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PERFORMANCE AND CAVITATION CHARACTERISTICS OF TWO HELICAL
ELECTROMAGNETIC-INDUCTION PUMPS OPERATING WITH POTASSIUM

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W. R. Huntley A. G. Grindell

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PERFORMANCE AND CAVITATION CHARACTERISTICS OF TWO HELICAL ELECTROMAGNETIC-INDUCTION PUMPS OPERATING WITH POTASSIUM

W. R. Huntley A. G. Grindell

Abstract

Two small, helical induction pumps of different design were operated with potassium at temperatures up to 1300°F to determine hydraulic, thermal, and cavitation-inception characteristics and to qualify them for use as boiler feed pumps in boiling-condensing potassium test facilities. The first pump tested had a helical two-pass reentrant pump cell fabricated of Nb-1% Zr alloy. The second pump had a single-pass helical pump cell fabricated of stainless steel. The data indicated that the pumps were suitable for their respective boiler feed functions. However, the data for the refractory-metal pump revealed a peculiar hydraulic response to a change in either applied voltage or system flow resistance. An instantaneous hydraulic response would first occur, followed by a slower thermal equilibration. The time required to achieve thermal equilibrium was relatively very long at low flow rates. For both pumps, two different values of net positive suction head (NPSH) were required to suppress cavitation at nearly identical pump operating conditions. The smaller value was associated with reducing NPSH by decreasing the amount of subcooling at the pump inlet in the absence of argon cover gas in the system; the larger value was associated with reducing NPSH by decreasing the pressure of argon cover gas on the potassium liquid surface in the loop expansion tank. In the absence of argon cover gas, the potassium liquid at the pump inlet would not cavitate at negative values of the suction head; this indicated ability to sustain tensile forces.

Introduction and Summary

The pumping requirements for reliable space power systems and for their supporting development work have sparked renewed interest in the use of electromagnetic pumps for liquid alkali metals. For example, an electromagnetic pump having a permanent magnet and a thermoelectric supply is an important component in the SNAP-10A¹ power system. Helical electromagnetic-induction pumps are being considered for space power systems.² The rotating magnet pump has been used to provide boiler feed³ in a variety of alkali-metal test systems.

At ORNL two helical electromagnetic-induction pumps with different pump-cell designs were purchased to provide the boiler feed for test facilities that boil and condense potassium. One pump had a two-pass re-entrant cell fabricated of a refractory-metal alloy, Nb-1% Zr. The other pump had a single-pass cell fabricated of an austenitic stainless steel. It was hoped that the absence of rotating machinery in the helical induction pumps would lead to good operational reliability. However, it was decided to pretest the pumps in an available test stand, mainly because of the lack of detailed information on their behavior.

Data were obtained on hydraulic performance, cavitation inception, and behavior of the pumps during transient operations. Some anomalies in behavior were observed for the refractory-metal pump. Initially the data indicated an unstable operating region at low flows, but additional testing showed the refractory-metal pump to be stable at all flows. At low flows, the head versus flow performance changed slowly after an operating transient as the pump attained a new thermal equilibrium. For both pumps, cavitation inception data taken by two different methods indicated a difference in the net positive suction head (NPSH) required to suppress cavitation. In one method, the argon-pressure method, NPSH was controlled by varying the static pressure of the potassium at the pump suction by changing the pressure of the inert gas that blanketed the potassium. In the other method, the vapor-pressure method, the temperature of the potassium at the pump suction was maintained approximately constant, while static pressure was varied by changing the temperature of the potassium in the loop expansion tank and thereby changing the vapor pressure on the system. The data indicated that greater NPSH was required to suppress cavitation with the argon-pressure method.

With the vapor-pressure method, the pumps developed undiminished head at suction static pressures less than the local vapor pressure. This fact indicates that potassium in the pump suction sustains tensile forces and thus agrees with reports of tension in liquid nitrogen in a venturi⁴ and in water in a cavitation tunnel.⁵ Tensile forces in liquids in the form of large degrees of superheating have been observed in other boiling-potassium systems.⁶

Description of Equipment

Refractory-Metal Pump

A cross-sectional view of the General Electric Model 5KY-414-PD1 refractory-metal helical induction pump is shown in Fig. 1. The pump has a squirrel-cage stator to supply the magnetic flux for the pump cell.

