\{ 1 + \mathcal{P} \left[g/u \ \left(\frac{\pi}{K_1 \lambda}\right)^2 + \ \frac{\mu}{g} \ \frac{(a\ (a+D) \qquad v_s}{k_1 \quad \rho_f} \right]^2 \right\}} \qquad (2\text{-}30)$$

The assumptions are that the pole slots are filled and that the sides of the slots are parallel.

In Figure 2-6, the ratio of power output to total stored energy was plotted against slip for nominal values of the parameters of equation 2-30. For a given value of slip the ratio decreases with increase in frequency.

Investigation of Flow in a Rectangular Duct

The following is a synopsis of work done by Ames Research Center and published in reference [88]. Fig. (2-7) shows the configuration of the equipment utilizing the DC conduction pump. The fluid, a special clear solution of copper sulfate and ink with approximately equal density, was used to show flow contours. In Fig. (2-8) the equipotential and current lines are displayed for an electrode length/channel width = 1/1. In Fig. (2-9) poles pieces with contours covering a square, 90%, and 98% of the current lines, effect the fluid flow as shown in Fig. (2-10), and influence the fluid velocity and pressure head as shown in Fig. (2-11).

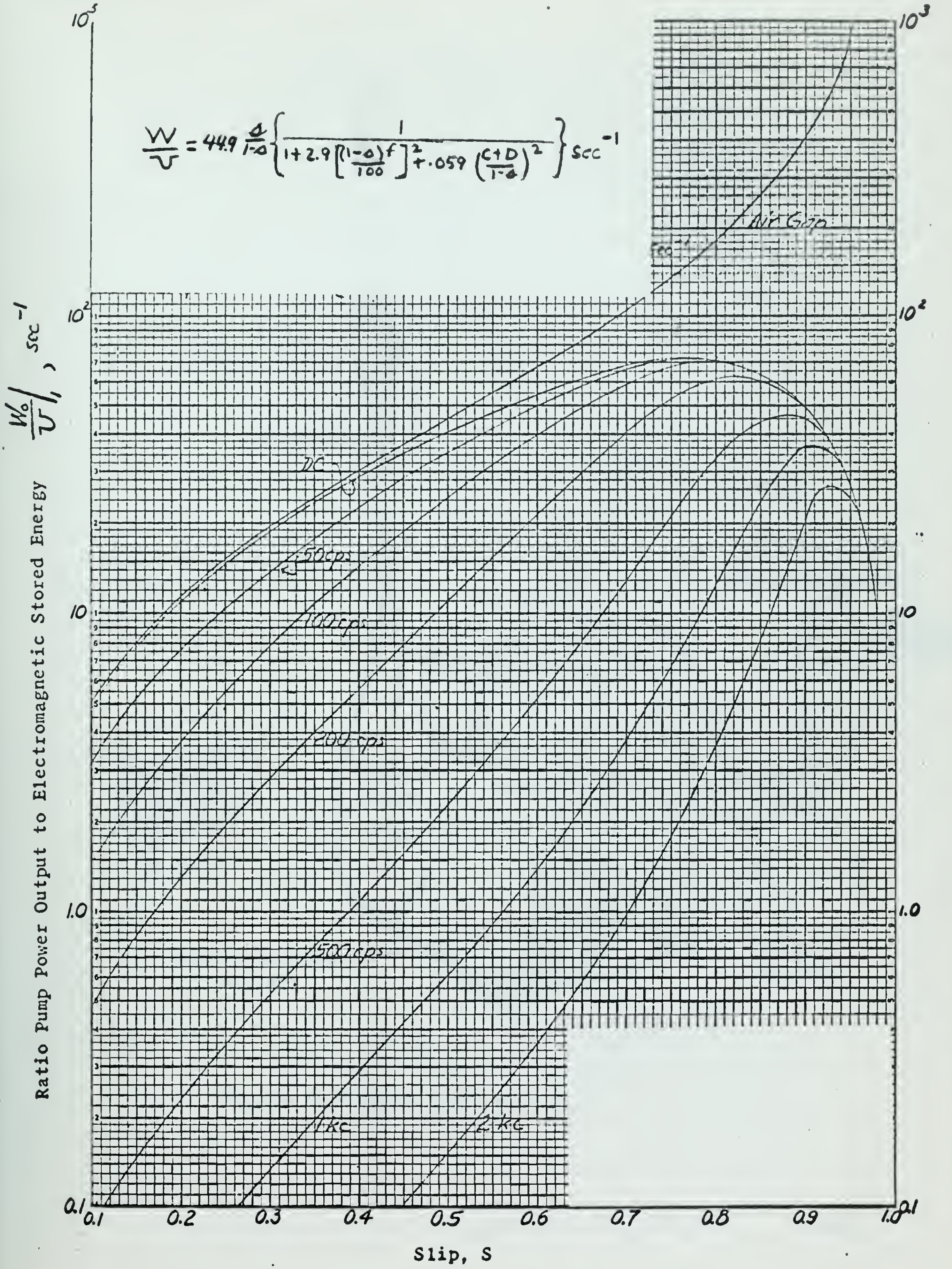


Figure 2-6 Stored Energy Relationships

[60]

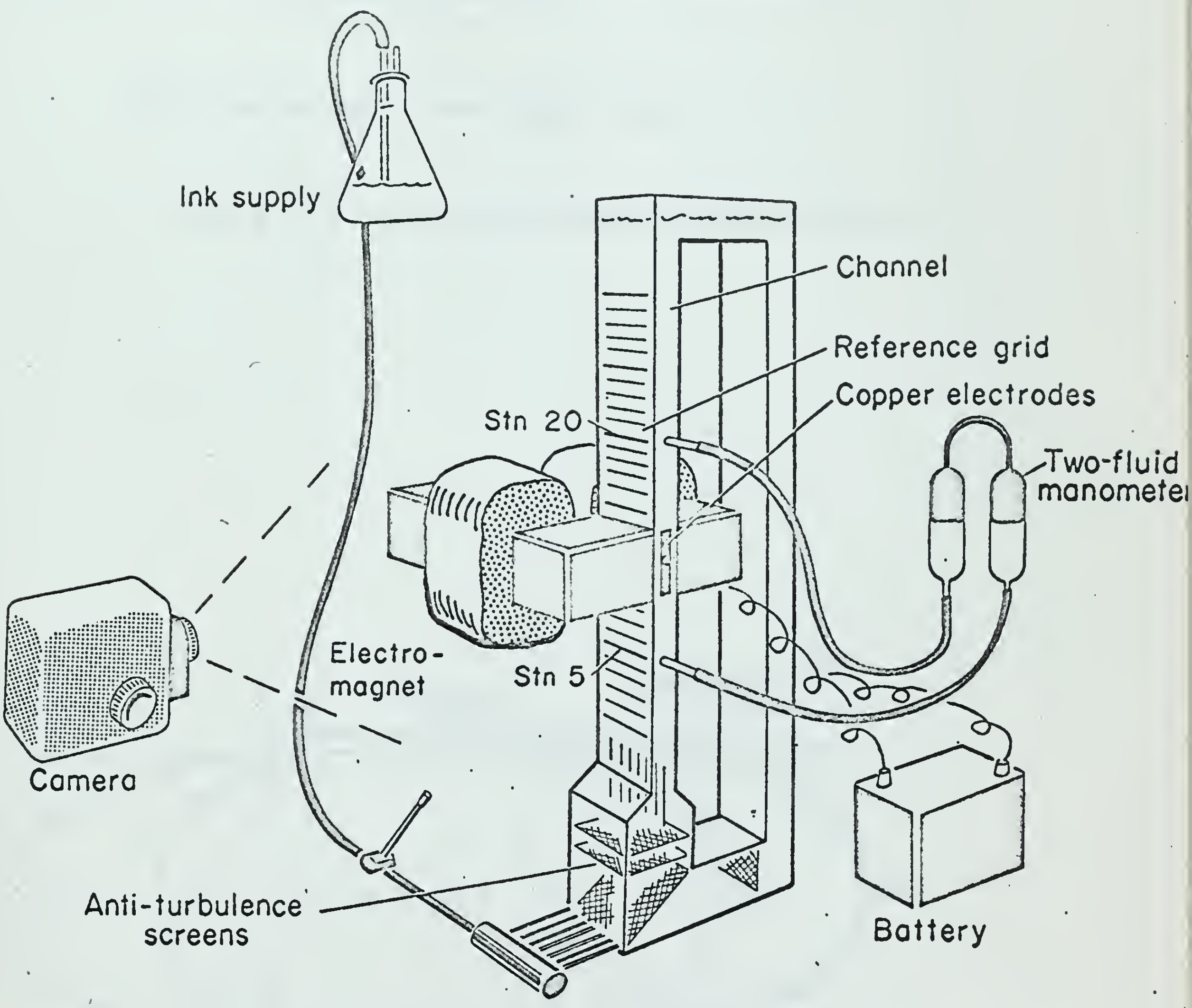
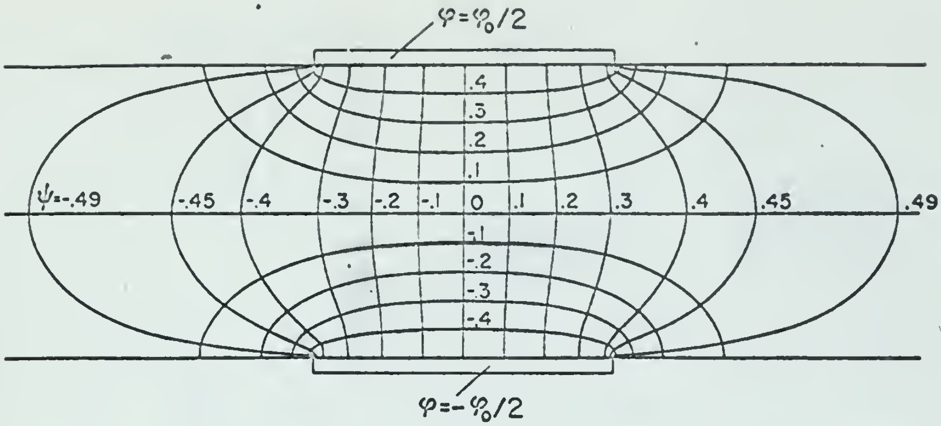


Figure 2-7 Ames Test Set Up



Electrode length/channel width = 1/1.

Figure 2-8 Electrode Length/Channel Width 1/1

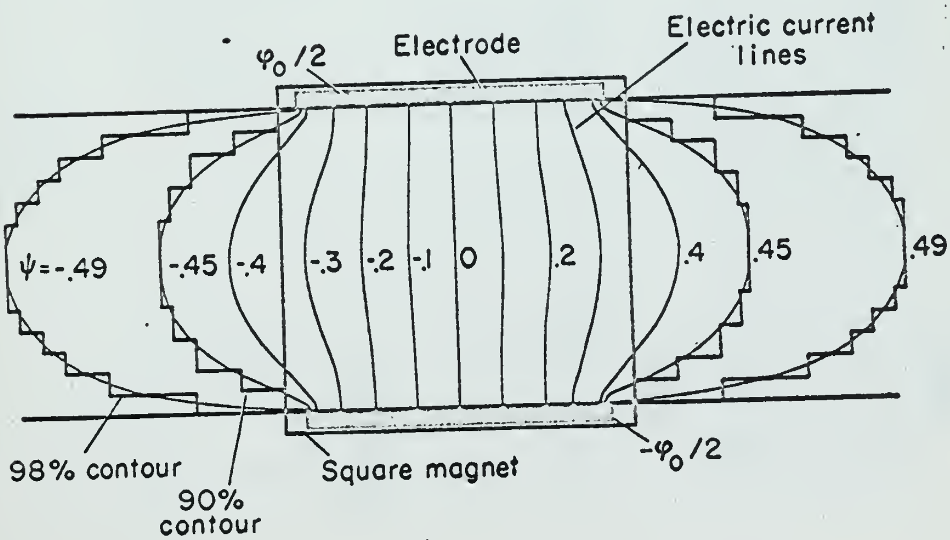


Figure 2-9 Electric Current Contours

[88]

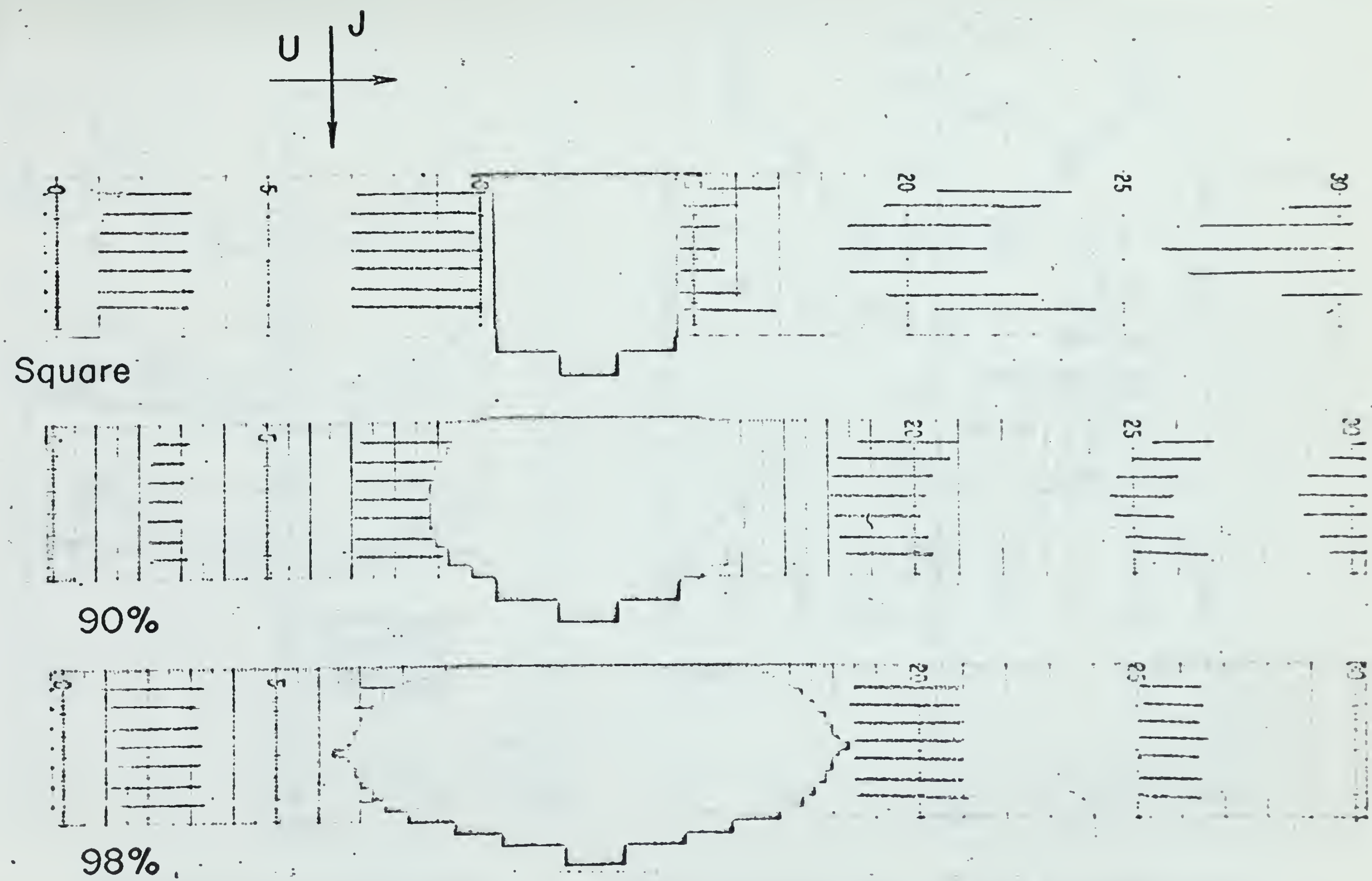
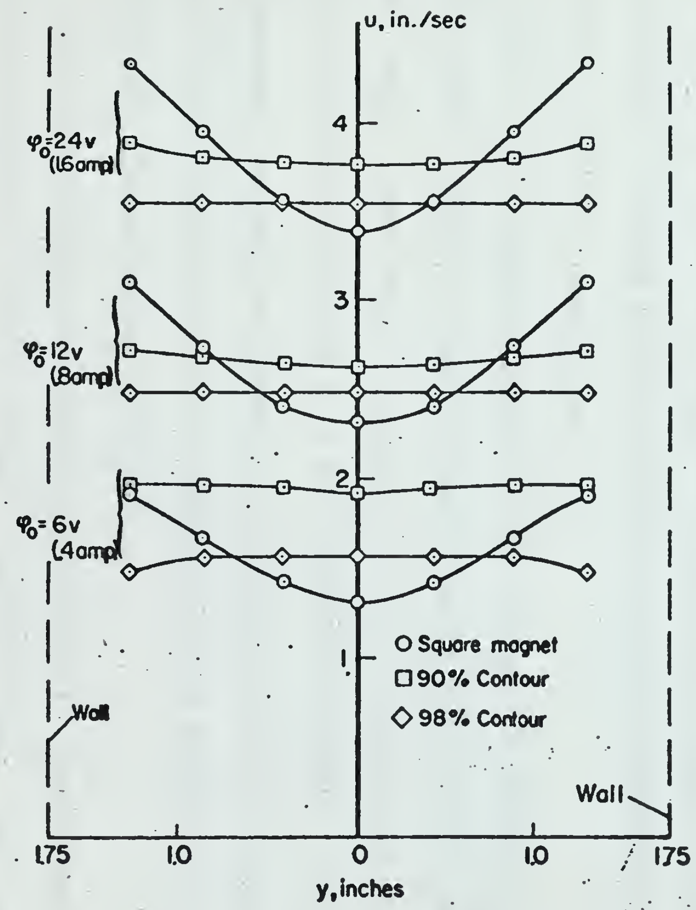
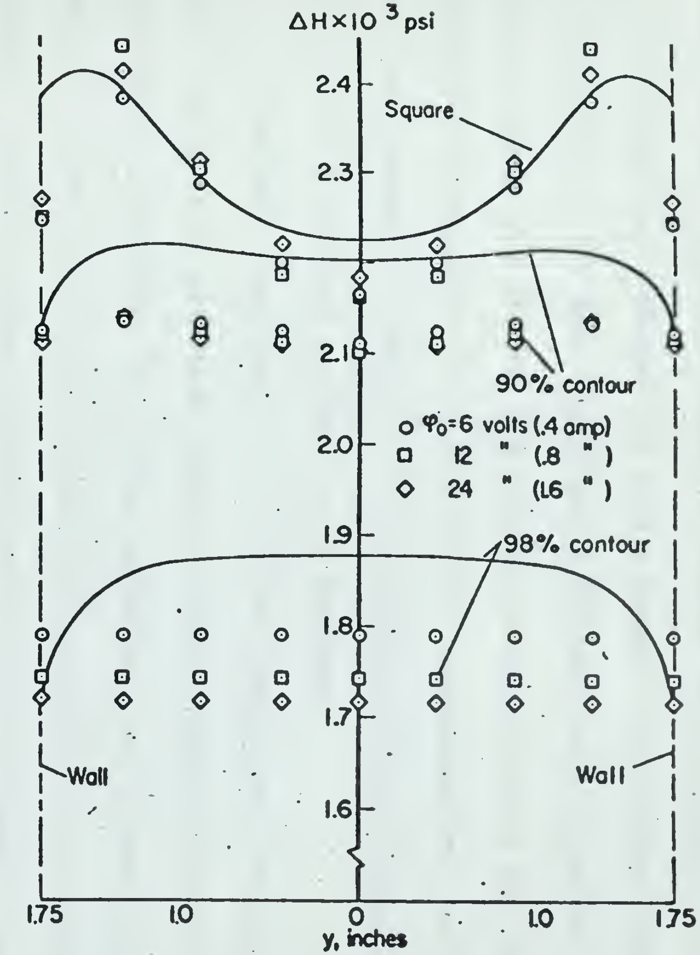


Figure 2-10 Velocity Distribution Produced By Pumps With Special Magnet Contour



(a) Velocities of ink filaments.



(b) Variation of pressure head in channel; all currents normalized to 1 ampere.

Figure 2-11 Measurements at Exit of Electromagnet Field Region

u in (in/sec.) is fluid velocity, Δ H(psi) is change in pressure head, and y is the cross-duct dimension between the electrodes. It is interesting to note that although the square magnet face creates a more uneven pressure head, the over all pressure differential is greater. It is evident that although the 90% and 98% contours utilize more of the current, the reduction of magnetic field density has a greater effect and hence the resulting pressure is reduced. In this experiment the shaping of pole pieces, to utilize the fringe current, was a detriment.

In another experiment, the electrode length was increased to 16" so that the ratio of electrode length to channel width was equal to 4.57. With this large ratio, the current end-effects were essentially eliminated and the current in the pump region was considered to be uniform. In Fig. (2-12), the ink filaments entering and leaving the pump were unaltered. The conclusion is that the nonuniformities are not caused by the magnetic field, however, it must be realized that only about one-third of the current was being interacted upon by the field.

Much of the literature suggests that the use of electric current barriers would alter the electric field, (see Figure (2-13)), so that current fringe losses would be reduced. Two 11" barriers were inserted parallel with the fluid flow in a 1" x 3-1/2" channel.Even though the barriers were partially effective, the resulting loss of pressure head in the center of the channel, due to the insertion of the barriers led to the conclusions that the net effect was nil.

