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Helical Induction Pump Design

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	3
II. DISCUSSION	4
III. PERFORMANCE OF BRAYTON CYCLE PUMP	8
IV. SIZE	14
V. EQUIVALENT CIRCUIT	14
VI. FLUID RESISTANCE	14
VII. MATERIAL SELECTION	16
VIII. FABRICATION	16
IX. RELIABILITY	16
X. HEAT TRANSFER	17
XI. DEVELOPMENT PROGRAM	18

TABLES

I. BRAYTON CYCLE PUMP REQUIREMENTS	3
------------------------------------	---

FIGURES

1. G.E. Equivalent Circuit	5
2. Conventional Equivalent Circuit	6
3. G.E. Pump	7
4. Brayton Cycle Pump	9
5. Brayton Cycle Pump Performance	10
6. Brayton Cycle Pump Performance	11
7. Brayton Cycle Pump Performance	12
8. Brayton Cycle Pump Performance	13
9. Pump for Brayton Cycle Application	14

I. INTRODUCTION

Based upon a request to do preliminary design work on a pump for a Brayton Cycle Power Conversion System utilizing the Polyphase Helical Induction Pump concept as described in NASA Report CR-911 and CR-380, the following report is submitted. The requirements of the Brayton Cycle pump are shown in Table 1.

The design objectives of this work were to provide a pump with the following characteristics:

Maximum Reliability
Maximum Efficiency
Minimum Volume and size
Minimum Cooling

TABLE I
BRAYTON CYCLE PUMP REQUIREMENTS

	<u>Minimum</u>	<u>Nominal</u>	<u>Maximum</u>
Pumped Fluid	NaK	NaK	NaK
Fluid Temperature	1000°F	1100°F	1200°F
Flow Rate	50 GPM	60 GPM	100 GPM
Pressure Rise	2 PSI	2 PSI	5 PSI
System Pressure	10 PSIA	11 PSIA	15 PSIA

The first step in this investigation, as in any other investigation, was to review the existing data. The most pertinent existing data in this case is contained in two NASA reports, CR-911 and CR-380. NASA report CR-911 covers the design of two Electromagnetic pumps (9#/sec and 3.25#/sec) and contains the resulting size of the pumps, calculated Equivalent Circuit Parameters, and the calculated pump performance using the Equivalent Circuit and Parameters as calculated by computer. The Equivalent Circuit represented in the report was different from the normal induction machine equivalent circuit, as found in text books. To determine the relative differences in calculated performance, using the G.E. and conventional equivalent circuit, and to determine if standard calculation methods developed for induction motors and canned motors would produce the G.E. calculated parameters, calculations were performed.

II. DISCUSSION

A. REVIEW OF DATA

Calculating and checking the pump rated at 9 lbs/sec indicated a number of discrepancies in the published data, the most noticeable being a stated operating voltage of 160 volts on Page 37, and 242 Volts for the same unit (9 lbs/sec T-111 duct) on Page 56. Due to these discrepancies, further calculation on the 9 lb/sec pump was abandoned.

Attention was then turned to the 3.25 lb/sec pump described in Report CP-911. Some variation in published slip values between Pages 37 and 56 were noticed, as well as variations between these values and apparent value of slip as calculated from the losses on Page 37 and flow velocity on Page 38.

Calculations were performed on the 3.25 lb/sec pump based upon the published dimensions on Page 7 and 17, as well as the slot detail on Page 15. These calculated values were compared with the published data on Page 56. This comparison is shown in Table II.

TABLE II

		<u>Published</u>	<u>Calculated</u>
Stator Resistance	(R_1)	.063	.0782
Stator Reactance	(X_1)	.221	.220
Iron loss Resistance	(R_c)	20.6	20.9
Can loss Resistance	(R_c)	25.9	15.4
Outer duct Resistance	(R_{d1})	3.35	2.58
Inner duct Resistance	(R_{d2})	4.96	6.96
Resistance fluid (rotor)	$(R_{F1} \text{ or } R_2)$	.392	.493
Fluid Reactance	$(X_{F1} \text{ or } X_2)$	.029	.030
Inner duct Reactance	(R_{d2})	.014	-
Magnetizing Reactance	(X_m)	.396	.205

The calculated values are for potassium at 1000°F and a frequency of 60 cycles/sec.