The pump cell was constructed of Nb-1% Zr alloy to match the material of the test loop in which the pump was ultimately to be used. The pump cell has a two-pass reentrant configuration consisting of two coaxial cylinders. The two-pass configuration is required to obtain the desired design pressure rise of 238 psi at a potassium flow rate of 37 lb/hr. The helical cell configuration can be seen in the x-ray photograph of the pump cell in Fig. 2. The pump cell is about 15 in. long, with a 2.2-in. OD, and the helical flow passages are 0.150 in. square in cross section.

The pump cell was designed by General Electric and fabricated at ORNL. The fabrication details of the pump cell were reported previously.⁷ The exterior of the pump cell is wrapped with layers of tantalum-foil reflective insulation to reduce heat losses. Two Chromel-P vs Alumel thermocouples sheathed with stainless steel and wrapped in tantalum foil are located against the outer surface of the pump cell at its axial midpoint to monitor the cell temperature.

The pump cell is mounted within a stainless steel vacuum jacket, which is evacuated during operation to prevent oxidation of the cell exterior surface at elevated temperatures. This stainless steel vacuum jacket is centered in the bore of the pump stator, which is surrounded by ambient air. Filtered cooling air for the stator windings is provided by a separate centrifugal blower. Throughout all tests of the pump, the cooling air was throttled to provide a flow rate of 350 cfm.

Stainless Steel Pump

A photograph of the General Electric Model 5KY-410-PB1 stainless steel helical induction pump is presented in Fig. 3. The pump cell is shown removed from the stator assembly. The cell, a single helix configuration made of AISI type 304 stainless steel, is designed to produce

Fig. 1. Helical Induction Pump with Reentrant Pump Cell Made of Nb-1% Zr Alloy.

Fig. 2. X-Ray Photograph of Two-Pass Nb-1% Zr Pump Cell for Helical Induction Pump.

Fig. 3. Pump Cell and Stator of Stainless Steel Helical Induction Pump Rated 40 lb/hr at 60-psi Head.

a 60-psi pressure rise at a flow rate of 40 lb/hr. The pump cell is wrapped on the exterior with three layers of 3/16-in.-thick fibrous thermal insulation and enclosed in an outer can of stainless steel. Two Chromel-P vs Alumel thermocouples sheathed with stainless steel are pressed to the outer surface of the pump cell at its axial midpoint. The helical portion of the pump cell is about 8 in. long, and the helical flow passages are 0.150 in. square in cross section. An auxiliary air blower is mounted on the pump frame to provide cooling air for the stator windings.

Test Loop

Both pumps were tested in an available facility. The stainless steel loop (see Fig. 4) was specifically designed for tests of high-head liquid-metal pumps at flow rates less than 1 gpm; thus most of the loop was made from relatively heavy walled tubing, 3/8 in. OD and 0.065 in. wall. A full-flow zirconium hot trap was used to reduce the oxide content of the system potassium and, particularly, to protect the Nb-1% Zr alloy pump cell during operation. The trap was maintained at 200 to 400°F above the pump cell temperature to insure effective oxide gettering during most of the tests of the refractory-metal pump. During the tests of the stainless steel pump, the hot trap was operated at 1400°F initially and then kept at the same temperature as the loop for the remainder of the test.

The loop has two small-diameter orifices and a stop valve mounted in series in each of three parallel flow passages to provide variation in system flow resistance. The diameters of the orifices ranged from 0.011 to 0.031 in. This scheme was used because no appropriate liquid-metal metering valves were available for the high heads and low flow rates involved in the pump tests. At the conclusion of the refractory-metal pump tests and prior to testing the stainless steel pump, a fourth parallel passage was added to provide additional flow control.

Vacuum System for Refractory-Metal Pump

The space between the stainless steel vacuum jacket and the Nb-1% Zr pump cell was evacuated during operation at elevated temperatures to protect the cell from oxidation. A Welch Model 1377A turbo-molecular vacuum

Fig. 4. Simplified Schematic Diagram of Electromagnetic-Pump Test Loop.

pump, rated at 140 liter/sec and an ultimate vacuum of 10^{-9} mm Hg (torr), was used to evacuate this space.