Also noteworthy was an experiment conducted by Ames Research to compensate the magnetic field to produce a uniform stream. One method used curved pole faces, with the intention of creating a magnetic field to match the electric field. The first approximation shown was based on the assumption that the local magnetic field strength varies inversely with the local

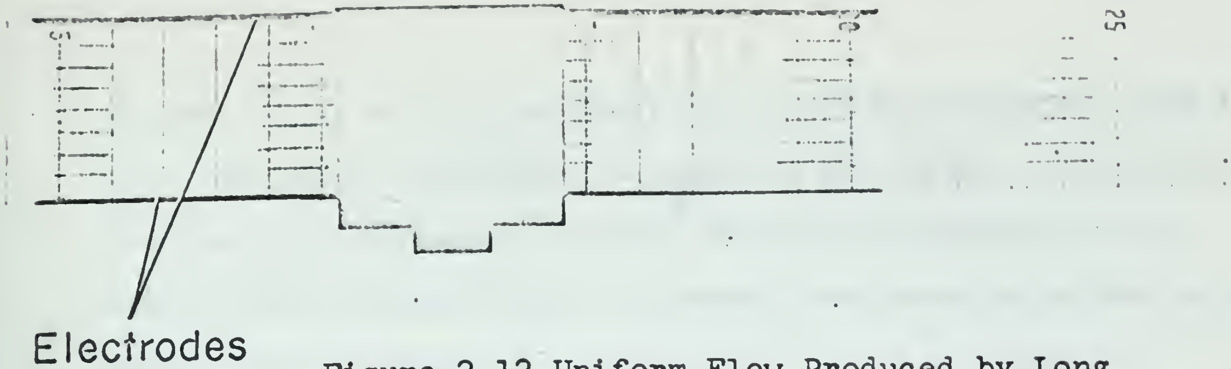
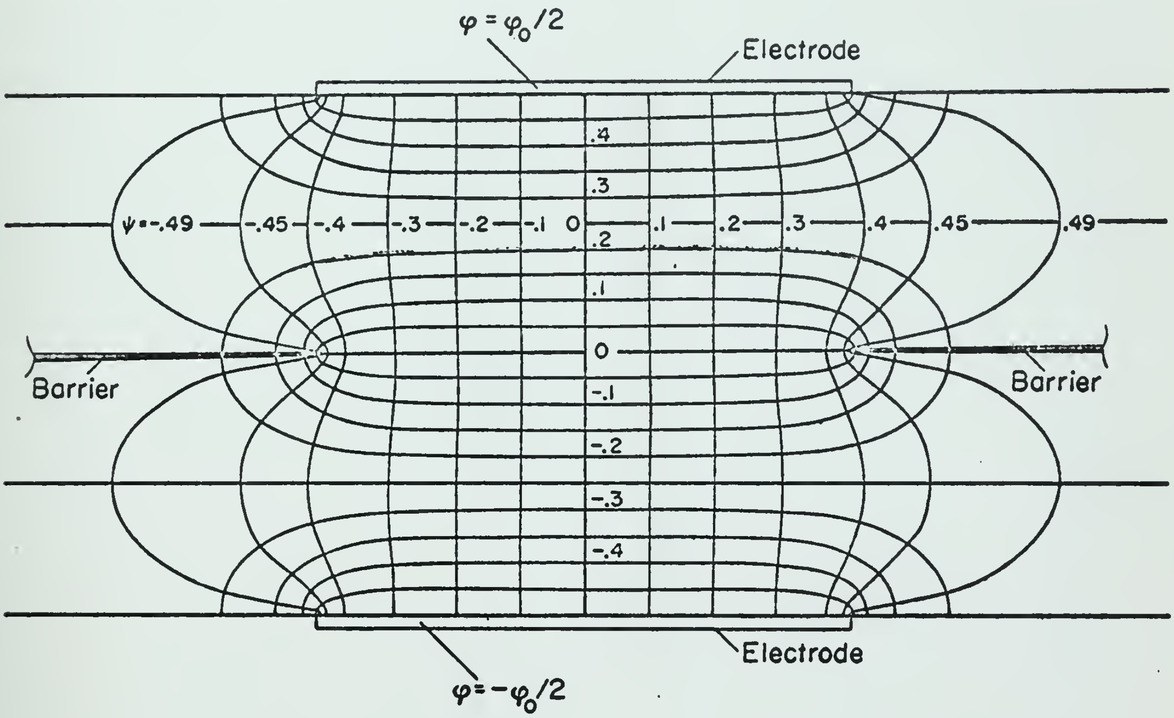
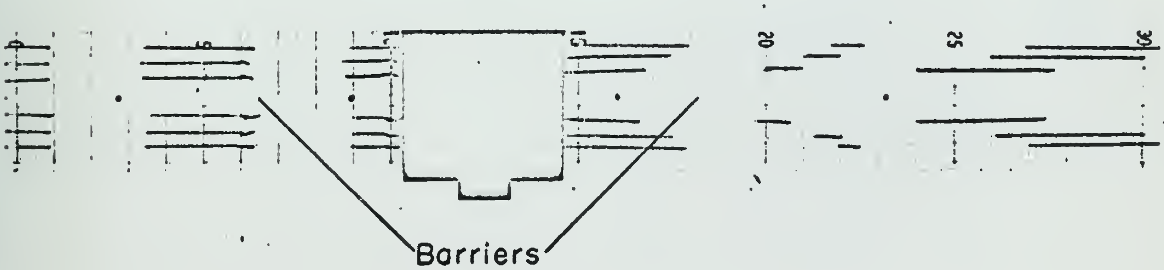


Figure 2-12 Uniform Flow Produced by Long Electrodes

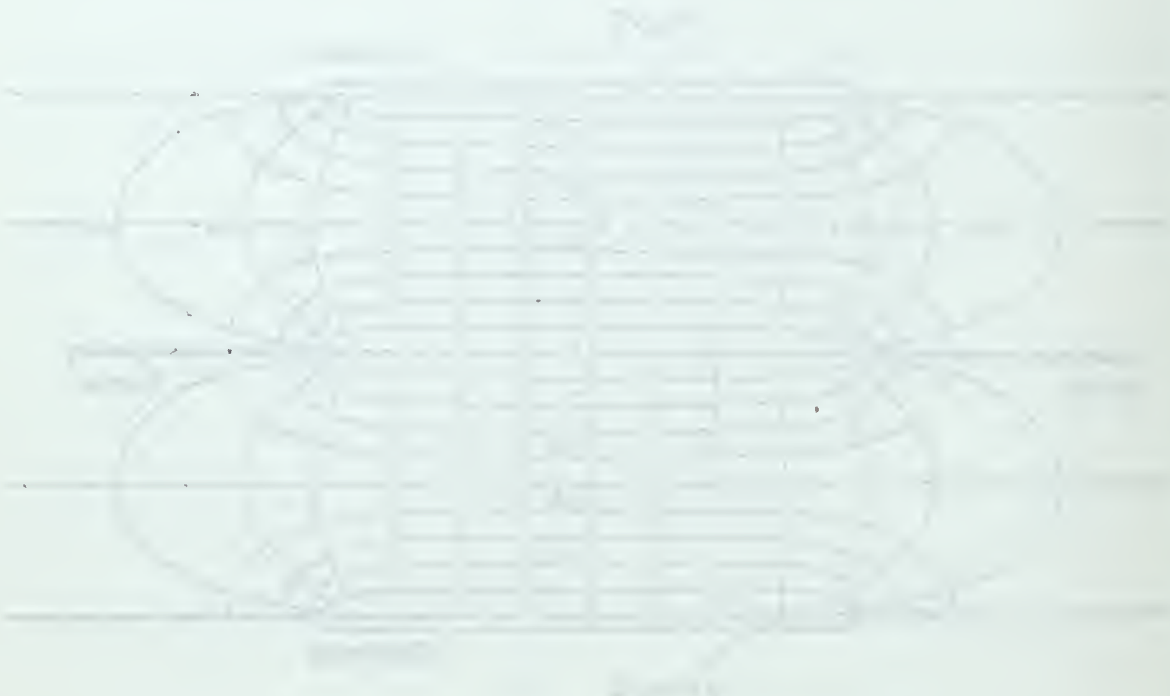


(a) Reduction in fringing of electric field brought about by very long barriers.



(b) Flow pattern.

Figure 2-13 Test Channel with 11-inch Electrical Current Barriers Placed on Channel Center Line



air gap. Trial and error modifications were used to obtain the final design. The effects on the fluid are shown in Fig. (2-14). No mention of pressure head measurements was made. However, the curvature of the magnetic field passing through the current field causes turbulence in the output side of the pump.

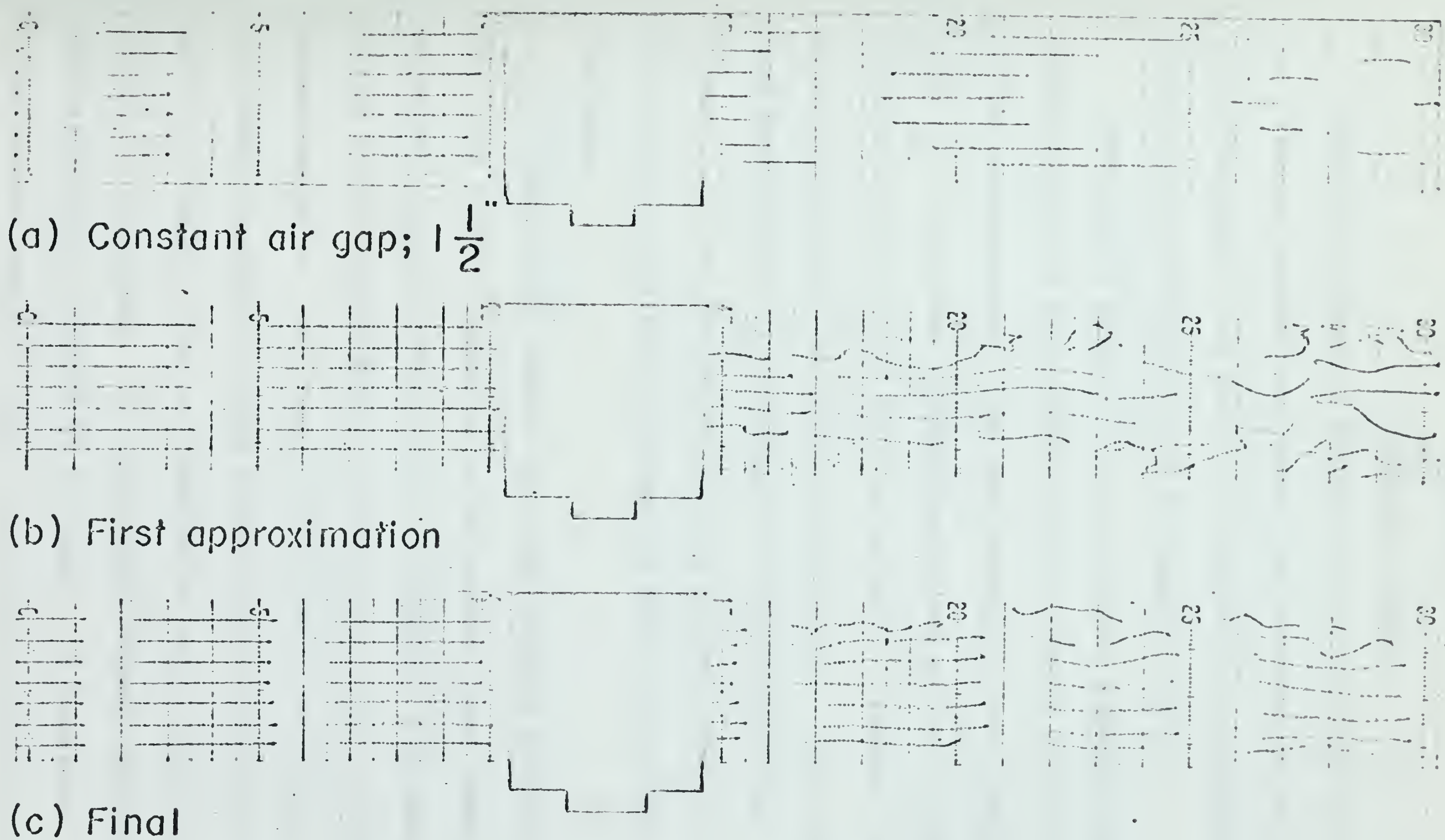


Figure 2-14 Flow Lines with Contoured Pole Pieces

CHAPTER III

Conduction Pumps

Conduction pumps are characterized by the fact that current is "conducted", from an external source into the liquid metal, via electrodes connected to the sides of the duct. The electrodes are generally located so the current flows perpendicular to the magnetic field.

Referring to Figure (3-1), we see that conduction pumps are categorized initially by their source, that is, either DC or AC. The majority of the conduction pumps have been constructed with rectangular cross sections due to the ease of manufacturing and due to the wide ranges of pressures which this type of pump can withstand. However, conduction pumps can be constructed with many other configurations. These pumps will operate with any liquid metal, including high resistivity metals, such as mercury, bismuth, and lead because of the high currents, however, when the duct and the fluid have resistivities that are nearly equal, duct losses will be increased.

DC pumps, which require very high currents (kiloamps) at about one volt, are further classified in two general types, namely pumps having permanent magnets or those with electromagnets. Permanent magnets are unique to small pumps since for larger pump sizes, the weight and cost become excessive. Two classifications which are peculiar to DC pumps are: (1) Homopolar generator pumps (Figure 3-2) which utilize the basic homopolar generator design with a new technique of using liquid metal brushes to increase the efficiency. The liquid metal brushes are necessary to conduct the high currents required by the pump. The generator is surrounded by a circular electromagnetic pump however, the necessity of metal lubricated

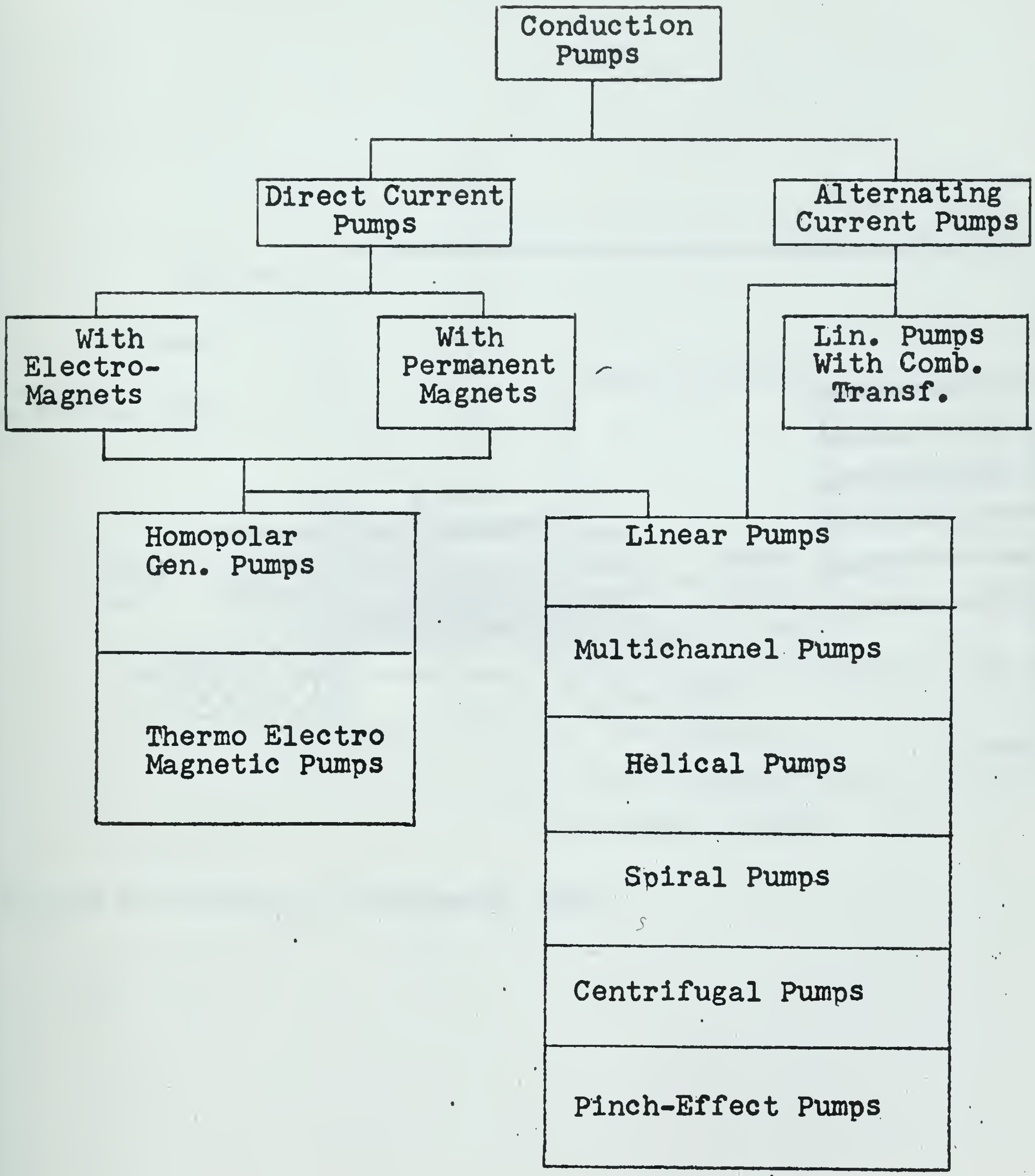


Figure 3-1 Conduction Pump Family Tree

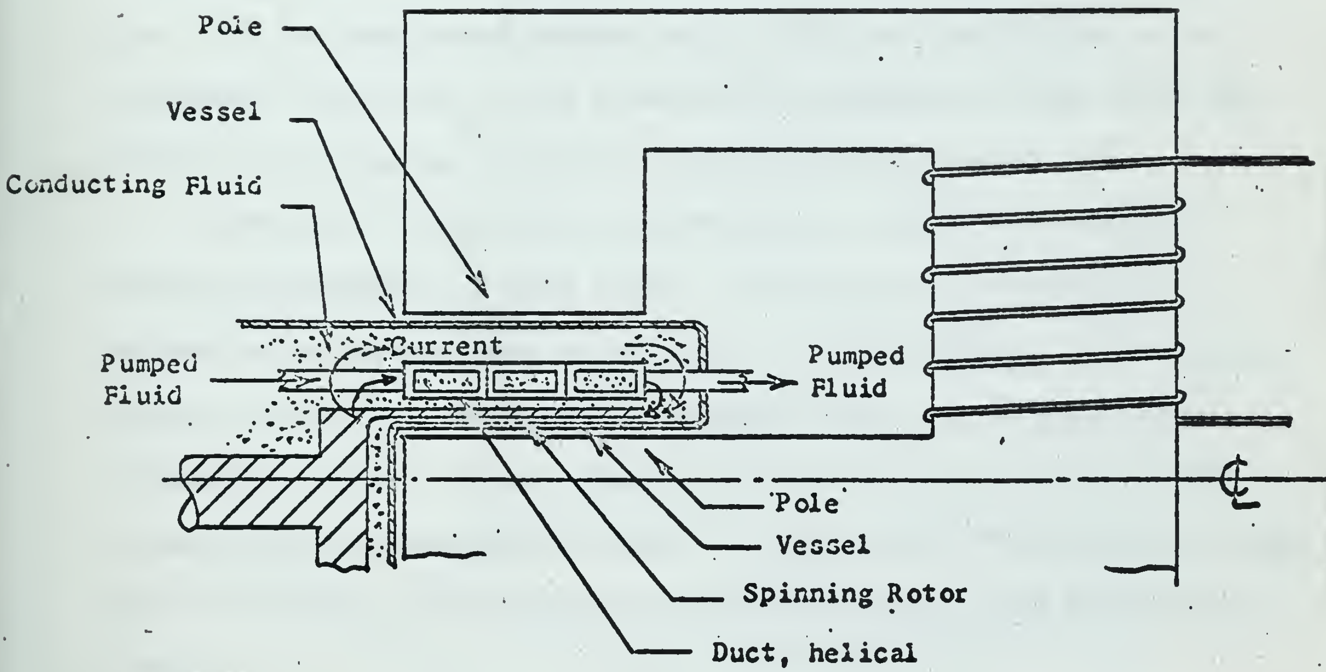


Figure 3-2 Homopolar Generator Pump

bearings and shaft seals present an obstacle. (2) The other design is the Thermoelectromagnetic (TEM) pump Figure (3-3). The power is obtained from a thermoelectric element (thermocouple) mounted directly on the pump structure with one junction in contact with the hot fluid and the other in contact with a cooler fluid. The generated voltage is in the neighborhood of 1/10 of a volt. Therefore, it is necessary to place the thermocouples in series to generate the desired voltage. The inherent problems of TEM are: (a) the complicated control of the fluid and pressure due to the temperature variations of the fluid and (b) starting the pump, since the pumping action depends on the heat supplied by the "pumped" fluid.

A pump which is peculiar to AC EM pumps is the "Linear Pump with Combined Transformer", Figure (3-4). In this pump the transformer is mounted as an integral part of the pump. The flux produced by the primary induces current into the secondary windings which in turn pass current through the liquid. The main flux is 90° out of phase with the induced current, hence produces no net work. But the counter flux which is in phase with the induced current produces net pumping action in the desired direction.

The primary disadvantage of the DC conduction pump is its inconvenient electrical supply of about one volt but supplying thousands of amperes. The homopolar generator is an example of a supply which fulfills this requirement at good efficiency. The ACconduction pump on the other hand can be supplied more easily but at the risk of lower efficiency and power factor.

The following Conduction Pumps can operate on either DC or AC, power: Linear, multichannel, helical, spiral, centrifugal, and pinch-effect pumps.

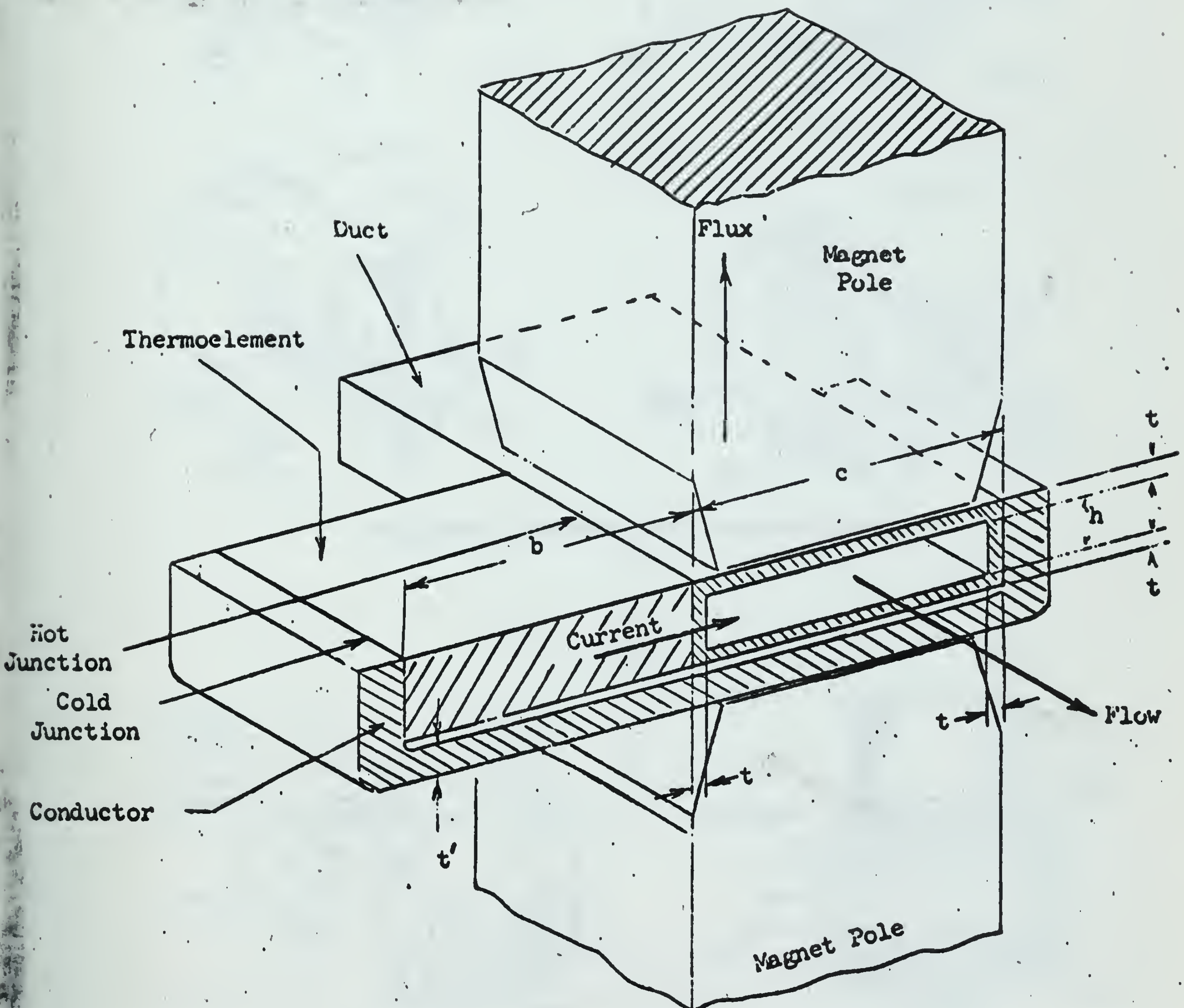
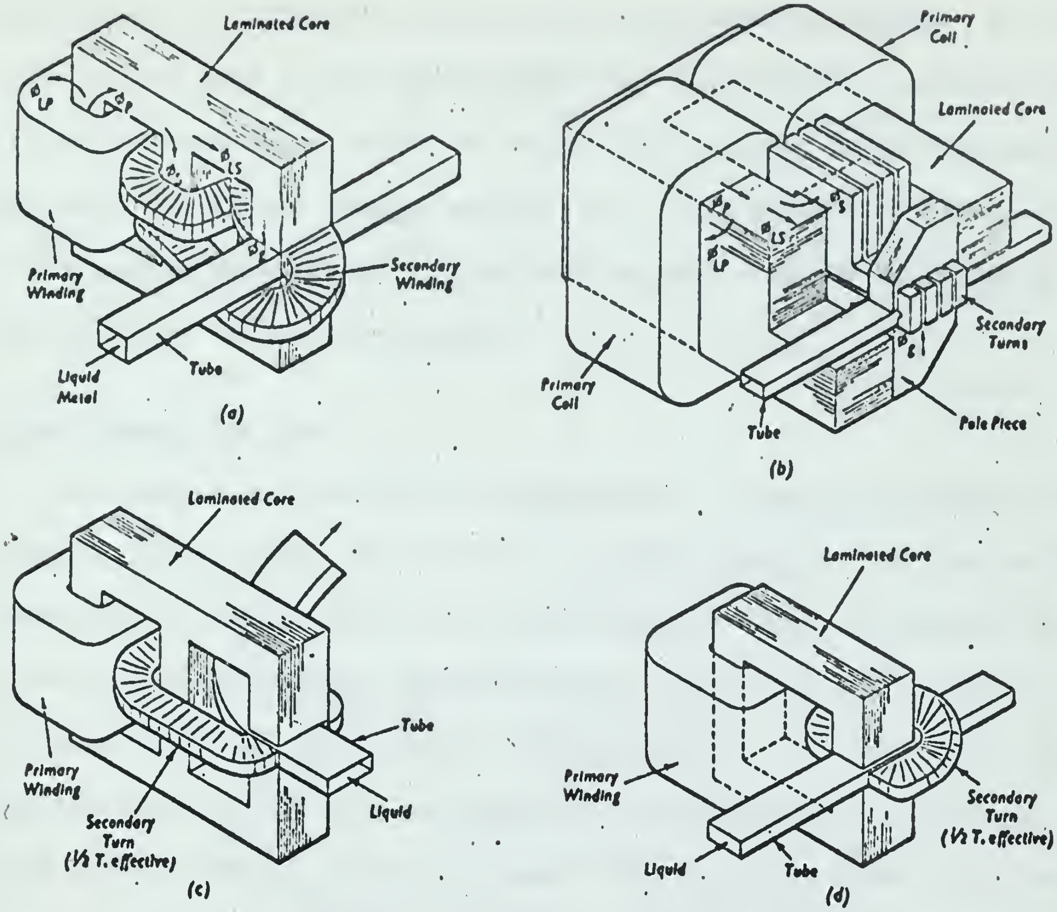
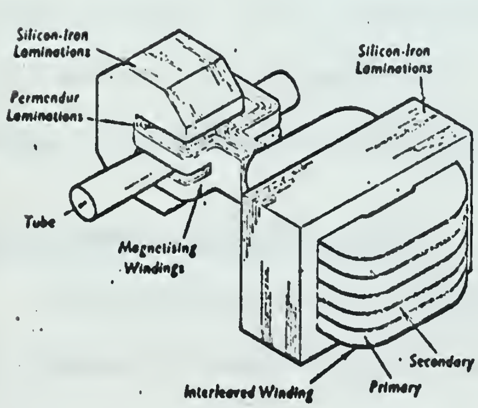


Figure 3-3 Thermoelectromagnetic Pump

[61]



Four kinds of A.C. conduction pumps with combined transformer.