As may be expected, since motor design is an established art, the agreement on the constants to represent the stator is very good (R_1 , X_1 , R_i). The can loss calculations were based upon work performed over a two-year period, by myself and others, which resulted in AIEE transaction paper #57-134. It is assumed, based upon the relative values of R_c , R_{d1} , and R_{d2} , that the equation for can loss published in the AIEE transaction paper was not used, or some additional factors were added. Time was not available to attempt to analyze this variation. The results of the variation would be to make the present calculation more conservative. This is also the case with the resistance calculation of the fluid. The greatest variation, as far as machine performance is concerned, is between the G.E. published value and the results of the calculation of X_m and its use in the equivalent circuit. No explanation can be offered for this difference.

The equivalent circuit offered by G.E. to calculate machine performance (Figure 1) is quite different from the conventional induction motor equivalent circuit (Figure 2). CR-380 References, other than No. 9, "Alger P.S., "The Nature of Polyphase Induction Machines", John Wiley and Sons, Inc. 1951, were not available for analysis. Reference No. 9 contains the conventional equivalent circuit. From machine theory, the equivalent circuit offered by G.E. should be optimistic.

Figure 1. . G.E. Equivalent Circuit

*The values R_i , R_c , R_{d1} , and R_{d2} are consolidated in the R_c value shown, and values X_{f1} and X_{d2} are consolidated in X_2 as shown.

Figure 2. Conventional Equivalent Circuit

The G.E. published constants were used in the G.E. equivalent circuit to determine if the published curves could be reproduced. Figure 3 shows the comparison between the published curves, and the calculated performance, from the published constants. It appears that the published constants contain a higher rotor, a lower can and/or duct loss, and a higher reactance, such as X_1 , than those upon which the published curves are based. A comparison of the published constants and calculated constants as shown in Table II, does not indicate sufficient difference to affect calculated results as expressed in performance curves. The variation between the two equivalent circuits as shown in Figures 1 and 2 was, however, expected to produce an appreciable difference in performance as expressed as curves, especially due to the location of the magnetizing reactance term (X_m) in the equivalent circuit. This difference does show up when the calculated performance using the calculated parameters in the conventional equivalent circuit is also plotted in Figure 3. It should be noted that this latter calculation is conservative with respect to the other calculations.

Figure 3.

III. PERFORMANCE OF BRAYTON CYCLE PUMP

A first pass attempt was made to design a pump for the Brayton Cycle application. The pump, as designed, is 11 inches in diameter and 24 inches long, and contains two fluid turns in the magnetic gap. The magnetic gap has been decreased from the G.E. designs to effect a saving in magnetizing requirements. This machine was calculated using both the normal equivalent circuit and the G.E. equivalent circuit, with equivalent circuit constants developed from dimensions. This design is not to be considered optimized, but rather, should be considered as a "first pass" design. The results of the calculations are shown as Figure 4.

As shown in Figure 4, at the rated voltage of 63.5 volts/phase, the developed head is in excess of the required, or rated head of 2 psi at 60 GPM, and the maximum head of 5 psi at 100 GPM. The developed head is a function of the applied phase voltage, frequency and temperature of the fluid. Control of the pump can be obtained by voltage control or frequency control, or a combination of the two. Examples of the pump performance under voltage control are seen in Figures 5, 6, 7, and 8, where a voltage was selected to produce the rated and maximum conditions for performance using both types of equivalent circuit. Some shifting of the peak efficiency point may be accomplished by using a frequency other than 60 HZ.

Figure 4.

BRAYTON CYCLE PUMP
PERFORMANCE AT 23.5V PHASE
NORMAL EQUIVALENT CIRCUIT 1100°F N₂H

Figure 5.

Figure 6.

BRAYTON CYCLE PUMP PERFORMANCE AT 40.6 V PHASE NORMAL EQUIVALENT CIRCUIT 12069F N.K.

Figure 7.

Figure 8.