The vacuum pump was connected to the 6-in.-diam stainless steel vacuum jacket with an 80-in.-long 2-in. sched-40 IPS pipe, as shown in Fig. 5. The total volume of the vacuum system was about 650 in.³ The 2-in. pipe was electrically heated and thermally insulated to promote outgassing. A bellows-sealed valve was located in the 2-in. pipe to isolate the vacuum pump from the rest of the vacuum system. System pressure was monitored with a Varian ionization gage, which was mounted at the midpoint of the 2-in. pipe. To protect the refractory-metal pump cell in the event of a pressure rise in the vacuum system, automatic valves were provided to isolate the vacuum pumps and to flood the vacuum piping with argon.

Instrumentation

The potassium flow rate was measured with an electromagnetic flowmeter. The flowmeter was calibrated in place and at temperature by means of the holdup tank and the metering tank shown in the schematic loop diagram in Fig. 4. The calibration procedure consisted of adjusting the liquid inventory until the metering tank was nearly full and then diverting the flow by valving into the holdup tank. The time rate of decrease in liquid level in the metering tank was observed with the aid of a calibrated resistance-probe level indicator and used to calibrate the electromagnetic flowmeter. The accuracy of the flow measurement is believed to be within $\pm 2\%$.

Pressures at the pump suction and discharge were measured with Bourdon-tube gages located in a furnace maintained at 250°F. These gages were periodically calibrated in place and at temperature by introducing argon pressure into the emptied loop. This argon pressure in turn was measured by mercury manometers and with precision-calibrated gages.

Chromel-P vs Alumel thermocouples were used for all loop piping temperature measurements. The accuracy rating of standard Chromel-P vs Alumel thermocouple wire is $\pm 3/4\%$ above 531°F. Thermocouple output was read on recorders, which have a rated accuracy of $1/4\%$ of full scale or 5°F. Bare-wire thermocouples, 0.031-in.-diam wire with ceramic-bead insulation, were used in most locations; these thermocouples were attached

Fig. 5. Facility for Testing Helical Electromagnetic-Induction Pump.

to the loop with a condenser-discharge welder. Stainless steel-sheathed, magnesium oxide-insulated, Chromel-P vs Alumel thermocouples were used on the exterior of both of the helical pump cells and in the thermocouple well in the metering tank. The sheathed thermocouples on the Nb-1% Zr pump cell were wrapped in tantalum foil and located 180° apart on the outer surface of the pump cell at its axial midpoint. For the refractory-metal pump, the pump inlet and exit thermocouples were located on the outer surface of the 3/8-in.-OD lines, exterior to the vacuum jacket, at a point 15 in. from the entrance and exit of the helical pump cell proper. The locations of these thermocouples can be seen in the cross-section drawing of the pump in Fig. 1. The thermocouples in the drawing are identified by bubbles labeled TE. For the stainless steel pump, the inlet and exit temperatures were measured by thermocouples in wells located 1 1/2 in. from the point where the lines emerge from the stator frame, much closer to the cell than for the refractory-metal pump.

Vacuum System Operating Experience

During a preliminary test of the vacuum pump, a pressure of 5×10^{-9} torr was attained after 300 hr of pumping. This test showed that the vacuum pump was adequate, and it was then attached to the vacuum system piping.

When the Nb-1% Zr pump cell of the helical induction pump and the surrounding layers of reflective insulation were first heated (by applying voltage to the pump stator), considerable off-gassing was observed. The histories of the vacuum-jacket pressure and the pump-cell temperature are shown in Fig. 6, where it may be seen that the pressure decreased throughout the test period.

A leak in the vacuum jacket occurred after 300 hr of operation, when a furnace-brazed joint failed. At that time the pump inlet and cell temperatures were 800 and 1300°F, respectively. The system was immediately flooded with argon. A visual inspection, made through an access port, showed that the foil surrounding the pump cell and inlet and discharge lines was bright in appearance and apparently undamaged. Repairs were made to the failed joint, and the test was continued.