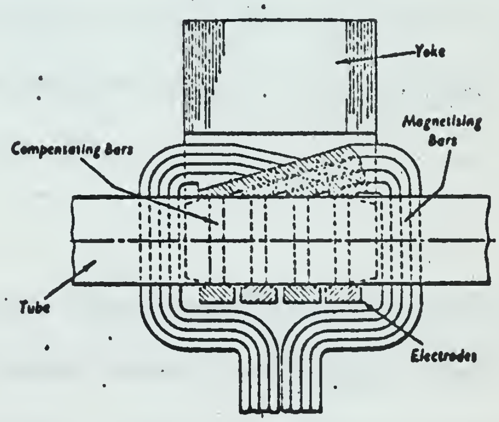


Figure 3-4 Linear Pumps with Combined Transformer

The differences in general stem from the duct configurations. When AC supplies are used it is necessary that the field winding and the armature (fluid) current be in series to insure that a proper phase relationship is obtained for maximum pumping action i.e., it is desirable that the force be a sine square function going from zero to twice its average value at double the frequency of the power supply.

Linear Conduction Pump

The linear pump is the most common and is simplest in design, refer back to Figure (2-3). The channel is usually made of stainless steel with electrodes brazed on either side. The magnetic field is produced by either AC or DC current supplied to the winding, and the current enters the fluid (in phase with the field) through the electrodes. The theory of operation was discussed in the previous section and will not be pursued here. Armature reaction, which will be discussed later, is a problem which can be compensated by returning the current through the air gap. Appendix 1 to this section contains an analysis for the DC conduction pump.

A commercial AC conduction pump built by MSA Research Corporation is shown in Figure (3-5), along with a Performance Curves and Characteristics for Various Styles Figure (3-6). The performance curve is for the pump using sodium-potassium alloy (56% K. by weight).

Multichannel Conduction Pump

The multichannel pump differs from the linear conduction pump only by the number of passes the duct and fluid makes through the magnetic field. Figures (3-7) shows a two pass configuration. Since the magnetic flux is used more than once, less magnetizing current is required. But the primary advantage is mechanical, in that the fluid entrance and exit duct and the current supply electrodes can be clamped together, thus minimizing the

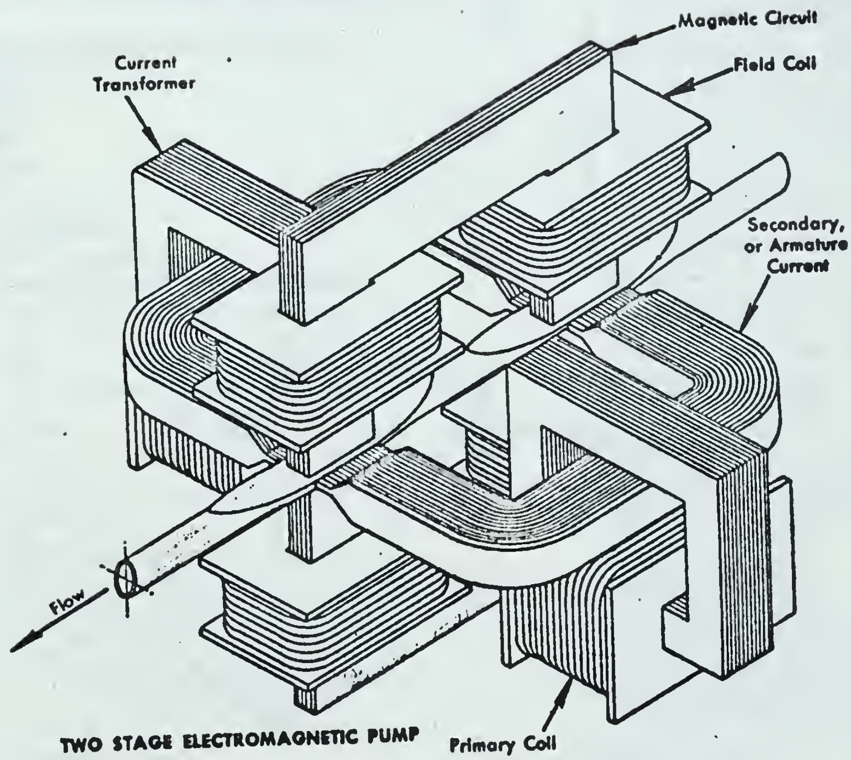
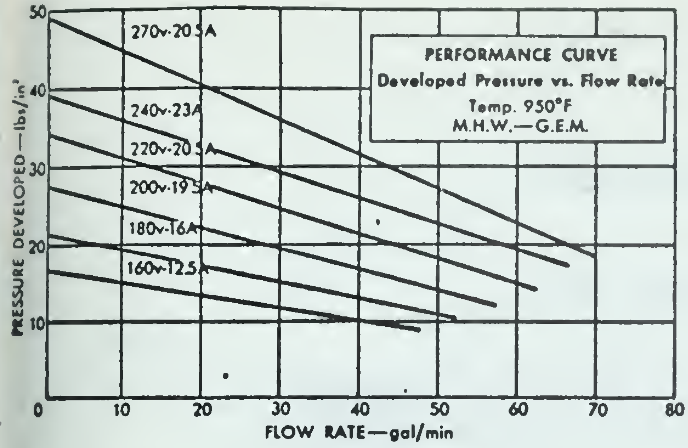


Figure 3-5 MSA AC Conduction Pump Design

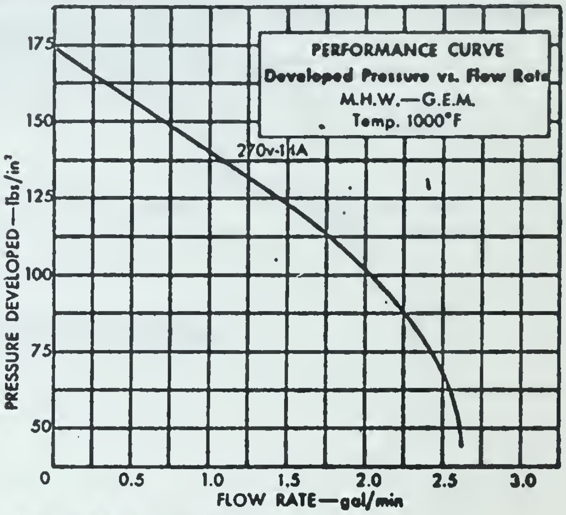


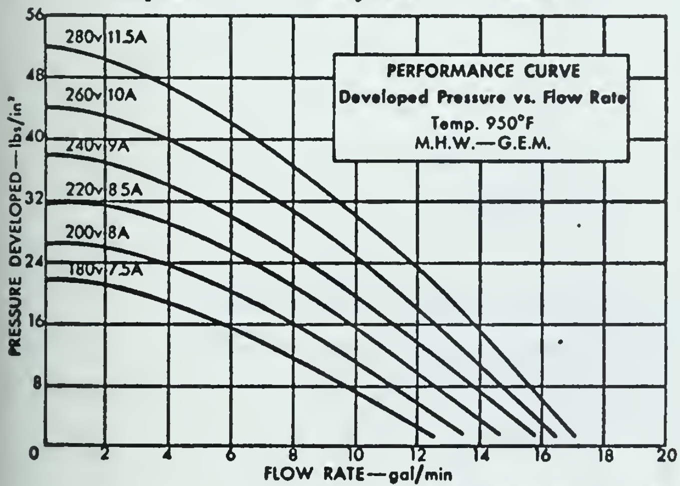
STYLE 25-30

Pumping section—
1" x 0.049" wall type 316 SS tubing, 48" long
Approximate dimensions—
Length—23 inches
Width —21 inches
Height—23 inches
Weight—280 pounds
Power requirements—
30 amperes—230 volts—1 ϕ ac
Auxiliary equipment supplied—
7.5 KVA—230-volt—1 ϕ capacitor
28 ampere—0-270-volt adjustable autotransformer

STYLE 0.5-150

Pumping section—
¼" x 0.035" wall type 316 SS tubing, 18" long
Approximate dimensions—
Length—15 inches
Width —18 inches
Height—16 inches
Weight—125 pounds
Power requirements—
15 amperes—230 volts—ϕ ac
Auxiliary equipment supplied—
5 KVA—230-volt—1 ϕ capacitor
28 ampere—0-270-volt adjustable autotransformer





STYLE 5-30

Pumping section—
½" x 0.049" wall type 316 SS tubing, 24" long
Approximate dimensions—
Length—15 inches
Width —17 inches
Height—15 inches
Weight—90 pounds
Power requirements—
10 amperes—230 volts—1 ϕ ac
Auxiliary equipment supplied—
5 KVA—230-volt—1 ϕ capacitor
9 ampere—0-270-volt adjustable autotransformer

STYLE 100-25

Pumping section—
1½" x .109 wall type 316 SS tubing, 48" long
Approximate dimensions—
Length—29 inches
Width —23 inches
Height—30 inches
Weight—800 pounds
Power requirements—
150 amperes—230 volts—1 ϕ ac
Auxiliary equipment supplied—
90 KVA—230 volt—1 ϕ capacitor
168 ampere—0-270-volt adjustable autotransformer

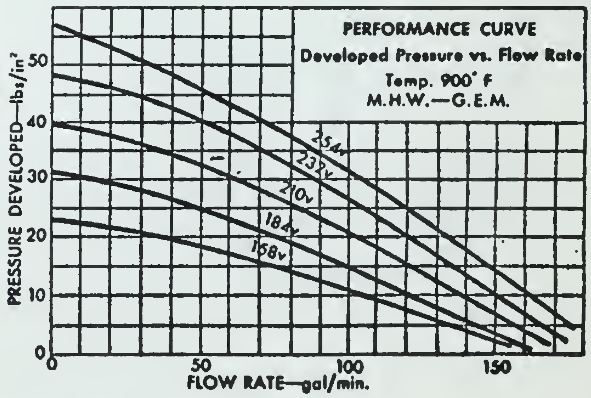
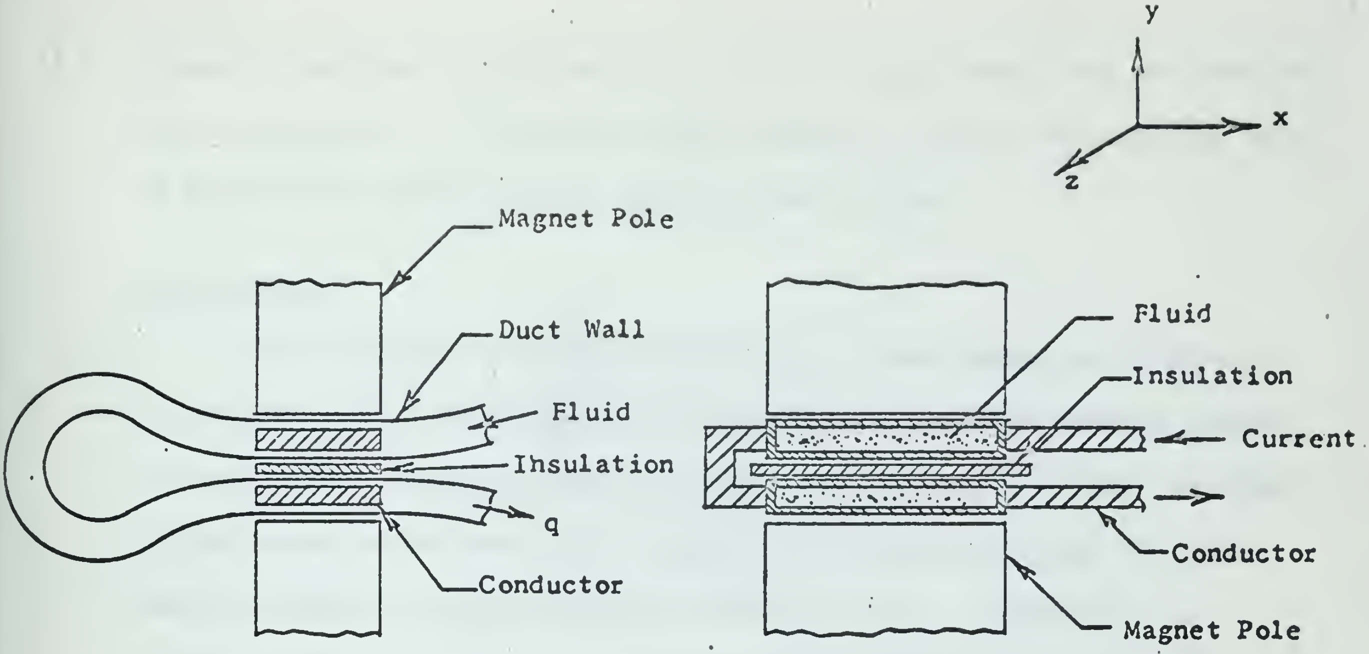
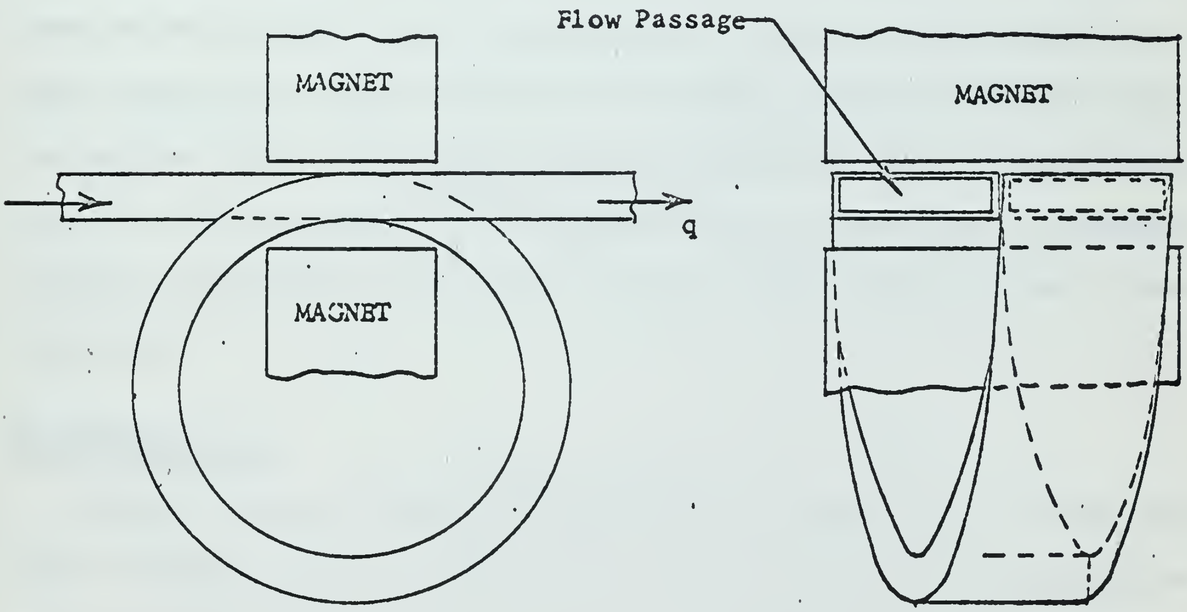


Figure 3-6 Performance Curves for MSA Conduction Pumps

[84]



Two-Stage Flat Duct, Common Flux, Common Current



Two-Stage Flat Duct. Common mmf, Common Current

Figure 3-7 Multichannel Conduction Pumps

[60]

forces transmitted to the pump duct from the liquid metal loop and from the power supply buses. Due to the higher hydraulic losses, this type of pump is restricted to applications requiring small pumps.

Helical Pump

In its simplest form, the helical pump is constructed by winding a rectangular duct into the shape of a spring with adjacent turns connected so that current can pass axially through the duct and fluid from ring-shaped electrodes on the ends. The magnetic field passes through the fluid radially between an inner and outer connected core. Compensation is obtained either by using a double helix arrangement or by returning the current through a hollow conductive cylinder fitted over or inside the helix. This pump is applicable for high pressure, low flow situations.

Spiral Pump

The spiral pump, which like the helical pump is applicable for high pressure and low flow uses, is constructed by winding a linear duct into a tight spiral with connected loops so that current can pass radially through the duct and fluid. The magnetic poles are above and below the face of the spiral to allow the field to flow perpendicular to the current. A pressure gradient is developed in the liquid along the spiral channel to cause pumping action.

Centrifugal Pump

Figure (3-8) and (3-9), show respectively, a spiral and a helical centrifugal conduction pumps. The ducts in these designs have no flow separators. The spiral and helical flow is produced by the interaction of the current and magnetic field. In both designs the excitation is provided by toroidal