IV. SIZE

The estimated overall size of the pump for the Brayton Cycle application is shown in Figure 9. This diagram shows the relative locations of the pumped fluid, core iron, stator, windings, and cooling fluid. The size selected for this application for the first analysis is 11-inch diameter and 24-inch length. Review of this design indicates that the length can be reduced to 21 inches by cutting down the allowances for core clamping and connection termination space. The relative slot size is shown near the center of the stator. A cooling channel is included in this diagram but may not be required, and will be covered in the section on heat transfer. Although some reduction in size can be obtained by using a straight-through duct design rather than the fold-back as shown, no significant decrease in overall diameter will be accomplished.

V. EQUIVALENT CIRCUIT

As noted before, the greatest variation in approach to calculating pump performance is in the selection of equivalent circuits to represent the performance of the pump. The conventional equivalent circuit, (Figure 2) of an induction motor contains the stator resistance (R_1) and reactance (X_1) in series, followed by the rotor reactance (X_2) and resistance (R_2) in series with two terms in parallel with the rotor reactance and resistance. These two terms are inserted to represent the iron core loss (R_c) and magnetizing requirements (X_m). The first approximation of this circuit is to move both the iron core loss (R_c) and magnetizing requirements to the line side of the stator so they will be constant, which will facilitate calculation.

In the calculation of canned motors this modification leads to excessive error and the conventional equivalent circuit must be used. In the equivalent circuit used by G.E., the iron loss (R_i) is moved to the line side of the stator. The can loss (R_c) and outer duct loss (R_{d1}) are located between the stator and rotor, and a reactance factor (X_{F1}) is in parallel with a network of inner duct reactance (X_{d2}), inner duct resistance (R_{d2}) magnetizing reactances (X_m). This circuit is not, on its face, representative of the machine being analyzed. However, if the machines developed and tested by G.E. do perform in accordance with the calculations, this equivalent circuit should be used as representing the performance of the machine being analyzed.

VI. FLUID RESISTANCE

The fluid flowing in the duct has a loss due to frictional drag on the outer walls, and undergoes a turbulent loss in traveling in a spiral path. G.E. has published in NASA CR-380; a curve of fluid friction head loss factors whose values of fluid friction are much less (about 10%) than the values normally published for fluid friction. In the calculations presently being performed, the higher normal values for fluid friction were used to provide some margin for the spiral hydraulic losses not accounted for in the G.E. calculation.

REDUCIBLE TO 21

Figure 9.

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VII. MATERIAL SELECTION

The calculation was based upon the use of stator and core lamination of Hiperco 27 magnetic material with the windings in the slots insulated from the lamination by alumina plates. Turn-to-turn insulation would be the glass serving on the wire supplemented by mica strips. Strand-to-strand insulation (two strands are in parallel for each turn), is only by glass serving on the wire. The selected wire (.090 x .280) is nickel clad silver (20% Ni). There are 20 wires in each slot. The stator can material is Inconel, while the duct is thick enough to be Inconel or stainless steel. It is preferable that the duct material be of minimum thickness to reduce losses and increase performance. Calculations were based upon a 0.060 in thick duct of stainless steel. Containment materials for the outside of the stator and the cooling jacket, if required, are expected to be stainless steel. Potting material is expected to be AI-1 cement as required. Potting material may be required for bracing or anchoring the windings, end turns, or connections.

VIII. FABRICATION

Fabrication of a high temperature (1200°F) stator is a difficult task. This task is made easier if the fabrication shop has experience in motor fabrication or high temperature winding. To facilitate fabrication, a relatively small pitch (2/3) has been selected rather than the pitch (5/6) used by G.E. It is expected that coils will be formed to their final shape external to the stator and the organic wire varnish removed by heat. These coils will have to be coated with some material such as aluminum orthophosphate, to hold the wire serving (insulation) in place during the subsequent operations. The coils will have to be deformed to be inserted into their slots and returned to shape with the ground wall intact. Ceramic slot wedges will be forced into place held by some type of lip projection, either on the tooth or ground wall insulation. After the belt connections (between adjacent coils) and phase connections (between belts) are made, a cement, or binder may have to be applied and cured. After this, the stator is installed in its housing, (press fit), keyed, and connected to the terminals. The stator can is then installed and expanded to seat and lock the can and wedges. Additional assembly of duct and containment is conventional, as is inspection etc. An alternate method of construction discussed later (under Development) may ease the problem of coil assembly.