Fig. 6. Relation of Pressure in Vacuum Jacket to Temperature of Pump Cell During Test of Refractory-Metal Helical Induction Pump.

Hydraulic Performance of Refractory-Metal Helical Induction Pump

Steady-State Head Versus Flow

Pump performance data with potassium were obtained at pump inlet temperatures of 800, 1000, and 1200°F. Argon was introduced above the liquid surface in the metering tank to suppress cavitation of the pump during these performance tests. A static pressure of about 5 psig was maintained at the pump suction. This static pressure provided a net positive suction head well above the cavitation-inception point for these conditions. The steady-state pressure rise versus flow relationships at 800, 1000, and 1200°F are shown in Figs. 7 and 8. The shape of the performance curves varied greatly with the inlet temperature, as can be seen in Fig. 9, where the pump performance at a constant stator voltage (400 v) is plotted for the three test inlet temperatures. The decrease in pressure rise with increasing inlet temperature is mainly caused by the decrease in the electrical conductivity of potassium at elevated temperatures.

The positive slopes in the 800 and 1000°F curves (Fig. 9) were of considerable concern, since they implied the presence of a flow instability. A tentative explanation has been based on the temperature response of the pump cell during flow variation at constant values of stator voltage. It is a characteristic of this pump cell to generate electrical heat, which is removed both by radiant transfer to the vacuum jacket and thence to the stator cooling air and by thermal transport in the potassium flow. As flow is reduced by throttling at the pump discharge, the amount of heat removed by the potassium is reduced, while heat generation within the cell is essentially constant. The increased radiant heat transfer load requires an increase in pump cell and potassium temperatures, that is, a new thermal equilibrium. Thus the increase in temperature of the pump cell potassium and the subsequent decrease in its electrical conductivity were thought to cause the positive slope in the performance curve. The results of transient tests of this hypothesis are presented in the next section.

Fig. 7. Refractory-Metal Pump Performance at a Potassium Inlet Temperature of 800°F.

Fig. 8. Refractory-Metal Pump Performance at Potassium Inlet Temperatures of 1000 and 1200°F.

Fig. 9. Effect of Inlet Temperature on Refractory-Metal Pump Performance.

Transient Pressure Rise Versus Flow

A pump performance curve having a positive slope usually implies unstable, pulsing operation in centrifugal pumps; however, this was not true for the test pump. The performance data, shown in the preceding section of this report, were taken after the pump had achieved thermal equilibrium (usually 20 to 30 min after a change in flow rate). The short-term pump performance characteristic taken at constant applied voltage had, at all times, a negative (stable) slope. This characteristic is indicated in Fig. 10, where the effects of step changes in flow rate are shown. The pump was permitted to reach thermal equilibrium conditions at point A at a flow rate of approximately 37 lb/hr and a pump head of 227 psi. The flow was quickly reduced to 23 lb/hr by throttling, and the head rose to point B and then slowly dropped to the new thermal equilibrium condition at point C. The decrease in head from points B to C resulted from the increased average temperature of potassium in the pump cell caused by the higher temperatures required to remove essentially the same pump power losses at the reduced flow rate. When the flow was quickly increased in a step from points C to D, the pump again reacted along a negative (stable) slope. The increase in pressure from points D to E accompanied a reduction in the average temperature of the potassium as substantially the same pump heat losses were redistributed. The same effect was demonstrated again starting at a flow rate of about 139 lb/hr, as shown at the right of Fig. 10.

A similar effect was demonstrated by this pump when step changes were made in the voltage applied to the pump stator. Figure 11 shows typical pump performance for both a step increase and decrease of applied voltage. In Fig. 11 the applied voltage was suddenly increased from 400 v at point A to 425 v, and the pump performance immediately rose to point B. The pressure rise then decreased as the pump cell temperature increased, and after about 22 min, the pump was at thermal equilibrium at point C. The same effect was then shown by again starting at point A at 400 v and suddenly reducing the voltage to 375 v.