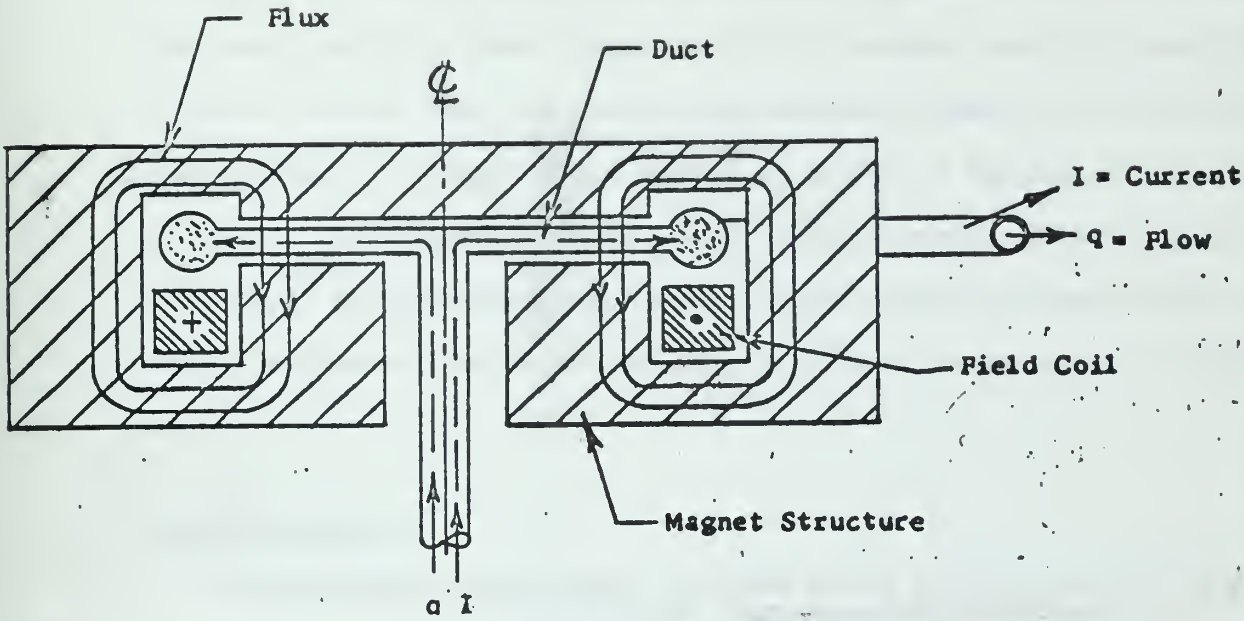


Figure 3-8 Spiral Centrifugal Pump

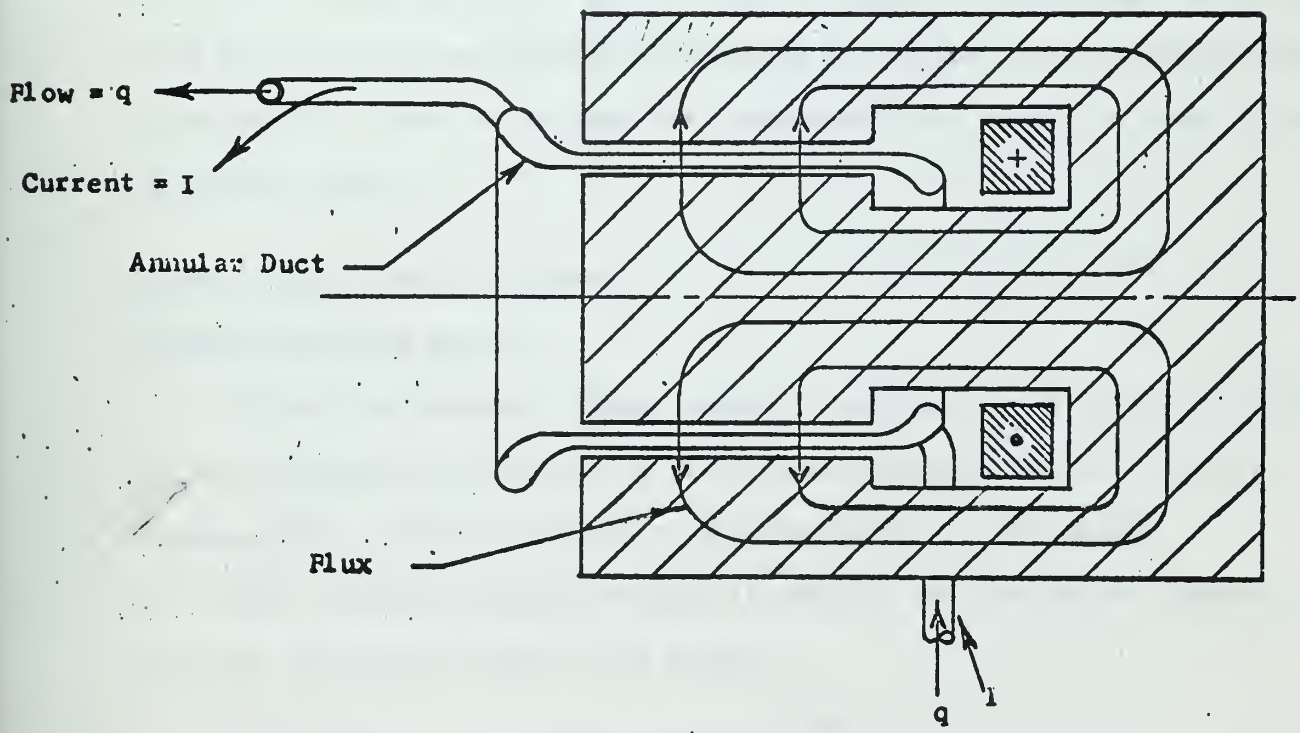
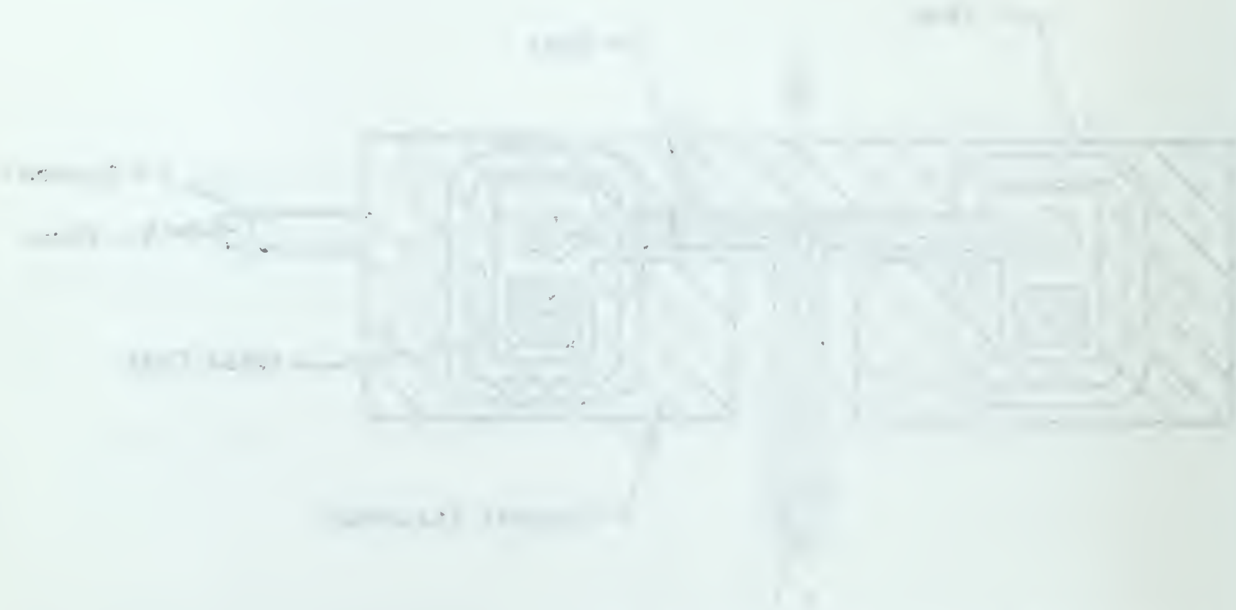


Figure 3-9 Helical Centrifugal Pump

[59]



coils and in both cases the current and fluid enter and exit the pump through the same duct. In the spiral centrifugal pump the radial current in the fluid reacts with the axial magnetic field to produce rotation about the centerline of the pump. In the helical centrifugal pump, the radial field interacts with the radial fluid current to produce a tangential force on the fluid. The tangential force on the fluid increases as the fluid passes in a helical fashion through the pump. After leaving the annular duct, the fluid is diffused, causing the velocity head to be converted to a static pressure.

Pinch-Effect Pump

The pinch-effect pump shown in Figure (3-10) produces pumping action in a different manner than those previously described. The current is conducted into the duct and fluid via two electrodes. The magnetic field surrounding the current is provided a low reluctance path by a C-shaped core. The flux which is in phase with the current travels around the magnetic flux path and then perpendicularly through the current carrying fluid. The pinch action is such as to push the fluid toward the center as shown in the f ollowing figure.

General Design Considerations.

Armature Reaction Effect.

In the electromagnetic pump, armature reaction is the effect produced by the circulating current which distorts the magnetic field, thereby increasing its strength at the inlet and reducing it at the outlet.

Since the total applied voltage is equal to the sum of the induced e.m.f. plus the resistivity drop in the liquid:

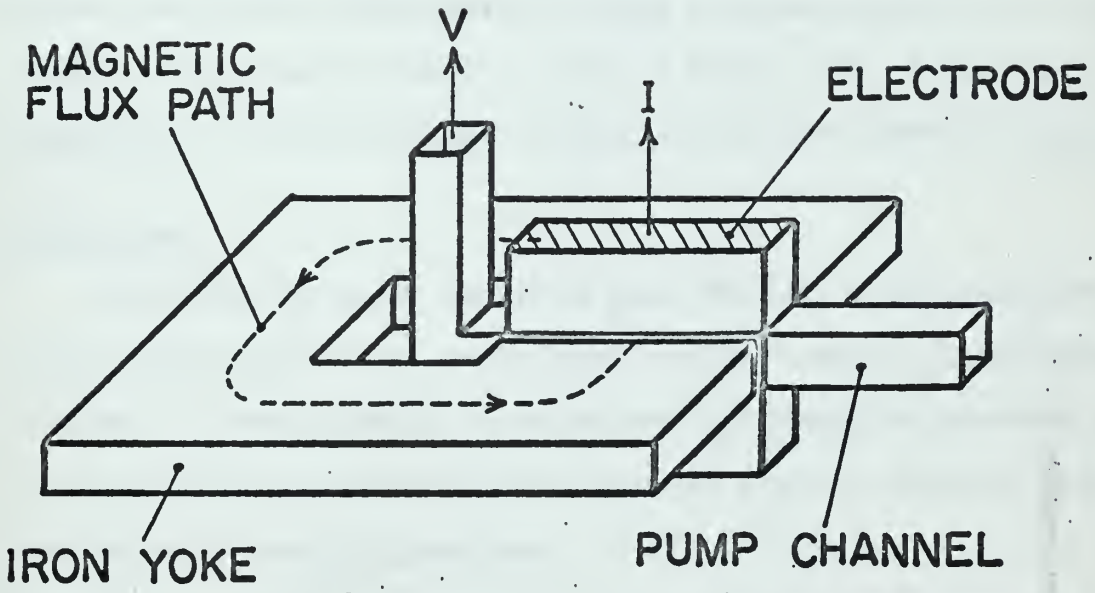


Figure 3-10 Pinch-Effect Pump

$$V = (vH + \rho J)b$$

a change in H is reflected by a change in J, or vice versa for a constant applied voltage. The distortion of J and H results in a reduction of pump pressure thereby reducing the pump efficiency. This situation is shown in Figure 3-11.

In the case of DC rotating machinery the field distortion can be virtually eliminated by compensating windings. In the case of electromagnetic pumps this is done by returning the current, that flows through the duct walls and liquid metal, in the opposite direction. The return current distribution should match as close as possible that of the duct and liquid. A compensation scheme is shown in Figure 3-12. Figure (3-13) shows compensation in an actual linear conduction pump with combined transformer.

Eddy-Current

In the case of the AC conduction pump, the main alternating flux will induce large eddy currents in the liquid and will cause fringing between the electrodes. These currents can be reduced by dividing the electrode into a number of sections and by connecting opposite pairs to different isolated windings of the supply transformer.

Windings

A good arrangement is to wrap the conductor, carrying the current that transverses through the liquid, around the pole. This ensures, in the case of the AC conduction pump, that the current and the flux are in phase to obtain maximum pumping action.

Channel and Magnet Geometry.

See Figure 2-3. The performance of a conduction pump is greatly affected by the relative proportions a:b:c of the duct. A large value of b/a

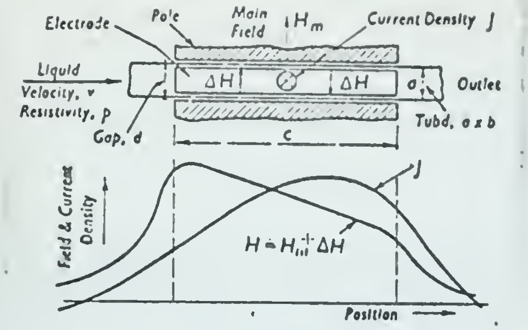


Figure 3-11 Field and Current Density Vs. Position

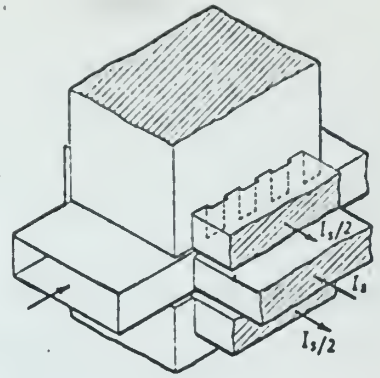


Figure 3-12 (a)

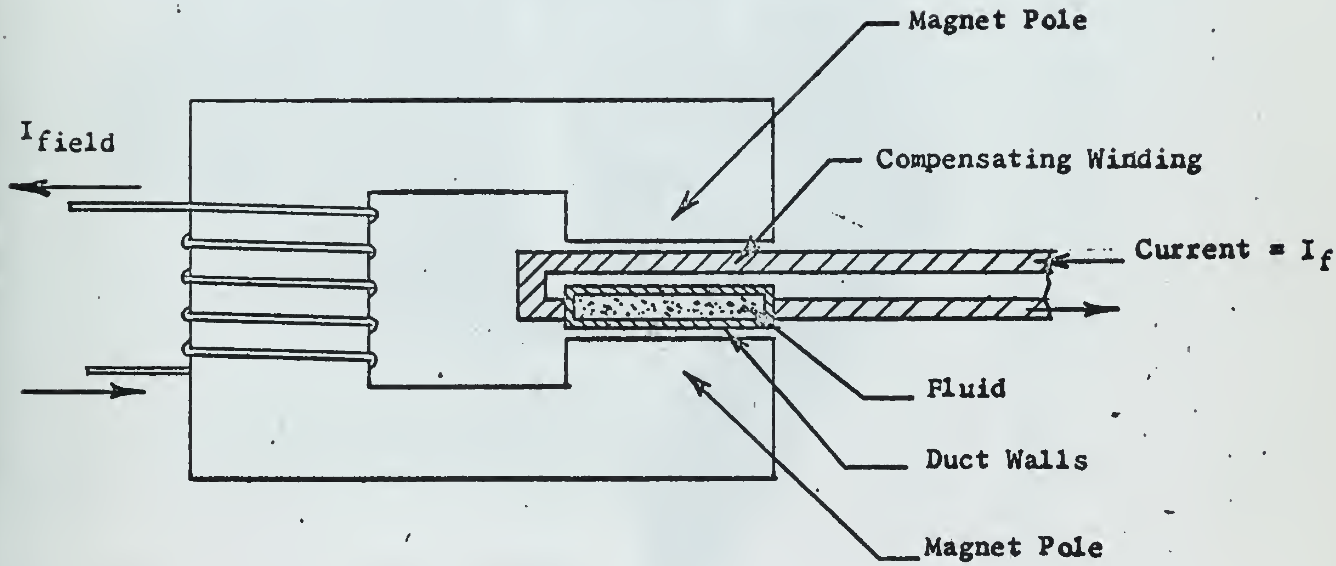
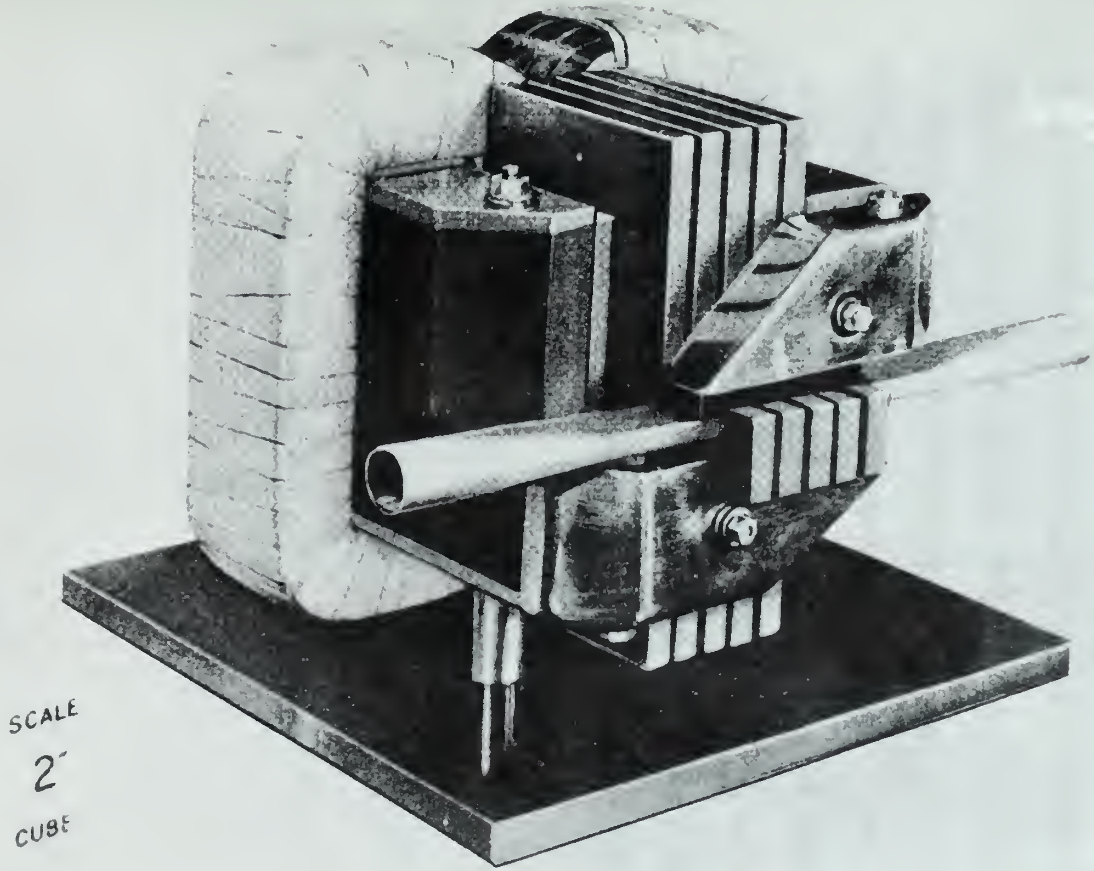


Figure 3-12 (b) Compensation Scheme

[31] [60]



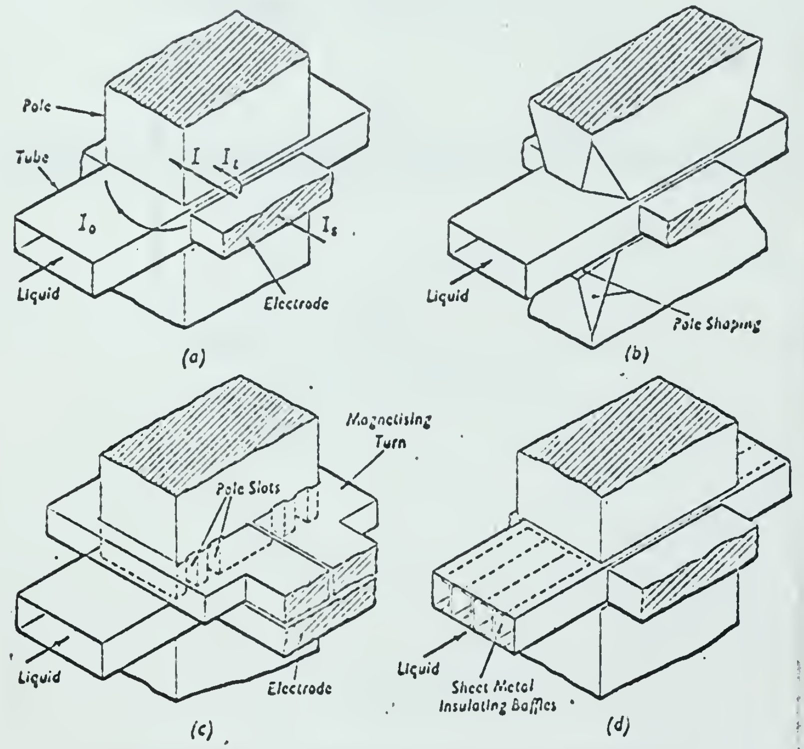
ELECTRO-MAGNETIC LIQUID-METAL PUMP
A.C. CONDUCTION TYPE.

Figure 3-13

is desirable to keep the supply current low. Also a large value of c/b is desirable to improve efficiency but both of these ratios increase the size of the pump. The cross section, ab, depends on the hydraulic losses tolerated. If ab is too small, the losses may become excessive. In the DC pump, low supply current, high efficiency, and small size are in opposition. Similarly in the AC pump, power factor, high efficiency, and small size are in conflict.

End Effects

The part of the electrode current (I_o) that flows at the ends of the pump outside of the pole region and the current that flows through the duct walls have no pumping effect thus contributing only to losses. To reduce or to make the end currents useful, it is necessary to grade the field and to match the natural fringing of the current density. This can be accomplished by pole shaping, by passing magnetizing turns through the pole, or both. Another method involves the use of sheet metal baffles in the duct ends outside the pole region. This arrangement however, leads to additional hydraulic losses. Some methods are illustrated in Figure 3-14.



I_e = electrode current; I = useful component; I_o = component in liquid outside pole; I_t = component in tube wall.

Figure 3-14 Methods to Reduce End Effect

APPENDIX I

Development of DC conduction pump theory from the equivalent circuit

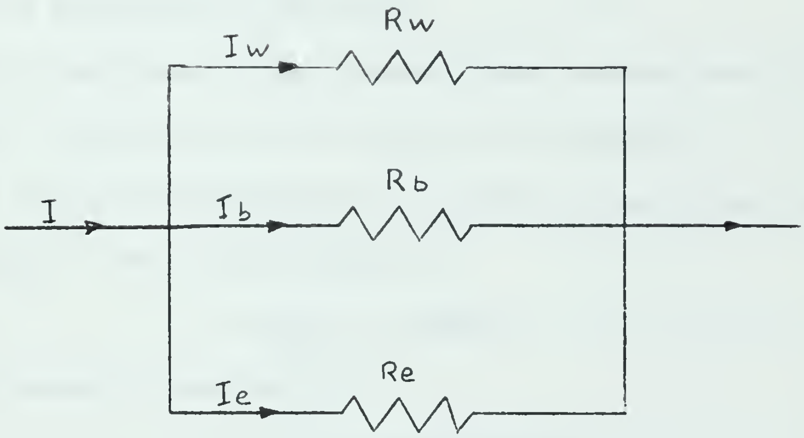


Figure 3A-1

DC conduction pump equivalent circuit

In Figure 3A-1 above:

- Ie = Current traversing the liquid which is between the poles
- Ib = Fringing current (current through the liquid outside the poles)
- Iw = Current that flows through the walls
- Ec = Counter e.m.f. developed in the duct due to the liquid flow through the magnetic field.
- Rw = Resistence of the walls
- Re = Resistence of the effective path through the liquid
- Rb = Resistence of the by-pass in the liquid
- b = Inside duct dimension in which current flows through the liquid

The magnetic force on the liquid is

$$F = B\,b\,Ie \quad \text{newtons} \tag{3-1}$$

And the pressure developed is

$$P = \frac{B\ \ Ie}{C}\ \text{newtons/meter}^2 \tag{3-2}$$

The total current traversing the duct is the sum of the currents in the liquid and in the duct walls. The current in the liquid consists of two parts, the one flowing between the poles (strong field) and the one that flows outside the pole region (weak field). The weak field contributes little or nothing to the pumping action.

$$I = Iw + Ib + Ie \tag{3-3}$$

$$Ie\ Re + Ec = Ib\ Rb = Iw\ Rw \tag{3-4}$$

Solving (3-4) and (3-3) for I

$$I = Ie\ Re\left(\frac{Rw + Rb}{Rw\ Rb}\right) + Ie + Ec\left(\frac{Rw + Rb}{Rw\ Rb}\right) \tag{3-5}$$

The back e.m.f., Ec is

$$Ec = B\ v\ b\ \text{volts} \tag{3-6}$$

and the velocity v in terms of the flow Q

$$v = \frac{Q}{ab} \quad \text{meters/sec.} \tag{3-7}$$

$$Ec = \frac{B\ Q}{a} \quad \text{volts} \tag{3-8}$$

substituting (3-8), (3-3) into (3-5) and solving for Q

$$Q = \frac{a}{B}\left[\frac{I(Rw\ Rb)}{Rw + Rb} - \frac{P\,a}{B}\left(Re + \frac{Rw\ Rb}{Rw + Rb}\right)\right] \quad m^3/\text{sec.} \tag{3-9}$$

This equation shows the dependence of flow on magnetic field density, current, and duct geometry. Rb is best evaluated from experimental tests; Rw and Re from resistivities and dimensions of the walls and liquid respectively.

Taking the partial, $\frac{\partial Q}{\partial I}$ shows the linear dependence of flow on current

$$\frac{\partial Q}{\partial I} = \frac{a}{B}\ \frac{Rw\ Rb}{(Rw + Rb)} \quad , \quad \frac{m^3/\text{sec.}}{\text{Amp.}} \tag{3-10}$$

The developed static pressure for no-flow condition, obtained from equation (3-9) is equivalent to equation (3-2).

$$P = \frac{B\ I\ Rw\ Rb}{a\ (Rw\ Rb + Re(Rw + Rb))} \quad \text{nt./m}^2 \tag{3-11}$$

Taking the partial $\frac{\partial P}{\partial Q}$ from equation (3-9) shows the linear dependence of pressure on flow, neglecting hydraulic losses

$$\frac{\partial P}{\partial Q} = \frac{-B^2}{a^2\left(Re + \frac{Rw\ Rb}{Rw + Rb}\right)} \tag{3-12}$$

In order to find the maximum flow as a function of B, take the partial $\frac{\partial Q}{\partial B}$ and set the partial equal to zero:

$$\frac{\partial Q}{\partial B} = \frac{-\ a\ I\ Rw\ Rb}{(Rw + Rb)B^2} + \frac{2\ \ a^2 P}{B^3}\left(Re + \frac{Rw\ Rb}{Rw + Rb}\right) = 0$$

$$\hat{B} = \frac{2 \quad P\,a}{I}\left(1 + \frac{Re}{Rb} + \frac{Re}{Rw}\right) \text{ webers} \tag{3-13}$$

The voltage applied to the pump, V_t

$$V_t = Ec + Ie\ Re + \frac{BQ}{a} + \frac{P\ a\ Re}{B} \tag{3-14}$$

The electrical power will be $W_t = I\ V_t$

$$W_t = I\left(\frac{B\ Q}{a} + \frac{P\ a\ Re}{B}\right) \tag{3-15}$$

The power transferred to the liquid divided by the total power is equal to the electrical efficiency

$$\text{Efficiency} = \frac{P\ Q}{I\ \left(\frac{B\ Q}{a} + \frac{P\ a\ Re}{B}\right)} \tag{3-16}$$

Substituting Q from equation (3-9)

$$\text{Efficiency} = \frac{P\ a\ (I\ Rw\ Rb - (Rw\ Rb + Re\ Rb + Re\ Rw)\ \ P\ a/B)}{B\ I\ \ \ (I\ Rw\ Rb - Rw\ Rb\ \ \ P\ a\ /B)} \tag{3-17}$$

for a DC pump with non-conducting walls. When high resistivity liquid metal, such as Mercury, is to be pumped by a DC conduction pump with conducting walls, a high loss results from the current that flows through the duct walls. Several experiments have been performed by Arnold Engineering Development Center by insulating the electrodes from the stainless steel duct by utilizing a high resistence ceramic cement. This configuration is illustrated in Figure (3A-2).