IX. RELIABILITY

The Polyphase Helical Induction type of pump for the Brayton Cycle application requires high reliability to be able to operate unattended for long periods of time. The causes of failures in standard motors are the moving contact parts (bearings), aging of the dielectric material (insulation), contamination with oil and grease, and windings coming loose in the slots. The loose windings failure mode is the least common of the failure modes and is the only failure mode common to the Polyphase Helical Induction pump. Coils will be tied and braced to prevent this.

The forces causing failure of this type are normally due to high (500% normal) starting inrush current, which, in the present design is low ($\approx$ 105% normal); therefore, the forces during starting are low (110% normal) rather than 25 times normal.

The proposed slot insulation does not degrade with time or temperature, leaving as the modes of failure the conductors themselves (sublimation), connections (sublimation, breakage) and differential thermal expansion (thermal ratcheting and abrasion of turn-to-turn insulation). Upon assembly, and after passing over voltage testing, the resultant unit should have a very high reliability (estimated greater than .9999 for 10,000 hours) based upon a feeling of this design as compared with the design, construction, and testing of actuator coils for high temperature as used in the S8DR components.

X. HEAT TRANSFER

Preliminary heat transfer calculations were performed on the calculated Polyphase Helical Induction Pump. Calculations based upon the pump operating at the nominal conditions of 60 GPM and 2 PSI head indicate the machine would operate cooler (by 150°C) when cooled by radiation cooling to space than when using the pumped NaK in a heat exchanger. Based on radiation cooling alone, the outer surface of the pump would operate at 450°C (842°F) and the winding temperature would be 515°C (959°F). Calculations were based upon the conventional equivalent circuit.

Although detail calculations were not performed for the maximum operating condition (100 GPM of 1200°F NaK developing 5 PSI head) using the conventional equivalent circuit, or for the temperature developed for the operating conditions as described by the G.E. equivalent circuit, estimates were made based upon the calculated losses and the data developed in the above calculation. This investigation indicates the winding temperature should be approximately 800°C (1472°F) with a 700°C (1292°F) surface temperature based upon the conventional equivalent circuit when pumping 100 GPM 1200°F NaK at 5 PSI head. At this operating condition the G.E. equivalent circuit losses indicate the winding temperature would be approximately 590°C (1094°F) and the surface temperature 550°C (1022°F). The G.E. equivalent circuit losses indicate the winding temperature should be 440°C (824°F) and the surface temperature should be 425°C (797°F) when operated at the nominal rating of 60 GPM and 2 PSI head.

The only calculated condition that is improved with the use of a cooling jacket, using the process fluid as a coolant, is the maximum rating condition (100 GPM 5 PSI head 1200°F fluid) if this is correctly described by the conventional equivalent circuit.

XI. DEVELOPMENT PROGRAM

A. STATOR AND CORE IRON

The magnetic material selected for the lamination is Hiperco 27. This material has been tested for magnetic properties for tens-of-thousands of hours under other programs, and as such, developmental testing in the new form is not required.

B. STACKING AND CORE PLATE

Any stable oxide coating such as black iron oxide, red iron oxide, or alumina oxide will be satisfactory. A supplier of one of these materials will have to be found and a test performed for quality, but a developmental program is not required. For stacking, some effort is required for fixturing and its rework, but likewise, a developmental program is not required.

C. COILS AND WINDING

The manufacture of coils and winding in the core will require a developmental program to determine the most desirable method of manufacture. It appears as if the coils will have to be pulled with final shaping on a coil form. Winding will be slow especially with the binder (varnish on the wire) removed. An alternate program that should be investigated, as it will facilitate winding if workable, is to remove the binder on the wire subsequent to winding.

D. DUCT MANUFACTURE

The manufacture of the duct is to be performed to AI standard liquid metal quality with special attention given to welding at the joints, to meet NaK containment vessel requirements. Calculations were based upon a 0.060-inch wall. Formations of the duct will not present unusual problems beyond those normally encountered in liquid metal components. Quality of welds should be dye penetrant white and leak tight to mass spectrometer testing.

E. ASSEMBLY

The assembly of the component parts should not present any great difficulty.