These tests were of interest because this pump was to be used for boiler feed service in a boiling-condensing potassium system. Pumps with

Fig. 10. Effect of Step Changes in Flow on Refractory-Metal Pump Performance.

Fig. 11. Effect of Step Changes in Stator Voltage on Refractory-Metal Pump Performance.

performance curves of positive slope would ordinarily be unsatisfactory for boiler feed use because unstable surging operation could occur. However, the tests indicated that the pump should provide satisfactory boiler feed even at the low flow rates. It is planned to vary stator voltage automatically within a rather narrow range to control the distribution of liquid inventory in the boiling-condensing test systems.

Pump Cell and Discharge Temperatures During Operation

The temperatures of the refractory-metal pump cell and pump discharge stream are of interest to the operators and designers of test facilities. Test data on these two temperatures versus flow rate for various values of applied voltage at a constant suction temperature of 1000°F are presented in Fig. 12. Similar data are presented for a constant inlet temperature of 1200°F in Fig. 13. These figures can be used in conjunction with the head versus flow curves of Fig. 8 to predict the pump-cell and discharge temperatures for any head and flow condition at 1000 or 1200°F inlet temperature. It is of interest to note that at low flow rates and applied voltages lower than 350 to 400 v, the outlet temperature is lower than the inlet temperature. However, it is emphasized that the refractory-metal pump inlet and exit temperatures were measured at a distance of 15 in. from the end of the pump-cell helix due to restrictions imposed by the geometry of the vacuum jacket surrounding the pump cell. Therefore, the temperature maps are exactly valid only for similar thermocouple locations. However, from a practical standpoint, the pump outlet temperature data appear to be generally of use for all flow rates greater than 30 to 40 lb/hr. The radiant heat losses from the 3/8-in.-OD supply and discharge lines within the vacuum jacket significantly affected the observed temperatures in the lower range of flow rates used in the pump tests. The 3/8-in.-OD lines within the vacuum jacket were insulated by several layers of tantalum foil, which were wrapped around the tubing. The tantalum foil served the dual purpose of reducing heat losses from the 3/8-in.-OD lines and minimizing oxidation in case of a failure of the vacuum system.

Fig. 12. Refractory-Metal Pump Cell and Discharge Temperatures at a Pump Inlet Temperature of 1000°F.

Fig. 13. Refractory-Metal Pump Cell and Discharge Temperatures at a Pump Inlet Temperature of 1200°F.

Cavitation-Inception Characteristics for the
Refractory-Metal Helical Induction Pump

Because the refractory-metal pump was later to be used in a Rankine-cycle system in which the very low value of NPSH available for the pump would invite cavitation, data on cavitation inception were taken at temperatures of interest: 800, 1000, and 1200°F. Two different methods were used to vary the net positive suction head (NPSH)* at pump suction. In the argon-pressure method, the suction static pressure was varied at constant temperature by changing the pressure of the inert-gas blanket in the metering tank. In the vapor-pressure method, the inert gas was first evacuated from the metering tank. The temperature of the potassium in the tank was adjusted to vary the vapor pressure on the liquid surface and thus change the pump suction static pressure. The NPSH required to suppress cavitation was markedly different between the two methods.

Argon-Pressure Method for Cavitation Inception

Cavitation-inception data obtained with the argon-pressure method were taken by first establishing the desired flow rates of about 20, 37, or 100 lb/hr (these flow rates were to be used in future applications of the pump) with the loop operating isothermally and with excess NPSH provided by pressurizing the metering tank with argon. The hot trap was not maintained at temperatures above the loop temperature during any phase

*Net positive suction head is defined as

$$\text{NPSH} = P_s + \frac{V^2}{2g} - V_p,$$

where

P_s = static pressure at pump inlet expressed in feet of liquid at suction temperature,

$\frac{V^2}{2g}$ = velocity head at pump inlet,

V_p = vapor pressure of liquid.

of cavitation testing to preclude boiling within the hot trap. While holding the flow rate and pump inlet temperature constant, the NPSH was reduced by withdrawing the argon-vapor mixture from above the liquid surface in the metering tank via the vapor trap (see Fig. 1). Typical cavitation-inception data taken at 1200°F inlet potassium temperature are shown in Fig. 14. The pump retains full performance up to the point of cavitation and then suddenly loses all pumping capability. The NPSH requirement for cavitation suppression is strongly affected by both mass flow rate and applied voltage.