It should be noted that this pump was designed to work in a "Collector System Complex" to remove the exhaust efflux from an evacuated chamber where space conditions were simulated to test the effects on electrical propulsion systems.

The first pump that was built consisted of a stainless steel jacket with a rectangular passage; copper electrodes were embelded into a slot

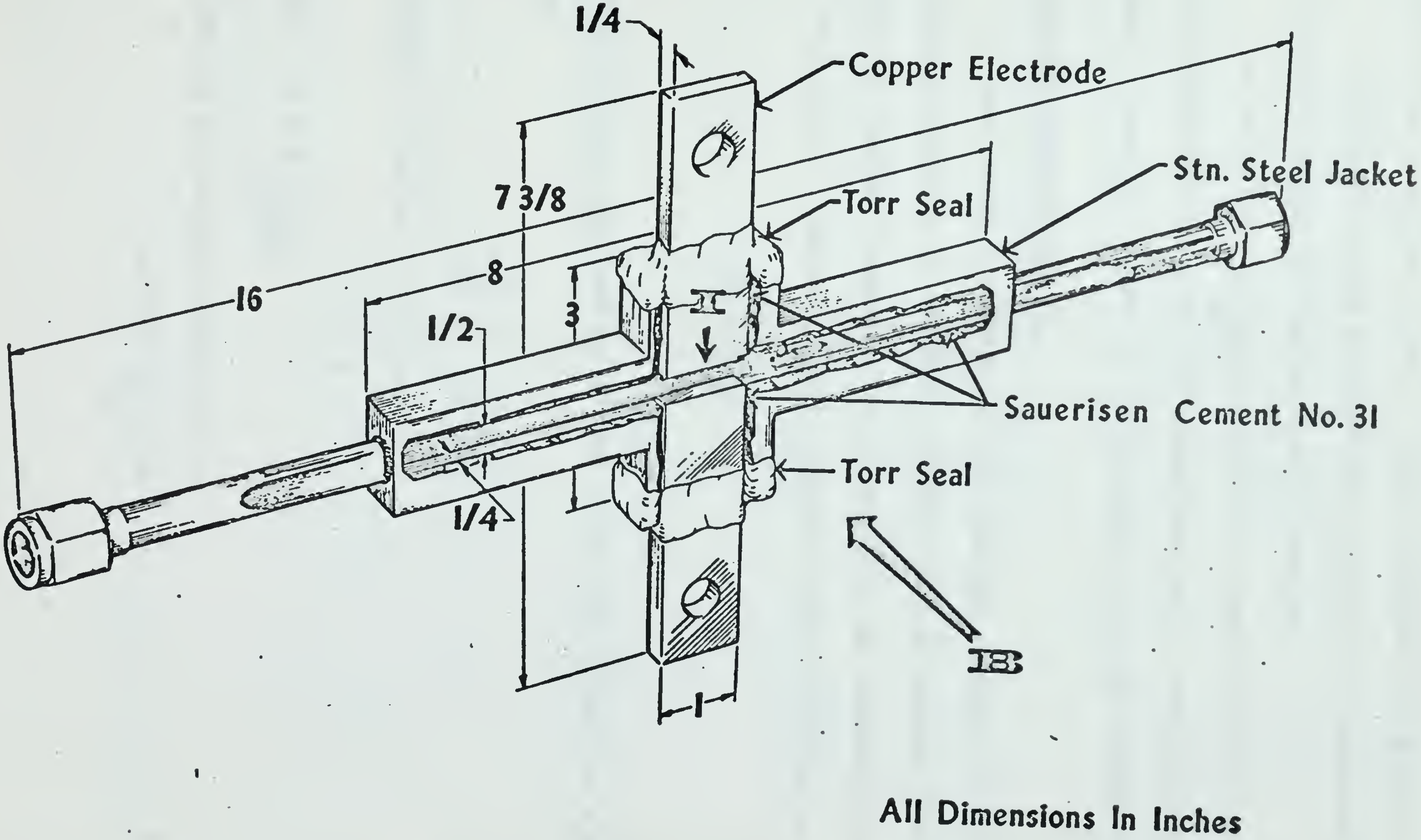


Figure 3A-2 Ceramic d-c Faraday Electromagnetic Pump [6]

perpendicular to the fluid flow. A ceramic cement (Sauereisen #31) was used to seal the system. The cement did not form a sufficiently tight bond with either stainless steel or copper electrode, resulting in a mercury leak.

A different cement Torr-Seal was tried and the pump performed adequately but the vacuum problems were still present.

The efficiency of the pump with the ceramic tube wall was found to be 46% higher than the pump with conducting walls. This non-conducting wall pump is specially suited to liquid metals with high resistivity.

Armature Reaction Analysis

A more detailed analysis of the armature reaction in the idealized DC conduction pump is as follows: Assuming that no current flows outside the pole and electrode region and also that only the components Jy, Hx and v_z to be present. Then the Maxwell equation can be expressed as

$$-\frac{dH}{dz} = \frac{4\pi J}{10} \qquad (3\text{-}18)$$

$$V = \rho J b + H v b/10^8 \qquad (3\text{-}19)$$

Differentiating equation (3-18) and (3-19) with respect to z and substituting

$$\frac{d^2H}{dz^2} = \frac{4 \quad v\, dH}{\rho\, 10^9} \qquad (3\text{-}20)$$

Assuming a solution of the form

$$H = A + B e^{\frac{2\beta z}{c}} \qquad (3\text{-}21)$$

Where $\beta = \frac{2\pi v c}{\rho 10^9}$

Expressing the boundary conditions as

$$Hm = 1/c \int_0^c H\, dz \qquad (3\text{-}22)$$

$$Jm = 1/c \int_{o}^{c} J\,dz = 1/c \int_{o}^{c} \frac{10\,dH}{4\pi} = \frac{10}{4\pi c} (Hc - Ho) \qquad (3\text{-}23)$$

where c is the length of the pump and Jm and Hm are the mean values of J and H respectively.

Substituting (3-21) into (3-22) and (3-23)

$$Hm = A - \frac{B\,c}{2\beta} (1-e^{2\beta}) \qquad (3\text{-}24)$$

$$Jm = \frac{10}{4\pi c} (1-e^{2\beta})B \qquad (3\text{-}25)$$

Solving for A and B

$$A = Hm + \frac{4\pi\ Jm\ c}{10\beta} \qquad (3\text{-}26)$$

$$B = \frac{4\pi\ c}{10(1-2e^{2\beta})} \qquad (3\text{-}27)$$

Substituting in equation (3-21)

$$H = Hm + \frac{2\pi\ Jm\ c}{\beta} \left(1 + \frac{2\beta\ e^{\frac{2\beta z}{c}}}{1 - e^{2\beta}}\right) \qquad (3\text{-}28)$$

Substituting in equation (3-18)

$$J = \frac{Jm\ 2\beta\ e^{\frac{2\beta z}{c}}}{1 - e^{2\beta}} \qquad (3\text{-}29)$$

Since the total pressure developed in the pump can be expressed as

$$Pz = \int_{o}^{c} Jy\ \ Hz\ dz \qquad (3\text{-}30)$$

Substituting equation (3-28) and (3-29) into (3-30)

$$P = Hm\ Jm\ c\ [1- \frac{2\pi Jm\ c}{Hm} (\frac{\beta \coth\beta\ -1}{\beta})] \qquad (3\text{-}31)$$

The gross output power Wo (Pump power output + hydraulic losses) can be expressed as

$$Wo = Pz\ v\ a\ b \qquad (3\text{-}32)$$

$$Wo = Hm\ Jm\ v\ c\ b\ a\ [\ 1- \frac{Jm}{Hm} c\,2\pi (\beta \coth\beta\ -1)] \qquad (3\text{-}33)$$

the Ohmic losses in the fluid are

$$W_f = a\, b \rho \int_0^c J^2 dz = \rho\, J_m^2 \quad a\, b\, c\, \beta \quad \coth \beta \qquad (3\text{-}34)$$

The pump efficiency can be expressed as

$$\text{Efficiency} = \frac{Wo}{Wo + Wf} = 1 - \frac{\beta \coth \beta}{1 + \dfrac{Hm\, \beta}{2\pi\, Jm\, c}}$$

$$= 1 - \frac{\beta \coth \beta}{1 + \beta \dfrac{Hm}{Hi}} \qquad (3\text{-}35)$$

Using the notation Hi which indicates the maximum field at the poles edges $z = 0$ and $z = c$ that would be produced by the current in the liquid metal;

$$Hi = 2 \quad Jm\, c = \frac{4\pi I}{2\, a} = \frac{Ho - Hc}{2} \qquad (3\text{-}36)$$

Let us consider the effect of increasing the current density, keeping v and Hm constant. With this condition, Wo can be expressed as

$$Wo = k_1\, Hi\, (1 - k_2\, Hi) \qquad (3\text{-}37)$$

where k_1 and k_2 are constants; this expression has a maximum at

$$Hi = \frac{1}{2\, k_2} \qquad (3\text{-}38)$$

$$Wo(max) = \frac{k_1 \quad Hi}{2} = \frac{Hm\; Jm\; a\; b\; c\; v}{2} \qquad (3\text{-}39)$$

Expressing k_2 from equation 3-38 in terms of equation (3-33) to obtain

$$Hi = \frac{Hm \quad \beta}{2\,(\beta \coth \beta \; -1)} \qquad (3\text{-}40)$$

Substituting (3-40) into (3-35)

$$\text{efficiency} = \frac{\beta \coth \beta \; -1}{2\, \beta \coth \beta \; -1} \qquad (3\text{-}41)$$

This expression has a maximum value of 50% for large β since $\coth B \rightarrow 1$ as $\beta \rightarrow \infty$.

From the previous development it follows that if Hm and v are kept constant and the current is increased, the power output increases up to a maximum then decreases, with maximum efficiency only 50% of that of a pump

perfectly compensated for armature reaction. Ideal compensation is not realizable in practice due to end currents and wall currents. If the total current is returned through the poles, the pump will be "Over compensated" and the magnetic field will be increased at the outlet and decreased at the inlet. The distortion of H and J again results in reduced pumping pressure which leads to reduction of efficiency.

CHAPTER IV

Induction Pumps

In induction pumps, as the name implies, the currents are induced inside the duct and hence in the liquid by a changing magnetic flux. The induced currents flow in closed loops and if the currents can be made to have a component perpendicular to and in phase with a magnetic flux, a force or a pressure gradient can be developed.

The inherent advantages over the conduction pump are: (1) that an external source of high current is not required, (2) nor are heavy electrode connections with their corresponding contact resistance losses. (3) The problem of designing efficient DC or very low frequency AC supplies is partially solved.

Since high currents must be induced, it is necessary that liquid metals have low resistivities. The primary fluids used to date are sodium and sodium-potassium alloy. High frequencies are not desirable, in fact as pump capacity increases, the frequency of the magnetizing current must be decreased.

In Figure 4-1 is a block diagram of the induction pump family tree. Most of the discussion in this paper will deal with stationary windings.

Single Phase Pumps

The single phase design is an annular duct configuration of which there are two types, the pump with a secondary iron circuit (Watt Pump), or the pump with a single iron circuit. These two types will be discussed later.

In the induction pump, symmetry can present a problem which is not considered in conduction pumps. In Figure (4-2) the eddy currents are shown for a single phase AC conduction Pump (assuming zero fluid velocity). Based

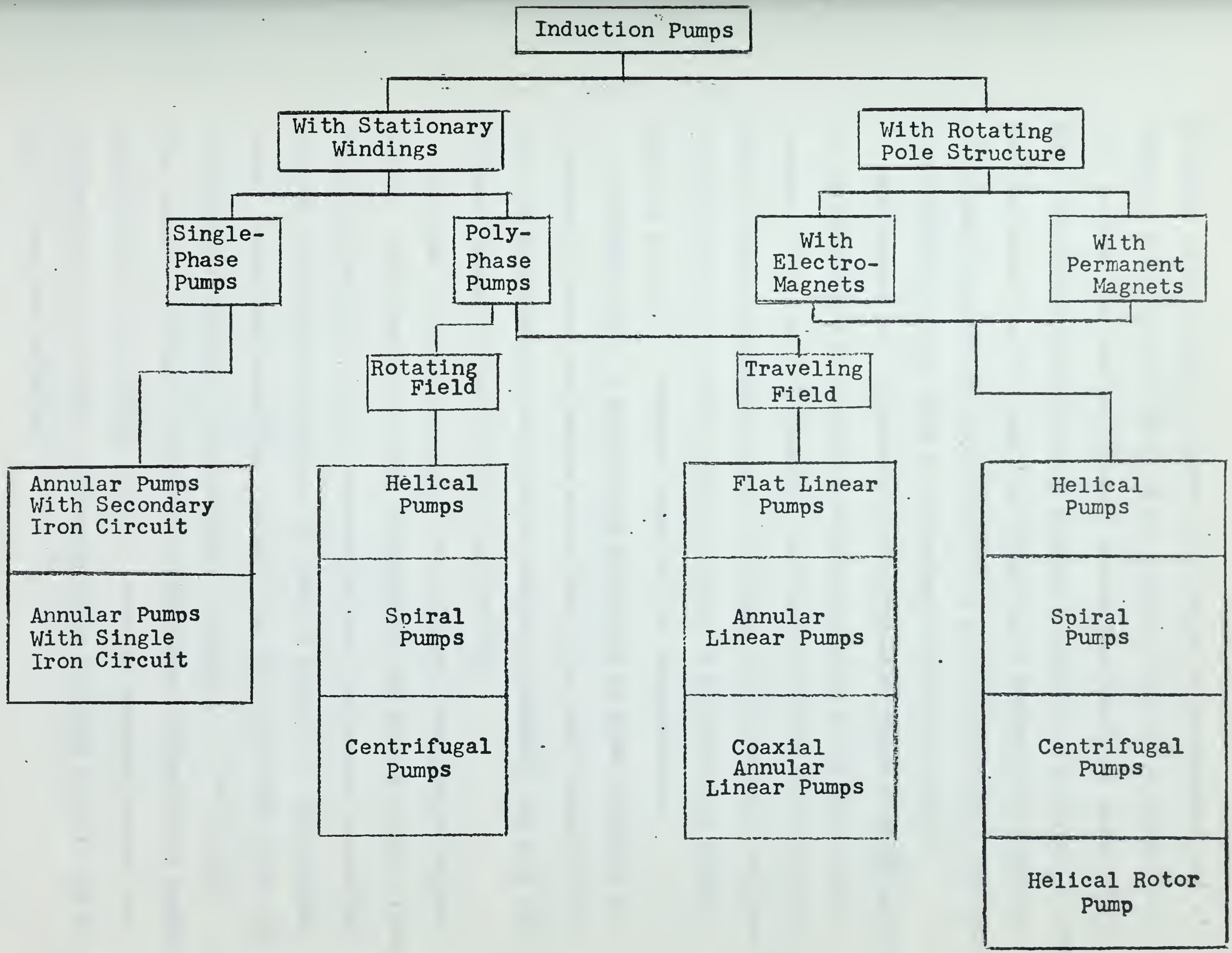


Figure 4-1 Induction Pump Family Tree

on Lenz's Law the currents are such as to oppose the exciting mmf with a resultant flux density as shown in the right hand sketch, of Figure (4-2), i.e., maximum flux near the periphery and minimum toward the center of the duct. The forces on the fluid are toward the center in this instant of time. When the magnetizing flux goes from increasing to decreasing, the current will change direction and the forces will be away from the center, but due to the symmetry the net force at any instant of time will be zero.

The symmetry can be destroyed as illustrated in Figure (4-3) by attaching low resistance bars to one end of the duct structure to off-set the eddy currents. The counter flux generated by the eddy current distorts the flux density so that the maximum occurs at the upper end of the duct. The force is now directed on the fluid toward the region of decreased flux density, hence the net force is downward toward the low resistance bars.

In Figure (4-4), an annular pump (Watt Pump) is shown to consist of an annulus (a) where the pumping action takes place, small pipes (b) which carry the liquid metal to and from the annulus, a secondary flux path (c), a primary winding (d), and the main flux path (e).

The pump is energized by single phase current flowing in the primary winding. The primary flux, which is produced by the primary current, flows through the main core. This alternating primary flux induces circulating currents in the annulus (secondary) as shown in Figure 4-5. The secondary current in the annulus produces a counter flux ($\emptyset_s$) which flows in the low reluctance path provided by the secondary flux path (c). The secondary iron circuit is designed so that the secondary flux transverses the annulus perpendicular to the secondary current. Since the secondary current and secondary flux are in phase, net pumping action will take place in the annulus in the axial direction.

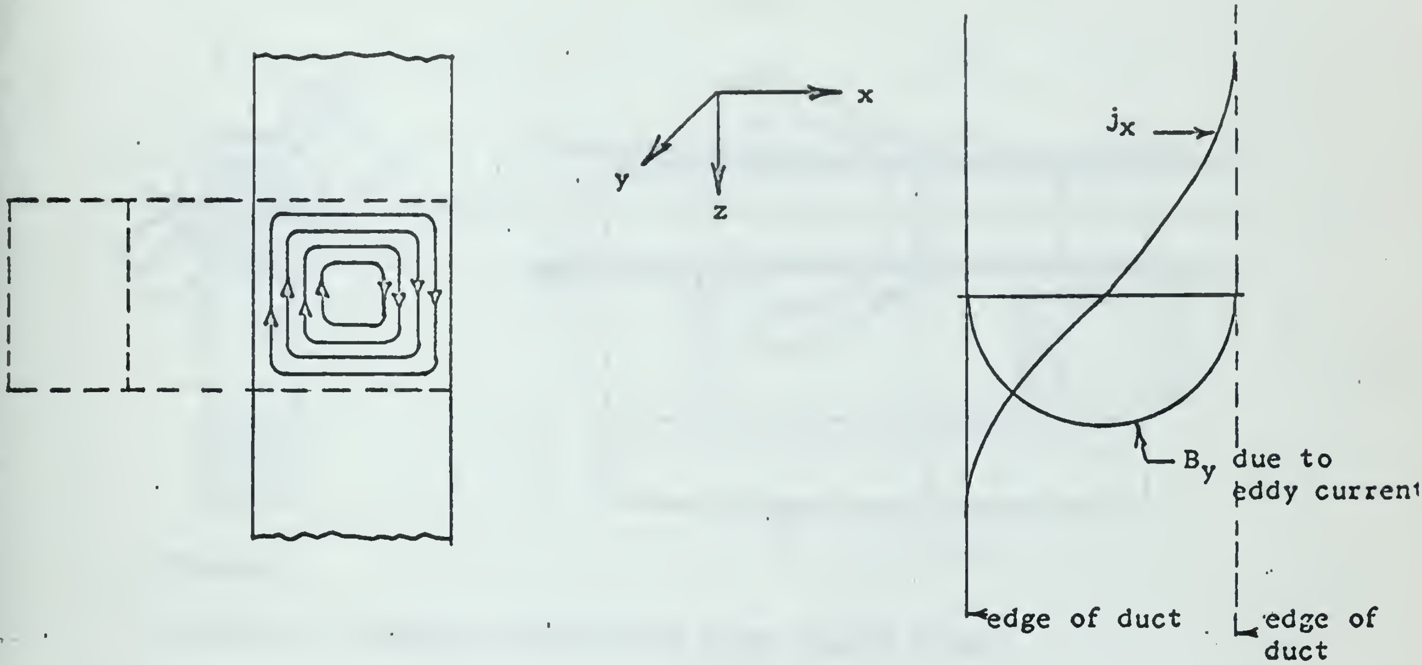


Figure 4-2 EDDY CURRENT & FLUX DENSITY DUE TO EDDY CURRENT
SINGLE PHASE AC CONDUCTION PUMP

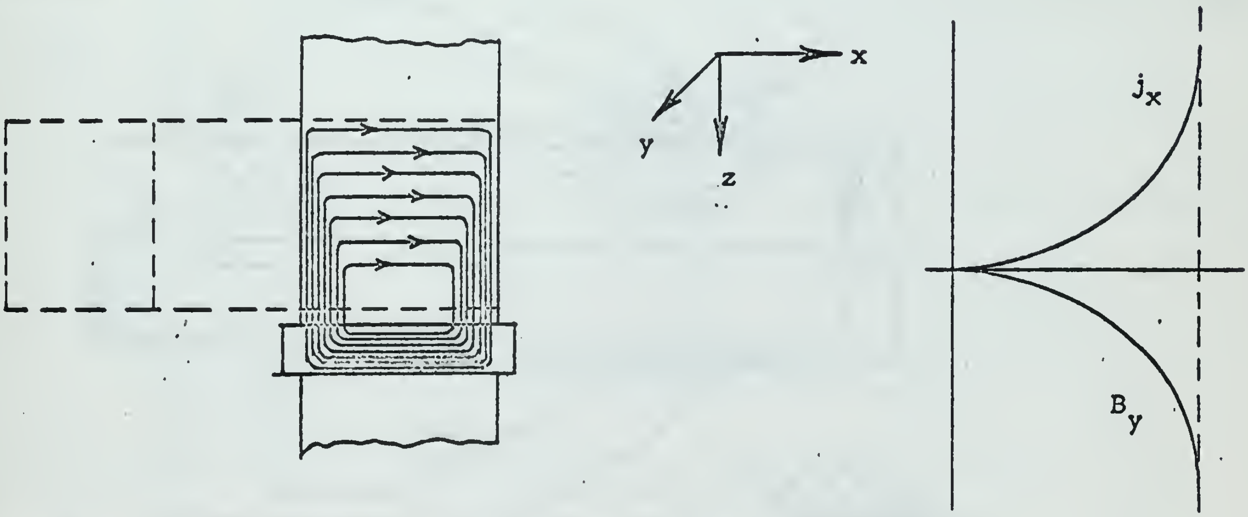


Figure 4-3 EDDY CURRENT & FLUX DENSITY DUE TO EDDY CURRENT
SINGLE PHASE INDUCTION PUMP

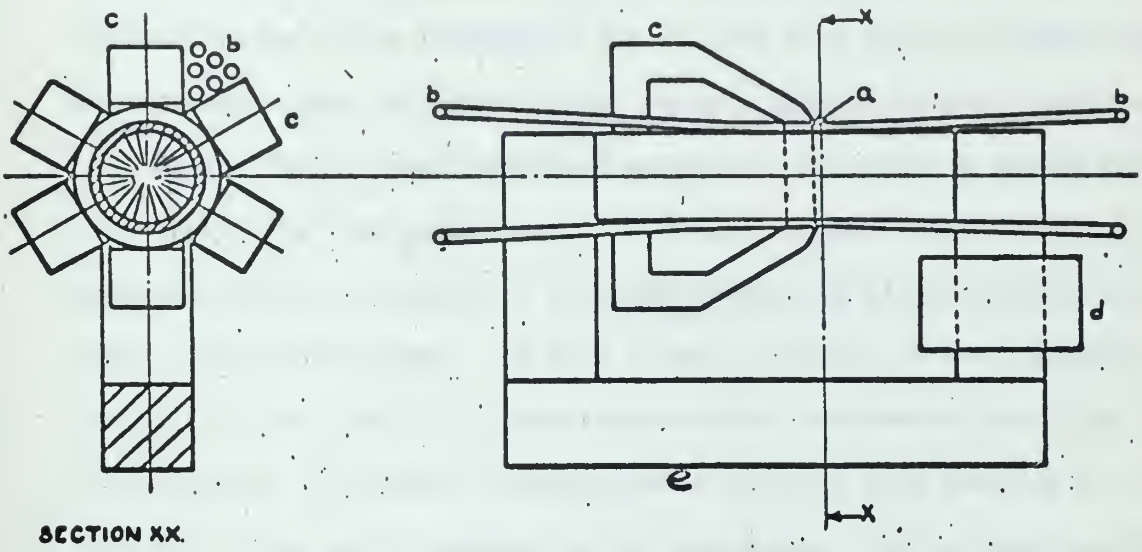


Figure 4-4 Annular Induction Pump (Watt Pump)

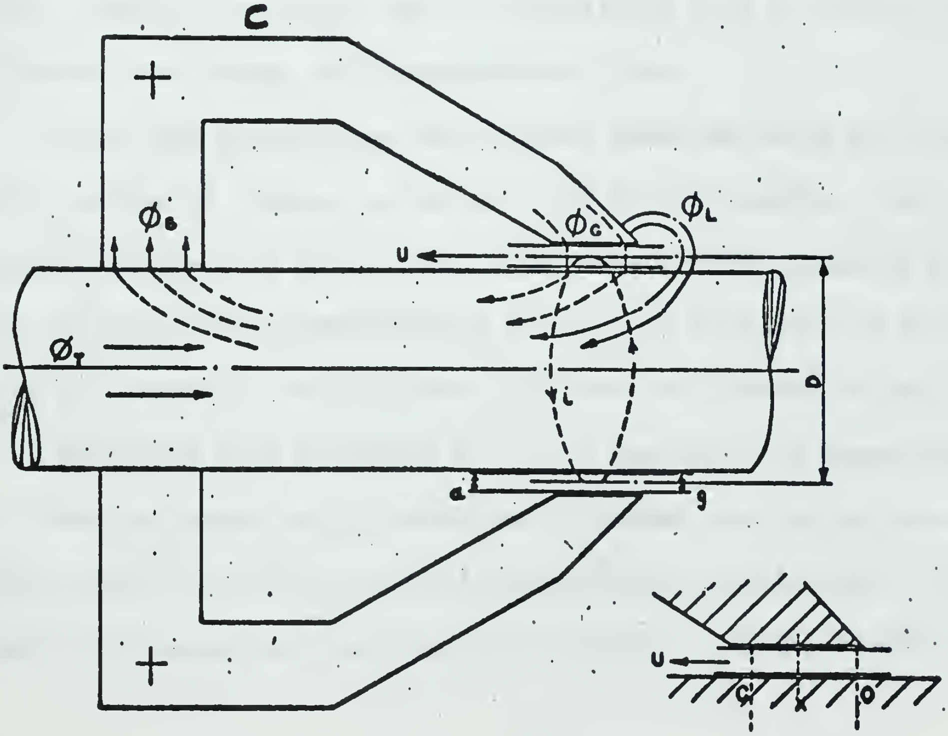


Figure 4-5 Annular Induction Pump (Watt Pump)

[21]

Flux fringing ϕ_1 is kept to a minimum by tapering the secondary circuit near the annulus as shown in Figure (4-5). The secondary current, which depends on total reactance of the secondary circuit, determines the maximum pressure rise obtainable for a given core size and channel width. End current losses are minimized by using a multiplicity of ducts (pipes).

Figure (4-6) is an example of an annular duct with a single iron circuit excited by a toroidal coil. To reduce unwanted eddy currents, the magnetic core is laminated so that the lamination plates contain the axial center line of the pump. The flux flowing parallel to the centerline induces currents in the fluid in closed circles about the center line. The sketch in the figure represents a particular instant of time where ϕ is in the direction shown and is assumed to be increasing. The currents are shown as tails of an arrow. Since the current and the main flux are 90° out of phase, no net work is done since for half a cycle the force is in one direction and for the other half of the cycle the force is in the opposite direction. However, a counter mmf is established with an induced flux generated to oppose the change of the magnetizing flux.

Since the magnetizing flux is more dense at point (a) than at point (b), more current is induced on the left end of the annulus, i.e., a current density gradient is established. The counter flux produced by the circulating current will be concentrated at the left hand side of the duct in phase with the current. The net force will now be directed to the right.

Referring back to Figure (4-1), we see that the second and larger group of induction pumps having stationary windings are the polyphase pumps which are divided into rotating field and traveling field group. The polyphase pump utilizes the principles of the polyphase induction motor. Polyphase

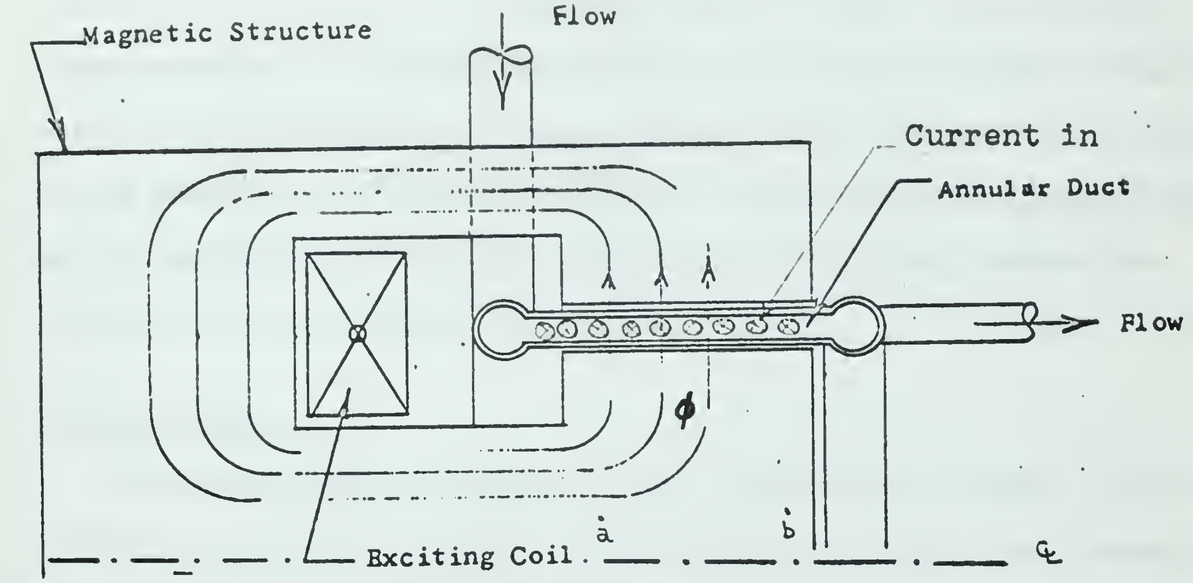


Figure 4-6 Annular Induction Pump

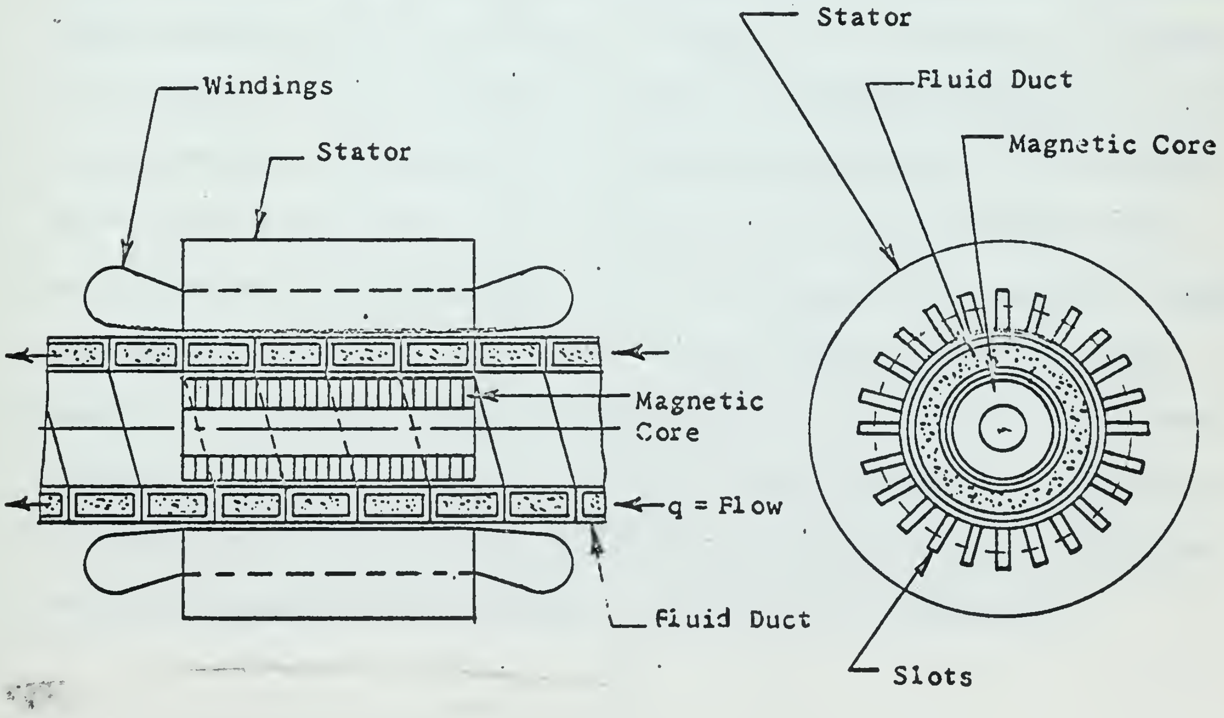


Figure 4-7 Helical Induction Pump

alternating current is supplied to stator windings which are distributed on one or both sides of the pump duct. The windings are located in such a manner in slots to produce a sinusoidal mmf which moves along the duct to induce voltages in the fluid and duct walls. The induced currents interact with the traveling magnetic field to produce a force component on the fluid in the direction of the axis of the duct. The advantages of polyphase pump are (1) adaptability to existing power sources and (2) the freedom from electrical contact with the duct.

Rotating Fields

Considering first the rotating fields, the classical example in most literature is the helical induction pump (HIP) which most closely resembles the squirrel-cage induction motor. The windings in the stator are distributed in slots similar to any polyphase induction motor or generator. In this case however, the copper conductors and the rotor have been replaced by a fixed magnetic core and an annulus through which the fluid flows. The central magnetic core provides a low reluctance flux path for the flux which flows radially across the air gap. The annulus is in the form of a helical duct network as shown in Figure (4-7). When the polyphase potential is applied to the windings, a rotating mmf is produced due to design of the windings. The rotating field induces axial voltages into the fluid and duct walls. The induced axial currents react with the rotating field to produce a tangential force on the fluid. The fluid is forced through the helical ducts, however, it is obvious that the axial component of the fluid velocity constitutes a loss which increases as the helix angle increases. This loss can be diminished by skewing the slots until a perpendicular angle between the slots and the helical flow passage is approached for optimum flow.

Compared to polyphase induction pumps, moving magnet pumps have the following advantages and disadvantages:

Advantages:

a. Lower volt-ampere input due to the low power factor of polyphase induction pumps.

b. Field windings are more effective, hence less volume of active material required.

c. Since lower voltage can be used, the insulation requirements are less stringent.

d. More design flexibility since speed and number of poles are not as inter-related with frequency.

By designing the pump with suction and discharge on the same end, see Figure (4-8), several improvements over the previous design are obtained, namely: (1) The pump can be assembled more easily, (2) The coils can be easily replaced without interferring with the duct work, (3) Pipe reaction stresses are reduced. However, in the two pass configuration the poles cannot be skewed for optimum flow and the change of direction of the fluid by 180° increases hydraulic losses.

A pump with an annular duct without helical flow passage separators and with skewed poles has been proposed. Although the pump is electrically and hydraulically inferior to pumps with helical ducts, the duct construction is greatly simplified. The helical pump is used for relatively low flow and moderate to high pressure applications.

Spiral Induction EM Pump

The spiral induction pump, like the helical induction pump uses a complicated duct and stator design as shown in Figure (4-9). The duct is

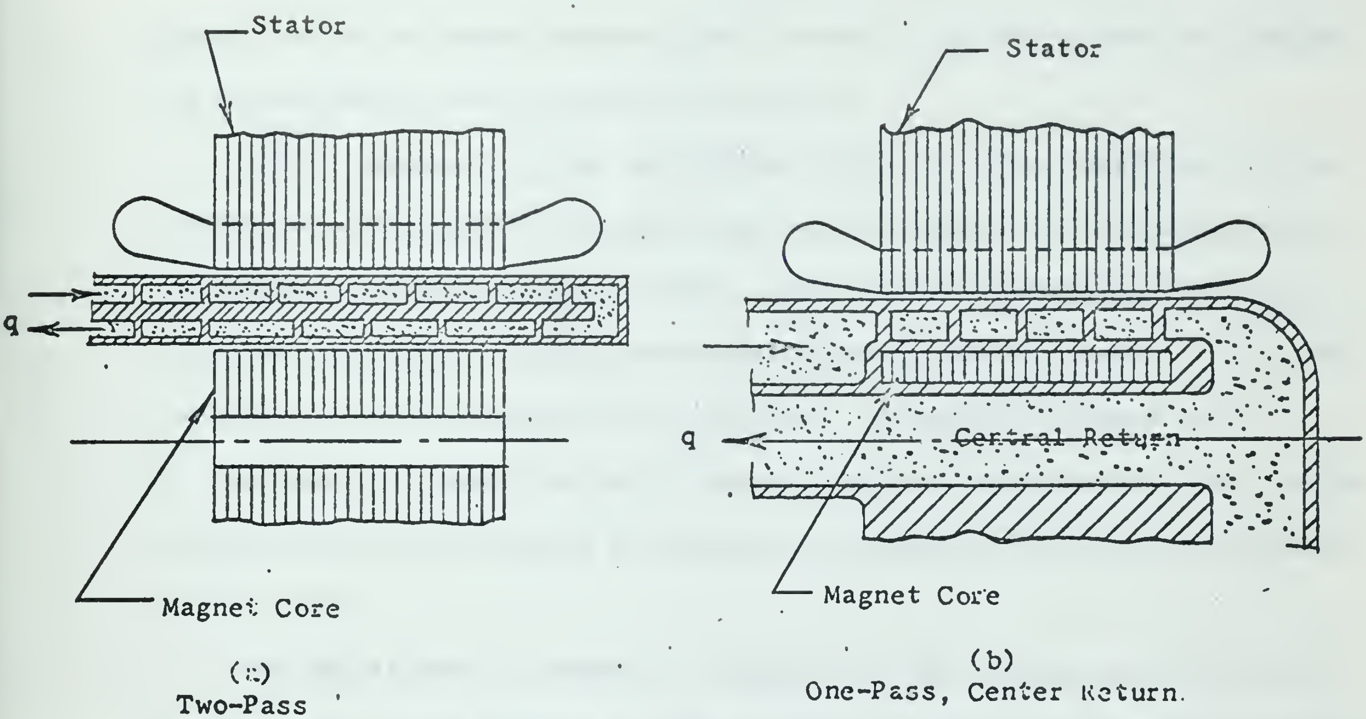


Figure 4-8 Two Pass Configuration

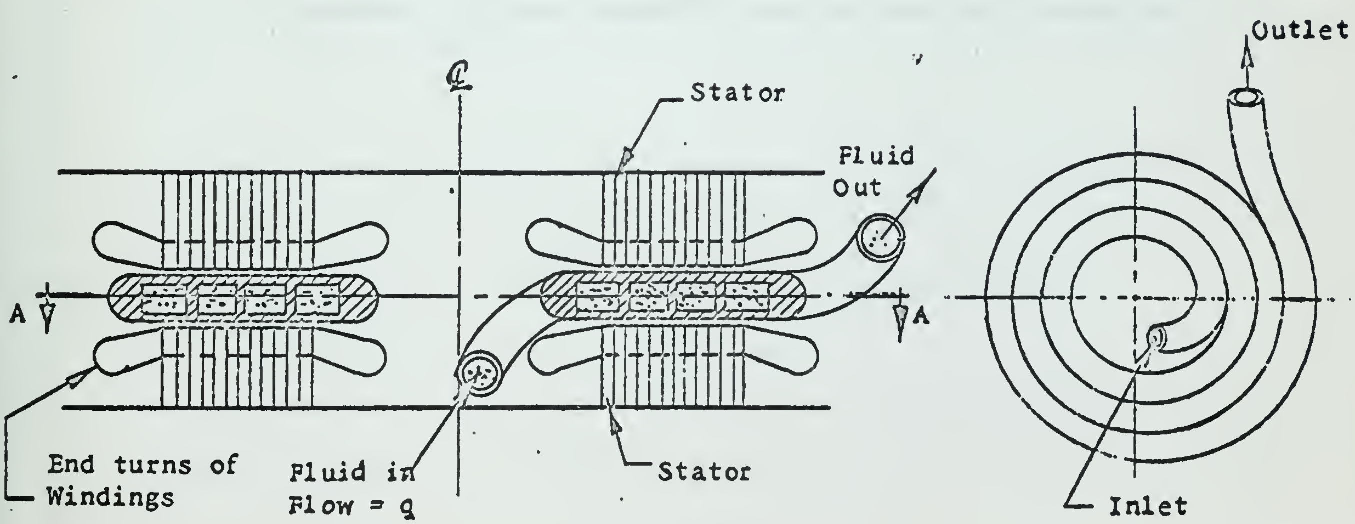


Figure 4-9 Spiral Induction EM Pump

[59]

a spiral network with the inlet at the center and outlet at the periphery. The duct lies between stators which have coils distributed in a radial or spiral design to reduce unwanted eddy currents, and the stators are laminated perpendicular to the radius of the coils.

With a constant air gap and uniform slots, the flux densities will be greater at the inside of the pump than at the outside. This effect can be corrected by an air gap which varies, approximately, inversely with radius. Also, as the stators become further apart, away from the center, the linear velocity of the revolving field increases. To maintain optimum slip, it is necessary to change the axial dimension of the duct inversely with radius so that the linear velocity of the fluid increases with the linear velocity of the field.

The spiral pump in general is inferior to the helical pump but due to the symmetry of the stators on both sides of the duct, the leakage reactance is lower than in the helical pump, hence a better power factor can be expected.

<u>Disadvantages</u>

a. Less reliability inherent with moving parts, bearings, etc.

b. Magnets structures cannot be used as duct wall supports.

Centrifugal Pump

The EM centrifugal pump is less developed than the previously mentioned pumps. This type of pump is limited to low pressure and low flow applications by hydraulic losses, however, the pump has some principles worth considering. The centrifugal pump differs from the other types mentioned in that it can develop relatively high fluid velocities in the pump, nearly independent of the system flow. The pressure is produced from the centrifugal force associated with the fluid velocity or by diffusion of the high velocity liquid to convert the dynamic head to a static pressure.

The basic configurations are either helical or spiral ducts except that separators are not utilized to direct the flow along a helical or spiral path. The desired flow is obtained from the motion of the travelling field. The configurations are similar to the DC Conduction Spiral and Helical pumps shown in Figures 3-7 and 3-8, except that the excitation comes from toroidal windings as shown.

Travelling Field Induction Pumps

Flat linear induction pump. (FLIP)

FLIP, which is in the travelling field category, has polyphase windings which are arranged in a form similar to the stator of an induction motor. Instead of being placed in a circular arrangement, the windings are distributed in a linear fashion to produce a sinousoidally distributed, mmf wave which moves linearly at a velocity depending on the frequency of the power supply and the pole pitch of the windings. Current and flux in the liquid are presumed to be in time and space phase. One of the major losses in FLIP is due to side effects, which are minimized by using high conductivity side bars. The bars are equivalent to the end-rings in the

induction motor. Another loss is created by discontinuities of the travelling wave of the exciting mmf at each end of the pump due to the fact that the mmf does not close upon itself. An arrangement usually adopted is to have half-wound end poles.

In order to simplify the mathematical analysis of this pump, it is assumed that the width of the duct in the y-direction is infinite (neglect side effect), and that only the components H_y and J_x of H and J exists. As seen previously, the total pressure Pz, the gross output Wo, and the Ohmic loss in the fluid Wf can be expressed as follows:

$$\frac{\partial Pz}{\partial z} = J_x \, H_y \tag{4-1}$$

$$Pz = \int_0^c J_x \; H_y \, dz \tag{4-2}$$

$$Wo = Pz \, Q \tag{4-3}$$

$$Wf = a \, b \int_0^c J_x^2 \, dz \tag{4-4}$$

Since the lines of flux are continuous

$$\phi_z - \phi_0 = \int_0^c b \; Hz \qquad \text{or} \qquad H = \frac{1}{b} \frac{\partial \phi}{\partial z} \tag{4-5}$$

From Faraday's Law the electromotive force (emf) is equal to the negative rate of change of magnetic flux linkage,

$$\text{e.m.f.} = -\frac{d\lambda}{dt} \qquad \text{where } \lambda = N\phi \text{ , in}$$

this case, $N = 1$

$$\rho \, b \, J_f = -\frac{d\phi}{dt} = -\left(\frac{\partial \phi}{\partial t} + v\frac{\partial \phi}{\partial z}\right) \text{ where } J_f \text{ is} \tag{4-6}$$

fluid current density.

By applying Ampere's law:

$$\left[H - \left(H + \frac{\partial H}{\partial z} dz \right) \right] d = 4\pi\, d(N\, Im) \qquad (4\text{-}7)$$

$$\frac{d(N\, Im)}{dz} = \frac{d}{2\pi} \frac{\partial H}{\partial z} \qquad (4\text{-}8)$$

Substituting eq. (4-5)

$$\frac{d\,(N\, Im)}{dz} = \frac{d}{4\pi b} \frac{\partial^2 \phi}{\partial z^2} \qquad (4\text{-}9)$$

The voltage per turn induced in the windings is

$$\frac{V_i}{N} = \frac{d\phi}{dt} \qquad (4\text{-}10)$$

Assuming flux of the form

$$\phi = \phi_1 \cos(wt - \psi) \qquad (4\text{-}11)$$

where $\psi = \frac{2\pi z}{\lambda}$

from eq. (4-5) and using boundary conditions

$$H = H_p \sin(wt - \psi) \qquad (4\text{-}12)$$

where $H_p = \frac{2\pi}{\lambda b} \phi_1$

Substituting eq. (4-6) and solving for J_f

$$J_f = \frac{\phi_1}{\rho_b} \left[w - \frac{v 2\pi}{\lambda} \right] \sin(wt - \psi)$$

defining syncronous velocity v_s, and slip s as

$$v_s = \lambda f = \frac{w \lambda}{2\pi}$$

$$s = \frac{v_s - v_f}{v_s}$$

$$J_f = \frac{2\pi \phi_1}{\lambda b \rho_t} (v_s - v_f) \sin(wt - \psi) = \frac{2\pi \phi_o}{\lambda b \rho_t} s\, v_s \cdot$$
$$\sin(wt - \psi) \qquad (4\text{-}13)$$

$$= \frac{s\, v_s}{\rho} Hp \sin(wt - \Psi)$$

Similarly for the duct where v = 0 and $\rho = \rho_t$

$$J_d = \frac{2 \pi \phi_1 v_s}{\lambda b \rho_t} \sin(wt - \Psi) = v_s \, Hp \sin(wt - \Psi) \quad (4\text{-}14)$$

From relation (4-9) and (4-12)

$$\frac{d(N\ Im)}{dz} = \frac{d}{4\pi} \frac{\partial H}{\partial z} = \frac{d}{2\pi} Hp \cos(wt - \Psi) \quad (4\text{-}15)$$

Substituting in eq. (4-10)

$$\frac{V_i}{N} = v_s\, b\, Hp \sin(wt - \Psi) \quad (4\text{-}16)$$

Substituting eq. (4-12) in (4-2)

$$P = \frac{s\, v_s \lambda Hp^2}{2 \rho} \quad (2\text{-}17)$$

The gross output power, Wo

$$Wo = \frac{\lambda v_s v_t\, s\, Hp\, a\, b}{2 \rho} \simeq W_\lambda (1-s) s \quad (4\text{-}18)$$

where $W = \frac{\lambda v_s^2\, Hp^2\, a\, b}{2 \rho}$

The Ohmic loss from eq. (4-4) is

$$Wf = \frac{a\, b\, s^2 v_s^2\, Hp^2}{\rho} \int_0^c \sin(wt - \Psi) dz \quad (4\text{-}19)$$

$$Wf = W_\lambda \quad s^2$$

The efficiency, similar to the ideal induction motor

$$\text{Efficiency} = \frac{Wo}{Wo + Wf} = 1-s \quad (4\text{-}20)$$

Anular Linear Induction Pump (ALIP)

In ALIP the flow is axial through an annular duct with the magnetic

wave travelling parallel to the flow. The field is created by polyphase windings in the form of toroidal coils, concentric with the annular duct axis. The component of the flux that flows in the radial direction is the one which interacts with the induced current creating a force in the liquid metal in the axial direction. The ALIP is not subject to the side effects present in the flat pump since the induced currents flow in closed circular path in the liquid. The circles are concentric with the duct axis. The end effects, however, are still present but can be reduced by proper design of the end coils. An actual picture of the ALIP is shown in Figure 4-10.