The effect of temperature at pump suction and mass flow rate on cavitation inception for the refractory-metal pump when using the argon-pressure method is shown in Fig. 15. Additional NPSH is required as temperature is increased or as flow rate is decreased.

Numerous test runs were made to see whether the rate of NPSH reduction affected the point at which cavitation-inception occurred. The combined argon and vapor pressure in the metering tank was reduced at rates from 0.2 to 4.0 psi/min with no consistent variation in the point of cavitation inception. Typical data on the effect of the rate of NPSH reduction are listed in Table 1.

Vapor-Pressure Method for Cavitation Inception

Cavitation-inception data were taken in the loop by the vapor-pressure method to simulate the suction conditions for a boiler feed pump in a Rankine-cycle system. First, the argon was stripped from the system by cooling the loop potassium to less than 500°F and evacuating the region above the liquid level in the metering tank with a mechanical pump for a period of at least 1 hr. The potassium flow was maintained constant during the evacuation. The loop was then isolated from the vacuum system and brought to the desired temperature.

Excess NPSH for the pump was provided by operating the metering tank about 200°F above the pump inlet temperature. NPSH was reduced by lowering the temperature of the metering tank and by simultaneously adjusting the loop piping heaters to maintain the pump inlet temperature as nearly constant as practicable. With this technique, the rate of NPSH reduction ranged from 0.02 to 0.4 psi/min.

Fig. 14. Cavitation Inception for the Refractory-Metal Pump When Using the Argon-Pressure Method.

Fig. 15. Effect of Inlet Temperature on Cavitation Inception for the Refractory-Metal Pump When Using the Argon-Pressure Method.

Table 1. Effect of Rate of Reduction of Net Positive Suction Head on Cavitation
Inception of Refractory-Metal Pump

Potassium inlet temperature, °F 1200
Flow rate, lb/hr ~38.5
Stator voltage, v ~422

Run No.	Approximate Rate of Pressure Reduction (psi/min)	NPSH at Which Cavitation Occurred (psia)	Remarks
1		9.25	NPSH reduced in step changes of 1 to 2 psi
2		10.0	NPSH reduced in step changes of 1 to 2 psi
3		10.4	NPSH reduced in step changes of 1 to 2 psi
4	1.5	13.2	Steady NPSH reduction
5	0.6	12.3	Steady NPSH reduction
6	4.0	10.9	Steady NPSH reduction
7	2.2	11.8	Steady NPSH reduction
8	0.7 to 1.0	14.7	Steady NPSH reduction
9	0.2 to 0.7	13.3	Steady NPSH reduction

Cavitation-inception data for the refractory-metal pump taken by this method are shown in Fig. 16. The difference in NPSH requirements for the two methods may be seen by comparing Figs. 14 and 16. At the approximate conditions of 36-lb/hr flow rate and 422-v applied, cavitation inception occurred at an NPSH of 10 psi with the argon-pressure method, Fig. 14. For the same conditions, the pump maintained its hydraulic performance with negative NPSH (liquid superheat) when using the vapor-pressure method, Fig. 16. It was not possible to obtain a large enough thermal gradient in the loop to cause cavitation inception in these runs; and, therefore, the cavitation point is not shown in Fig. 16. In one case, a run was terminated by suddenly increasing the flow rate, which immediately caused the pump to cavitate; however, this procedure did not promote cavitation in later attempts to repeat the phenomenon. To account for the large difference in cavitation-inception data with the two methods, we speculate that the presence of argon entrained or in solution in the potassium (which could occur with the argon-pressure method) provides nucleation sites for the initiation of boiling.