Another version of the annular pump is the "Coaxial Annular Linear Induction Pump (CALIP), in which the inlet and the outlet of the pump are on the same side. The liquid metal flows along a pipe inside the core and returns in the annular gap between the core and the windings.

The advantage of this design is that the windings can be removed from one side of the pump without disturbing the duct system.

Pumps with Rotating Pole Structure

This last group of induction pumps utilizes mechanically rotated field poles similar to the rotor of a synchronous machine. The principle is the same used in polyphase pumps with a rotating field and as noted in Figure 4-1, the sub-groups are the same. If the field windings are wound around the rotating poles, dc or ac current may be supplied by slip rings. Alternating power may be supplied by induction, then supplied to the field via rectifiers mounted on the rotating structure. The alternate configuration utilizes stationary, toroidal-shaped, field windings, which supply a constant mmf across the duct. By rotating a rotor containing magnetic

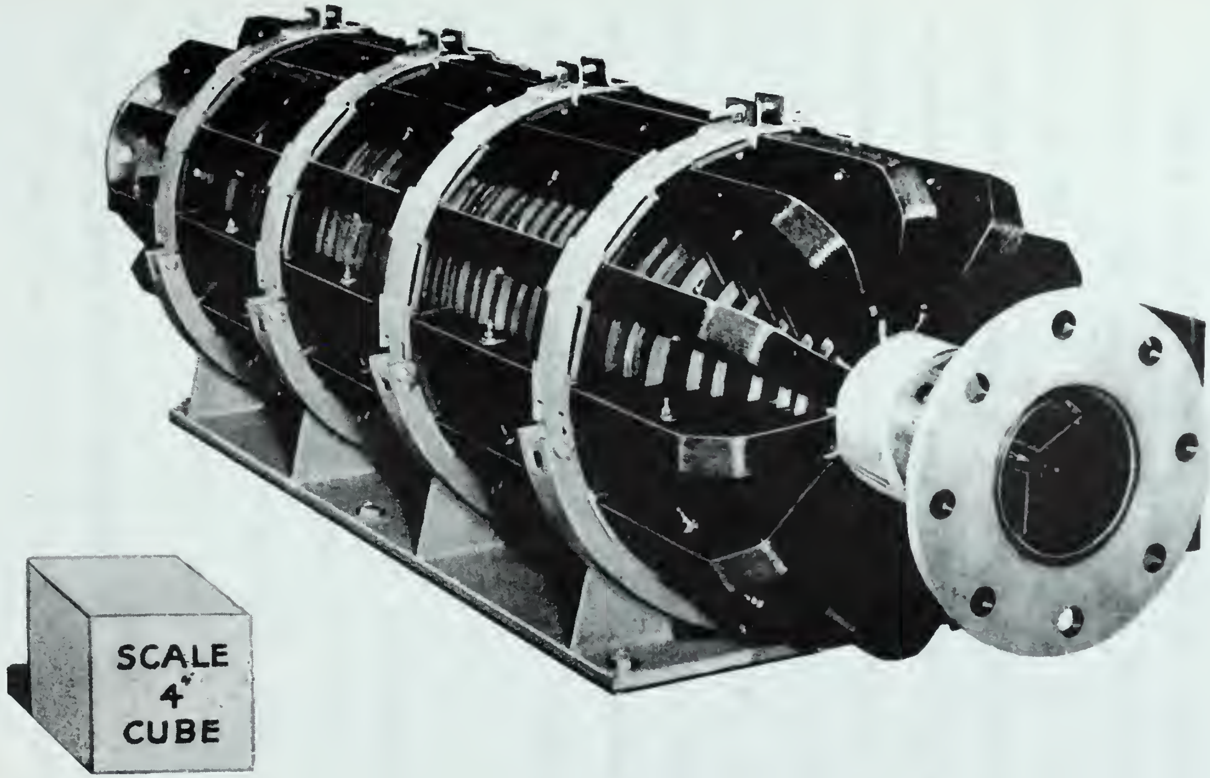


Figure 4-10 Annular Linear Induction Pump

salients in the region across which the exciting mmf flows, a travelling wave is, in effect, produced.

Figures (4-11) and (4-12) shows a Helical-Rotor Assembly and Duct respectively, of a 2000 gpm Sodium Pump and Fig. (4-13) shows actual performance curves for this pump. This particular pump was tested, (Ref. 8), as a pump and as an eddy-current braking device.

When a nuclear reactor is shut-down, high stresses can be incurred in the metals between the hot core and the relatively cool primary coolant. This pump was found to react very quickly to a shut down, and it effectively throttled the coolant to prevent excessive stresses. The analysis of the pumps braking ability is given in the above mentioned reference. The important conclusions reached in the testing of this pump: (1) It is suitable for applications requiring capacities in the range from near zero to over 50,000 gpm. (2) It is possible to pump any alkali metal at temperatures of at least 2200°F by using the proper annulus wall, i.e., material and thickness. (3) Operating experience demonstrated that the helical-rotor EM pump is a reliable, well-sealed, low-maintenance system.

Spiral-Duct Moving Magnet Pump

Figure (4-14) shows one concept of a Spiral-Duct Moving Magnet Pump. In this example the rotating magnets are on only one side but the pump can be designed with rotating magnets on both sides. The use of spiral flow passage separators is arbitrary.

Centrifugal Pumps with Moving Magnets

The spiral and helical centrifugal pump designs discussed in Section 4 can be configured with moving magnets. The literature on this particular design is quite sparse, and as a result the pump is only mentioned here.

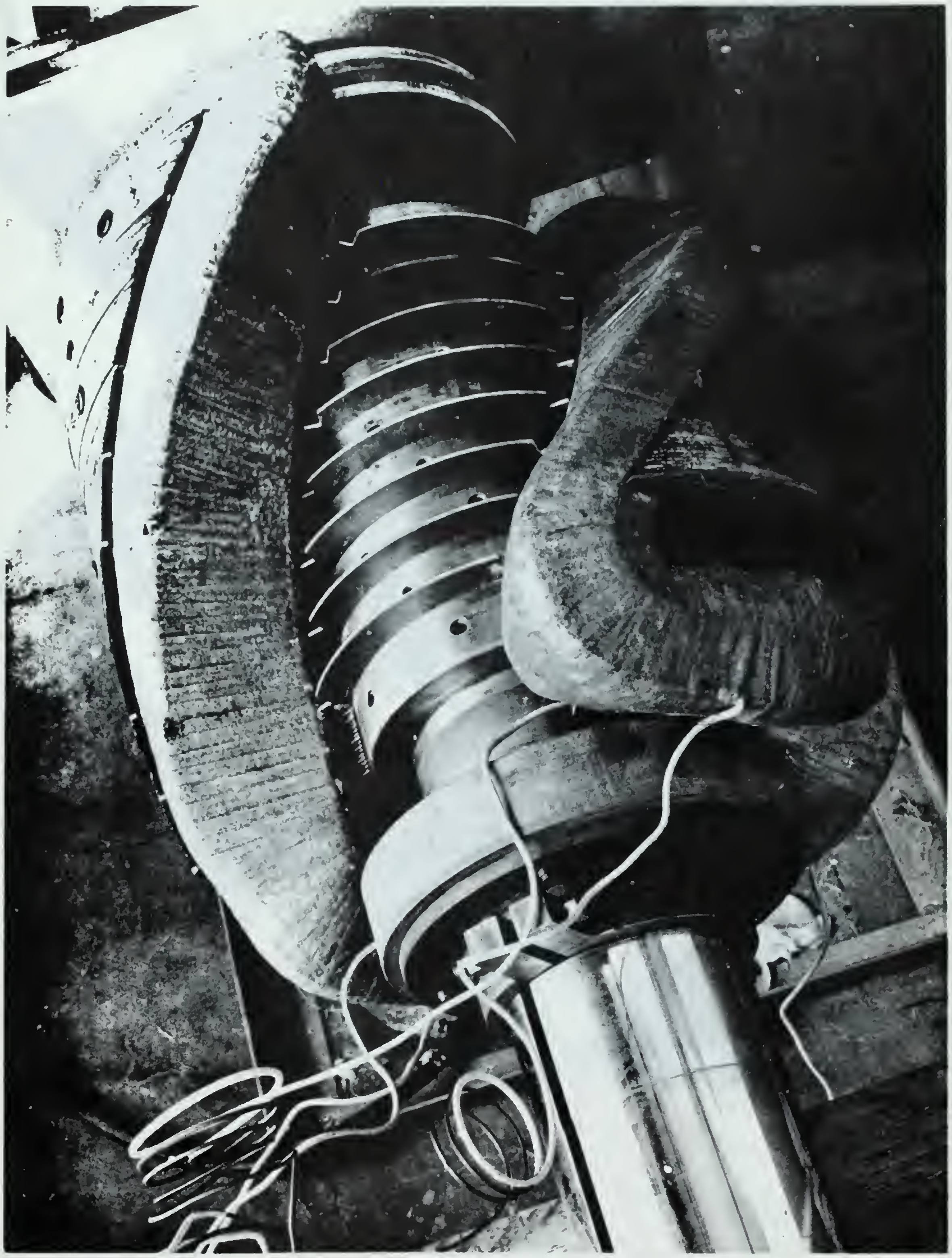


Figure 4-11 Helical Rotor Dur:ng Assembly

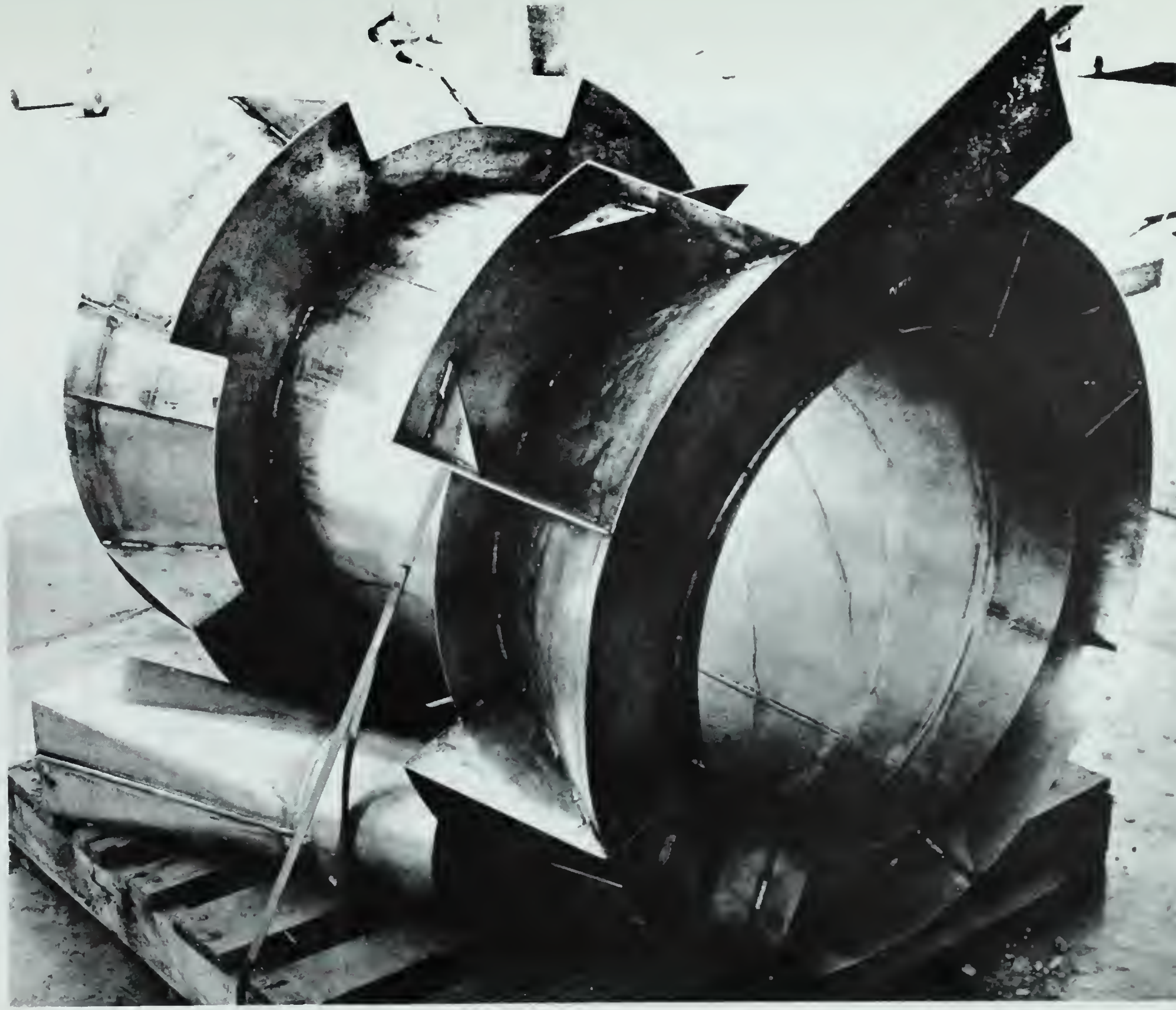


Figure 4-12 Pump Annulus Assembly

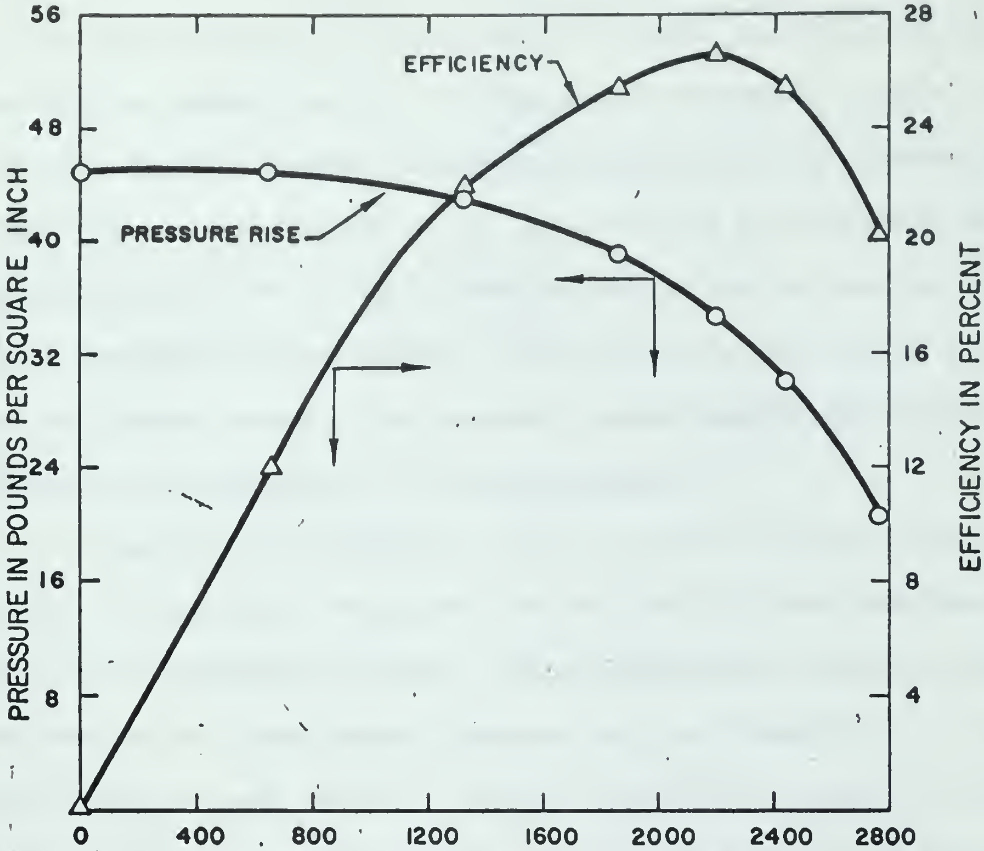


Fig. 4-13

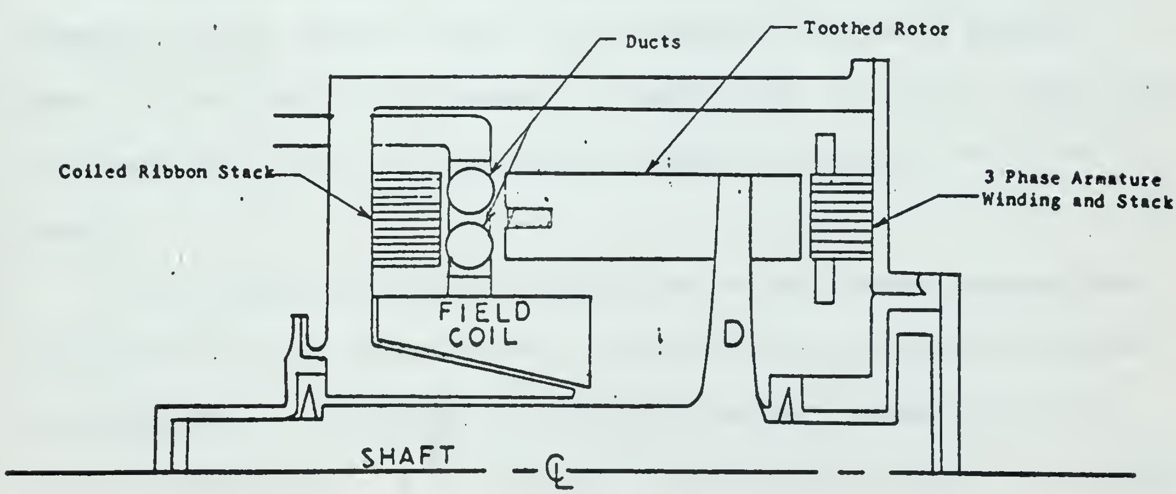


Figure 4-14 Spiral Duct Rotating Magnet Pump

[60]

CONCLUSION

Electromagnetic pumps have unique features which are not found in conventional pumps, namely: (a) Stationary components (pumps not having rotating magnets) require little or no maintenance and bearings and shaft seals are eliminated. (b) The fluid can be completely enclosed, permitting safe use of highly reactive metals such as sodium and potassium which are good heat conductors. If the fluid is used as the primary coolant for atomic reactors, the enclosed system essentially encapsulates the radioactivity absorbed in the cooling process.

In general, electromagnetic pumps are less efficient electrically, and A. C. pumps have lower power factors than do electrical rotating machines of comparable ratings. Lower efficiency is caused by higher resistivity of liquid metals compared with the resistivity of copper, the larger air gaps involved, and the trade-off of electrical efficiency to improve hydraulic efficiencies. Duct-wall power losses which can be quite large in some designs have no direct parallel in electrical rotating machines.

The choice of type of electromagnetic pump for a particular job depends on cost, power to weight ratio desired, flow rate, pressure head, and availability of sources, to name a few. Table 5-1, taken from reference [31], shows the relationship between conduction and induction pumps.

A. C. conduction pumps are restricted to small power applications, since size and eddy current losses increase rapidly with power increases in large pumps. In general, electrical efficiency decreases with increase in frequency. A D. C. pump of similar output can be made smaller

—Relative Merits of 50 c/s, 5 c/s, and D.C. Conduction Pumps

Form of supply	50 c/s A.C.	5 c/s A.C.	D.C.	D.C.
Auxiliaries	Induction regulator or variable tap auto-transformer. P.F. correction capacitor	A.C. motor and L.F. generator	Motor and homopolar generator	Induction regulator or alternative and conventional metal rectifier
Flow control	Voltage regulator position	Control of field of L.F. generator	Control of field of homopolar generator	Voltage regulator position
Field system	Single-turn or half-turn series winding	Single-turn series winding: possibly two turns in small pumps	One turn in large pumps; up to 3—5 turns in small pumps	Tendency to employ more turns than with homopolar generator arrangement to keep current lower
Overall efficiency	Usually lowest	Next highest	Highest	Possibly lowest
Maximum pump output	About 100 g.p.m.	About 500 g.p.m., but higher at lower frequency	Very large	Large
Cost	Usually cheapest	Becoming comparable with 50 c/s near upper limit of output	Usually more expensive than a.c. pumps but this need not necessarily remain true when homopolar generators are an established line	Most expensive
Layout	Pump and transformer adjacent. Correction capacitor near, regulator remote	Pump and transformer adjacent. Motor-generator remote	Pump, homopolar generator, and motor adjacent	Pump and rectifier adjacent
Pump size	Pump small	Similar to 50 c/s pump	Could be smaller than A.C. pump, but generally same size for better efficiency and low current	
Size of complete equipment	Capacitor and transformers each usually several times larger than pump	Machines much larger than pump, overall size somewhat larger than 50 c/s arrangement	Machines larger than pump; this arrangement normally gives smallest overall size	Rectifiers very large in comparison with pump. Complete equipment very bulky

—Comparison of 50 c/s, 15 c/s, 5 c/s, and D.C. Conduction Pumps

Bismuth at 400°C. Tube wall, 85 microhm-cm. resistivity at 400°C.

Power supply	50 c/s	15 c/s	D.C.	5 c/s	D.C.
Output:					
Flow, gals. per minute		60		250	
Pressure, pounds per square inch		40		75	
Power, kilowatts		1·25		9·8	
Input:					
Voltage, volts	3·54	1·4	0·89	2·6	1·1
Current, kiloamp.	11·6	11·6	8·6*	40	39
Power:					
Kilowatts	12·3	11·4	7·7	61	42
Kilovolt-amperes	41	16·5	—	101	—
Power factor	0·30	0·69	—	0·60	—
Efficiency:					
Pump only, per cent	12	13	16	20	23
Including transformer, per cent	10	11	—	16	—
Design details:					
Liquid velocity, feet per second	18	18	18	24	24
Tube dimensions, inches	0·61 × 0·21	0·61 × 0·21	0·61 × 0·21	1·4 × 2·8	1·4 × 2·8
Wall thickness, inches	0·032	0·032	0·028	0·064	0·064
Peak field in gap, kilogauss	9·7	9·7	10·6	15·2	10·6
Weight:					
Pump, pounds	90	85	100	1200	800
Transformer, pounds	260	380	—	2600	—
Correction capacitor, pounds	300	—	—	—	—
Dimensions:					
Pump, inches	9 × 8 × 8	9 × 8 × 8	9 × 9 × 8	20 × 16 × 11	14 × 15 × 14
Transformer, inches	10 × 14 × 13	11 × 16 × 15	—	18 × 28 × 25	—
Other auxiliaries	Voltage-regulating transformer	Motor/L.F. frequency changer	Motor/homopolar-generator	Motor/L.F. generator	Motor/homopolar-generator
Relative total cost	—	Not much greater than 50 c/s arrangement	Shows promise of being cheapest arrangement when homopolar generator developed	Use of conventional equipment keeps cost low at moment	Shows promise of being cheapest arrangement

Fig. 5-1 Comparison of 50c/s, 15c/s, 5c/s and DC Conduction Pumps

however, due to D. C. power supply problems (i.e., kiloamps at about 1 volt) the less efficient and larger A. C. pumps may be used in the medium power range.

In general, for high power levels, a D. C. pump using bismuth is the best selection and for low power levels, inductions pumps using sodium are the best choice.

Conduction pumps perform best with bismuth while induction pumps operate best with low resistivity, low viscosity, and low density fluids such as sodium, sodium-potassium alloys, and lithium.

In the induction pump group, Spiral Induction Pump (SIP) operate more effectively for low power and high pressure-low flow applications while the Annular Linear Induction Pump (ALIP) and the Flat Linear Induction Pump (FLIP) handle larger power applications more effectively. Comparing the D-C conduction pump and ALIP (Table 5-1) for flow of 8300 gpm, the efficiencies are comparable but the ALIP has a power rating of 4.5 hp/cubic ft. verses .5 hp/cubic ft. for the D-C conduction pump. In this particular example sited by Dr. Blake, the ALIP, operating off the mains, replaced a D. C. pump, a homopolar generator, and an induction motor.

The use of the electromagnetic pump is not restricted to pumping primary coolant for atomic reactors. Development has led to its use as an actuating device for valves, mixing of metallic liquids in chemical processes, stabilizing space vehicles, and suspension of liquid metals in casting processes. The reverse process is used in flowmeters to measure flow rates of liquids or gases, and magnetic flowmeters are being used in the field of medicine to measure cardiac output.

The electromagnetic pump is presently being exploited as a prime mover for gases, plasma for example. The principle is also being applied in reverse in MHD generators, where hot ionized gases flow through a magnetic field to generate a voltage.

The above paragraph lists only a few of the important present day uses of electromagnetic pumps. It is a certainty that the applications for electromagnetic pumps will continue to increase with improved designs and with increased knowledge of the pumps capabilities by engineers.

ACKNOWLEDGEMENTS

The authors wish to express indebtedness to the following persons at the U. S. Naval Postgraduate School:

Dr. Rudolph Panholzer, Associate Professor of Electrical Engineering, for the thesis topic and for guidance during the thesis preparation. A special thanks to Dr. Panholzer who was the instrumental in acquiring a six month extension for LT(JG) Gutierrez.

Commander Bruno Mussetto, USN, Curricular Officer for Ordnance Engineering and LCDR R. L. Keenan, USN, Assistant Curricular Officer for their administrative assistance in obtaining special extentions for both authors.

BIBLIOGRAPHY

1. Acton, O., "Small Electromagnetic Pump for Liquid Metals", Ingenere, Vol. 31 No. 2 125-34, February 1957.

2. Allis Chalmers, "Einstein-Szilard Pump Report", By C. E. Gyger, November 1950.

3. Allis Chalmers, "Progress Report of the Loop Type Electromagnetic Pump", by G. C. Taggi, November 1949.

4. Allis Chalmers, "Development of Electromagnetic Pumps Suitable for Pumping Liquid Metals", by J. F. Asti, Report No. 43-109.

5. Allis Chalmers, "Development of Electromagnetic Pumps Suitable for Pumping Liquid Metals", by E. F. Brill and W. Richter, Interim Progress Report No. 8, April 1951.

6. Arnold Engineering Development Center, "Comparison of Electromagnetic Pumps with and without Conducting Walls", by C. W. McKinney, AEDC-TDR-64-174 December 1964.

7. Atomic International, "Theory, Design, and Performance of an Helical-Rotor Electromagnetic Pump", by R. S. Baker, NAA-SR-7455, May 1963.

8. Atomic International, "Design of a Linear, Induction, Electromagnetic Pump", by E. R. Smith, NAA-SR-MEMO-Rev B, May 1960.

9. Atomic International, "Tests of Linear Induction Electromagnetic Pump for HNPF" by R. S. Baker, Report TDR-5777, October 1960.

10. A.E.R.E. (Atomic Energie Research Establishment, England), "Liquid Metal Utilization Conference", A.E.R.E. Report X/R 1381 H.M.S.O. 1954.

11. A.E.R.E., "Electromagnetic Pumps and Flowmeters", by M. Greenhill, A.E.R.E. Bibliography Inf/Bib 93, 4th Edition, October 1956.

12. A.E.R.E., "Homopolar Generators and Liquid Metal Brushes", by M. Greenhill, A.E.R.E. Bibliography Inf/Bib 92 2nd Edition, September 1957.

13. A.E.R.E., "Liquid Metal Pump for Laboratory Use", by D. A. Watt, A. E.R.E. Report ED/R 1856 HMSO January 1956.

14. A.E.R.E., "Design of Travelling Field Induction Pump for Liquid Metals", by D. A. Watt, A.E.R.E. Report R/M 144 HMSO September 1957.

15. A.E.R.E., "A Homopolar Generator for High Current Low Voltage DC Supply", by D. A. Watt, A.E.R.E. Report ED/R 1843 HMSO January 1956. Declassified edition of CE/R 825 1951/52

16. A.E.R.E., "Liquid Metal Brushes", by D. A. Watt, A.E.R.E. Report CE/R 840 HMSO November 1951.

17. A.E.R.E., "Analysis of Experimental DC Pump, Performance and Theory of Design", by D. A. Watt, A.E.R.E. Report R/R 2275 HMSO, July 1957.

18. A.E.R.E., "Tests on an Experimental DC Pump for Liquid Metals", by D. A. Watt, A.E.R.E. Report R/R 2274, HMSO, May 1957.

19. A.E.R.E., "A Study in Design of Travelling Field Electromagnetic Pump for Liquid Metals", by D. A. Watt, A.E.R.E. Report ED/R 1696 HMSO, June 1955.

20. A.E.R.E., "Direct Current Pumping of Liquid Metals", by D. A. Watt, A.E.R.E. Report CE/R 757,September 1951.

21. A.E.R.E., "Single Phase Annular Induction Pump for Liquid Metals," by D. A. Watt, A.E.R.E. Report CE/R 1090, January 1953.

22. A.E.R.E., "Theory of the Ideal DC Conduction Pump", by W. Murgatrody, A.E.R.E. Report ED/R 1566, December 1954.

23. A.E.R.E., "The DC Electromagnetic pump for liquid metals", by J. Woodrow, A.E.R.E. Report ED/R 452,December 1949.

24. A.E.R.E., "The Commissioning and Operation of a Small Bismut Loop and Test of a DC Electromagnetic Pump", by E. H. Aldworth, A.E.R.E. Report R/M 148 HMSO, October 1957.

25. Armstrong D. S., "Linear Induction Pump for Liquid Metals", AEI Engineering, Nov-Dec 1962.

26. Bainbridge K. T., "Liquid Conductor Pump", U.S. Patent 1,660,407 February 1928.

27. Barnes A. H., "Direct Current Electromagnetic Pump", Nucleonics Vol. 11, No. 1, pp 16-21, January 1953.

28. Berthier, L. J., "Pompe Electromagnetique", French Patent 888,532, Dec. 1943.

29. Birzvalks, Yu, "Analysis of Optimal Criteria Being Applied in Calculations of Pumps of Constant Current", LATV. PSR Zivat Akad. Vestis (URSS) No. 11(160) 91-96, 1960.

30. Birzvalk Yu, "Analtical Determination of the Potential Distribution in the Boundary Zone of an Electromagnetic Pump with Constant Current", LATV. PSR Zivat Akad. Vestis No. 12(149) 49-58, 1959.

31. Blake L. R., "AC and DC Conduction Pumps for Liquid Metals", Engineer Vol 202, No. 5256, pp 541-4, Oct. 19, 1956.

32. Blake, L. R., "Conduction and Induction Pumps for Liquid Metals", IEE Proceedings Vol. 140A pp 49-63, February 1957.

33. Blake, L. R., "Electromagnetic Pumps for Liquid Metals", Nuclear Reactor Technology Pt. B., Vol. 1, August 1959, pp. 65-76.

34. Branover, H. and Lieulausis O., "The Effect of a Transverse Magnetic Field on Internal Structure and Hydraulic Resistence in Turbulent Flows of Liquid Metals", Phisics Institute of the Academy of Science of the Latvian SSR, August 5, 1960.

35. Brill, E. F., "Development of Special Pumps for Liquid Metals", Mechanical Engineering, Vol 74, No. 5, pp-269-273, May 1953.

36. Bruckel W., "Elektrodynamische Pumpe", German Patent 511, 137, October 1930.

37. Cage, J. F., Jr. , "Electromagnetic Pumps for High-Temperature Liquid Metals", Mechanical Engineering, Vol. 75, No. 6, June 1953 pp. 467-71.

38. Cage, J. F., Jr., "Electromagnetic Pumps for High-Temperature Liquid Metals", Machine Design, Vol 25, pp 178-79, March 1953.

39. Cambillard, E., "Polyphase Annular Electromagnetic Induction Pumps for Liquid Metals", Liquid Metal Colloquium of the European Society of Atomic Energy, Aix-en-Provence, September 30 - October 2, 1963.

40. Chepele, Tu, M., "A Pump for Pumping Liquid (Molten) Metal", Russian Patent 143,982, Or. FTD-TT-63-496/1 and 2.

41. Ciampolini, "Electromagnetic Pump with Spiral Flow", Energia Elett. Vol 34, No. 9, pp 915-927, Sept 1957.

42. Ciampolini, F., "The Conduction Type Electromagnetic Pump", Energia Elett. Vol. 35, No. 11, pp 1053-70, Nov 1958.

43. Cole, R. H., "Modulated Electromagnetic Pump", U. S. Patent 3,066,607, December 4, 1962.

44. Cornell University, "A Study of Magnetohydrodinamic Induction Devices", by J. M. Lyons and D. L. Turcotte, AFOSR 1864, Feb 1962.

45. Crever, F. E., "Electromagnetic Centrifugal Pump", U. S. Patent 2,652,778, September 1953.

46. Defense Documentation Center, "Electromagnetic Pumps (U)", A Report Bibliography, ARB-No. 035512, June 1965.

47. Devidas, M. R., "Single Phase AC Electromagnetic Pump", Bull. Soc. Franc. Electr. (Ser 8), Vol 1, No. 6, pp 411-16, June 1960.

48. Donelian, K. O., "Electromagnetic Pump", U. S. Patent 2,658,452, November 10, 1953.

49. Einstein, A., and Szillard, L., "Pump Especially for Refrigerating Machine", British Patent 344,881, 1931.

50. Fenemore, A. S., "Linear Induction Pumps for Liquid Metals", The Engineer, May 17, 1957.

51. Findlay, J. M., "Apparatus for Pumping Liquid Metal", British Patent, 746,456, March 1956. U. S. Patent 2,915,973, December 8, 1959.

52. Findlay, G. R., "Research on Fundamental Electrodynamic and Hydrodynamic Phenomena Involved in Electromagnetic Pumping of Liquid Metals", Final Report, Contract NASr-33, Liquid Metals, Inc., March 31, 1962.

53. Fishman, F., "End Effects in Magnetohydrodynamic Channel Flow", Research Note 135, AVCO-Everett Research Laboratory, June 1959.

54. Fraser, W. J., "DC Electromagnetic Pump Study for Thermionic Conversion Reactors", NAA-SR-Memo-5501, North American Aviation, July 15, 1960.

55. Germeles, A. E., "Channel-Flow of Conducting Fluids Under an Applied Transverse Magnetic Flow", J. Appl. Mech., Trans. ASME, June 1964.

56. General Electric Company, Sherman, A., "Exact Solutions for Magnetohydrodynamic Channel Flows", Report R62SD991, Missile and Space Division, December 1962.

57. General Electric Company, Fernard, J., and Collins, G. D., "Test of 1200 GPM Linear AC Electromagnetic Pump", Report AECD-3460, Knolls Atomic Power Laboratory.

58. General Electric Company, "Results of Analysis of A.C. Electromagnetic Pump", by Cage J. G., Collins, G. D., GEL-56, October 1949.

59. General Electric Company, "Electromagnetic Alkali Metal Pump Research Program", Quarterly Progress Report No. 1, by Verkamp, J. P.

60. General Electric Company, "Electromagnetic Alkali Metal Pump Research Program", Quarterly Progress Report No. 2, by Verkamp, J. P., NASA-SR-54019.

61. General Electric Company, "Electromagnetic Alkali Metal Pump Research Program", Quarterly Progress Report No. 3, by Verkamp, J. P., NASA-SR-54036.

62. Hammitt, F. G., and Summers, J. L., "Similarity Relations for Electromagnetic Pumps", Nuclear Power, No. 71, March 1962.

63. Hanka, L., "The Geometry of Induction Pumps for Liquid Metals", Elektrotech. Obzor (Czechoslovakia), Vol 50, No. 1, pp 38-44, 1961.

64. Hartmann, J. F. G. P., "Improvements in or Relating to Apparatus for Producing a Continuous Electrically Conducting Liquid Jet", British Patent 126,947, December 1919.

65. Hartmann, J., "Mercury Dynamics. I. Theory of the Laminar Flow of an Electrically Conductive Liquid in a Homogeneous Magnetic Field," Kgl. Danske Videnskab. Selskab Math. - fys. Medd., Vol. 15, No. 6, 1937.

66. Hartmann, J., and Lazarus, F., "Mercury Dynamics. II. Experimental Investigations of the Flow of Mercury in a Homogeneous Magnetic Field", Kgl. Danske Videnskab. Selskab Math. - fys. Medd., Vol. 15, No. 7, 1937.

67. Hilditch, J. A. S., "The Electromagnetic Pumping of Liquid Metals-1", Atomics and Nuclear Energy, February 1958.

68. Hilditch, J. A. S., "The Electromagnetic Pumping of Liquid Metals-2", Atomics and Nuclear Energy, April 1958.

69. Hlasnik I., "Reaction of Armature of an Electromagnetic Pump", Elektrotech. Obzor, Vol. 49, No. 3, pp 135-46, 1959.

70. Hohn H. and Steiner J., "Ueber Electromagnetishe Pumpen Ohne Bewegte Teile zur Foerderung Fluessiger Metalle., Chomie-Ing-Techn. No. 6, 1956.

71. Jackson, W. D., Pierson, E. S., and Porter. R. P., "Design Considera- tion for MHD Induction Generators", Paper No. 61, National Symposium of Magnetohydrodynamic Electrical Power Generation, Paris, July 6-11, 1964.

72. Jackson, W. D., "Liquid Metal Faraday-Type MHD Generators", Paper No. 62-1401, AIEE Conference, October 7, 1962.

73. Jackson, W. D., "Liquid Metal Faraday-Type MHD Generators", IEEE Trans. on Power Apparatus and Sys., December 1963.

74. Jaross, R. A., and Barnes, A. H., "Design and Operationof a 10,000 GPM DC Electromagnetic Sodium Pump and 250,000 Ampere Homopolar Generator", Second United Nations International Conference on the Peaceful Uses of Atomic Energy, A/CONF. 15/P/2157, June 1958.

75. Kendall, J. W., and Fry, T. M., "The Dounreav Fast Reactor Proyect", Proceeding of the International Conference on Peaceful Uses of Atomic Energie, Vol. 3, Power Reactor, pp 193, United Nations, 1955.

76. Khablenko, A. I., and Il'yashenko O. I., "Electromagnetic Pumps", English Translation in: Instrum. Exper. Tech. (U.S.A.), No. 2, March-April 1962.

77. Knolls Atomic Power Laboratory, General Electric Company, Vandenberg, L. B., "Homopolar Generator Pump for Liquid Metals", Report No. 590, August 1951.

78. Kolin, A., "Electromagnetic Blood Flow Meters", Science Vol. 130, October 1959.

79. Lago, U. S. Patent 2,258,415, October 7, 1941.

80. Laithawaite, E. R., "Linear Induction Motor", Proc. Instn. Electr. Engrs. Paper 2433U pp 461-70, December 1957.

81. Ledr, Z., "Single Phase Electromagnetic Conduction Pump for Liquid Metals", Elektrotech, Obzor, Vol. 51, No. 7, pp 324-8, 1962.

82. Lewis Research Center, "Travelling Wave Electromagnetic Pump of Anular Design", by Schwiriam, R. E., NASA-TDD-2816 May 1965.

83. Miley, D. C., "A Toroidal Thermoelectric -Magnetic Liquid Metal Pump for Space Application", Report R59FPD624, Flight Propulsion Division, General Electric Company, July 1959.

84. MSA, Research Corporation Bulletin No. EP-2.

85. Murgatroyd, W., "Experiments on Magneto-Hydrodynamic Channel Flow," Phil. Mag., Series 7, December 1953.

86. Murgatroyd, W., "Theory of the Ideal A. C. Conduction Pump", Report ED/R 1566, A.E.R.E., Harwell, December 2, 1954.

87. NASA, Rossow, V. J., "On Flow of Electrically Conducting Fluids Over a Flat Plate in the Presence of a Transverse Magnetic Field", Report 1358.

88. NASA, Rossow, V. J., Jones, W. P., and Huerta, R. H., "On the Induced Flow of an Electrically Conducting Liquid in a Rectangular Duct by Electric and Magnetic Fields of Finite Extent", Technical Note D-347, January 1961.

89. Northrup, E. A., "Some Newly Observed Manifestations of Forces in the Interior of an Electric Conductor", Phys. Rev., Vol. 24, 1907, p. 474.

90. Okhremenko, N. M., "Optimum Geometrical Ratios in Induction Pumps for Liquid Metals", Elektrichestro, No. 9, 1961.

91. Okhremenko, N. M., "Electromagnetic Phenomena in Flat-Type Induction Pumps for Molten Metal, J. ARS, Supp., September, 1962. (Translated and Reprinted from Elektrichestvo, No. 3, March 1960).

92. Okhremenko, N. M., "Magnetic Field of a Planar Induction Pump", Electrichestvo (USSR) No. 8, August 1964.

93. Osterle, J. F., and Angrist, S. W., "The Thermoelectric-Hydromagnetic Pump", J. Heat Transfer, Trans. ASME, May 1964, pp. 166-168.

94. Panholzer, R., "Electromagnetic Pumps", Electrical Engineering, Vol. 82, No. 2, February 1963.

95. Petrick, M., and Lee, Kung-You, "Performance Characteristics of a Liquid Metal MHD Generator,"Paper No. 62, National Symposium of Magnetohydrodynamic Electrical Power Generation, Paris, July 6-11, 1964.

96. Phister, C. G., and Dunham, R. J., "DC Magnetic Flowmeter for Liquid Sodium Loops", Nucleonics, Vol. 15, No. 10122-24, October 1957.

97. Pierson, E. S. "A Hydromagnetic DC Converter", Contract Nr AF33(616) -7624, Report DSR7672, Res. Lab. of Electronics, MIT, January 1961.

98. Phillips, J. H., "Improvements in Pumps for Producing a Flow of Conducting Liquid", British Patent 528,091, October 22, 1940.

99. Pully, O. O., "Electromagnetic Pump", U. S. Patent 2,686,474, August 17, 1954.

100. Rex, D., "Thermoelektrische Pumpen Fuer Fluessige Metalle", VDI A. (Germany) Vol. 103, No. 1, pp 17-19, January 1961.

101. Schilder, J., "Electromagnetic Field Moving in a Conducting Medium" Elektrotech. Obzor, Vol 48, No. 3, pp 146-149, 1959.

102. Shirer, H. W., Shackleford, R. B., and Jochim, K. E., "A Magnetic flow Meter for Recording Cardiac Output", IRE Proceedings, Vol. 47, November 1959.

103. Schwab, B., "Theory of Annular Electromagnetic Pumps and Comparison with Experiments", Liquid Metal Colloquium of the European Society of Atomic Energy, Aix-en-Provence, September 30 - October 2, 1963.

104. Schwab, B., and Cambillard. "Multiphase Annular Electromagnetic Pump, Design and Construction. Bull. Soc. Franc. Electr. (Ser 8) Vol. No. 6, pp 417-24, June 1960.

105. Schwab, B., "Different Types of Electromagnetic Pumps", Bull. Soc. Franc. Electr. (Ser 8), Vol. 1, No. 6, pp 404, June 1960.

106. Shercliff, J. A., "The Theory of Electromagnetic Flowmeasurement", London Cambridge University Press 1962.

107. Seim, O. S., and Jaross, R. A., "Characteristics and Performance of 5,000 GPM AC Linear Induction and Mechanical Centrifugal Sodium Pumps", Proceedings of United Nations Conference on the Peaceful Uses of Atomic Energy, A/Conf. 15/1, 7, 1958.

108. Siegfried W., and Bronieswky, "Control of Flow of Liquid Metal during Continuous Castin", Journal Iron and Steel Institute London, Vol. 190, October 1959.

109. Spencer, U. S. Patent 1,792,449, February 10, 1931.

110. Sudan, R. N., "Interaction of a Conducting Fluid Stream with a Travelling Wave of Magnetic Field of Finite Extension", J. Appl. Phys. Vol. 34, No. 3, March 1963.

111. Sutton, G. W., Hurwitz, H., Jr., and Poritsky, H., "Electrical and Pressure Losses in a Magnetohydrodynamic Channel Due to Current Loops", AIEE Paper No. 61-1078, October 15, 1961.

112. Tama, M., "Electromagnetic Pumping of Molten Metals", Iron Age, December 4, 1947.

113. Tanaka, K. Itaya, S., Tomita, Y., and Satoyama., "Studies on the Electromagnetic Centrifugal Induction Pump", Bull. JSME (Japan), Vol. 6, No. 24, pp 718-29, November 1963.

114. Translation, "Problems of Magnetohydrodynamics and Plasma Dynamics" Proceedings of the Conference on Magnetohydrodynamics, Riga, July 2-10, 1958, Tr. AEC-tr-4509.

115. Translation, Problems of Magnetohydrodynamics and Plasma Dynamics II", Proceedings of the Conference on Theoretical and Applied Magnetohydrodynamics, Riga, June 27 - July 2, 1960, FTD-TT-62-1301.

116. Vandenberg, L. B., "Heat Exchanger Pump", U. S. Patent 2,478,710, June 1956.

117. Vautrey, M. L., "The use of Electromagnetic Pumps", Bull. Soc. Franc. Electr. (Ser 8), Vol. 1, No. 6, pp. 399-403, June 1960.

118. Voldek, A. I., "Electromagnetic Pumps for Liquid Metals", Elektrichestvo, No. 5, 1960.

119. Von Hufnagel, S., "Die Thermoelektromagnetische Pumps", Aus dem Institute fur Thermodynamik der Technischen Hockschule Munchen (Tr.)

120. Wakefield, K. W., "Electromagnetic Pump", U. S. Patent 2,612,109, September 30, 1952.

121. Watt, D. A., "The Design of Electromagnetic Pumps for Liquid Metals," Paper No. 2763 U, IEE, December 1958.

122. Watt, D. A., "The Design of EM Pumps for Liquid Metal", J. Inst. Elec. Engrs. (London), December 1958.

123. Watt, D. A., "Electromagnetic Pumps for Liquid Metals", Engineering, April 1956.

124. Weber, H. E. and Martson, C. H., "Liquid Metal Vortex MHD Generator" Paper No. 63-WA-209, ASME Sept 1963.