Upon completion of runs with the vapor-pressure method, argon was again introduced into the metering tank, and the cavitation performance with an argon partial pressure was rechecked. The results were in good agreement with the earlier performance data shown in Fig. 14 and in marked contrast to the data taken without argon in the system. It is believed that argon goes into solution or is entrained in the potassium at the gas-liquid interface in the metering tank and greatly affects cavitation characteristics. The ability of the refractory-metal helical induction pump to operate with superheated liquid at the pump inlet in the absence of argon was a confirmation of similar unpublished observations, which had been made earlier in the same pump test stand with a Liquid Metals, Inc., rotating-magnet pump. Also, these results were later confirmed during the operation of the stainless steel helical induction pump, which is described in a following section of this report.

It was concluded from the cavitation data that the pump would perform satisfactorily in the proposed boiler feed pump application.

Fig. 16. Cavitation Inception for the Refractory-Metal Pump When Using the Vapor-Pressure Method.

Postrun Examination

Postrun examination of the pump after about 1100 hr of operation at elevated temperatures showed that the equipment was in excellent condition. The pump stator and pump cell are shown in Fig. 17 during posttest disassembly. The pump cell material was bright and glossy, as shown in the close-up view in Fig. 18. Metallographic examination of sections of the 3/8-in.-OD, 0.065-in.-wall Nb-1% Zr tubing taken from both the pump inlet and discharge showed no significant corrosion on either the interior or exterior.

Hydraulic Performance and Cavitation-Inception Characteristics of Stainless Steel Helical Induction Pump

Steady-State Pressure Rise Versus Flow

Pump performance data with potassium were obtained at pump inlet temperatures of 1000 and 1200°F. Argon was introduced above the liquid surface in the metering tank to maintain a suction static pressure of approximately 6 psig. This static pressure provided excess NPSH to prevent cavitation inception. The pressure rise versus flow rate performance for the stainless steel pump is shown in Fig. 19. The slope of the performance curves is negative at all conditions for this pump in contrast to the slope for the refractory metal pump shown in Fig. 9. The differences in slope of the performance curves of the two pumps are a direct result of the temperatures attained in the pump cells. As the flow is reduced at constant stator voltage, the refractory pump cell experiences a temperature rise due to its thermally isolated location within the vacuum jacket and to regenerative heat transfer between the two coaxial helical flow passages (Figs. 12 and 13). This increased temperature results in a corresponding loss in pump efficiency due to increased electrical resistivity of the pump cell and potassium. For similar conditions, the stainless steel single-helix pump cell temperature decreases because the cell is not thermally insulated as well as the refractory pump; its pumping efficiency is therefore increased slightly at low flow rates.

Fig. 17. Disassembled View of Refractory-Metal Helical Induction Pump Taken After 1100 hr of Operation.

Fig. 18. Closeup View of Refractory-Metal Helical Induction Pump After 1100 hr of Operation.

Fig. 19. Stainless Steel Helical Induction Pump Performance with Potassium.

Pump Cell and Discharge Temperatures During Operation

It was mentioned previously that the temperatures of the pump cell and the pump discharge are of interest to both pump users and the designers of test facilities. These data for the stainless steel pump at inlet temperatures of 1000 and 1200°F are presented in Figs. 20 and 21, respectively. The data in Figs. 20 and 21 can be used in conjunction with the pressure rise versus flow curves in Fig. 19 to predict the pump cell and discharge temperatures for any head and flow condition at 1000 or 1200°F inlet temperature. The inlet and exit temperatures were measured in thermocouple wells located 1 1/2 in. from the point where the lines emerge from the stator frame. These data indicate that the cell and discharge temperatures for this pump are generally lower than inlet temperature and thus contrast with similar data for the refractory-metal pump shown in Figs. 12 and 13. As explained in the preceding section, the data for the stainless steel pump are lower because the thermal heat loss at the pump cell at low flow rates exceeded the induced heating.

Cavitation-Inception Data

Cavitation-inception data for the stainless steel pump were taken at approximately 80 lb/hr and 1000, 1200, and 1300°F, with each of the two methods of NPSH reduction described. Figure 22 shows the cavitation-inception data at three temperature levels when using the argon-pressure method. The stainless steel pump retains full hydraulic performance until the NPSH approaches zero at test conditions. Further data taken with the argon-pressure method at flow rates of about 15 and 45 lb/hr and at the same three temperature levels also indicated cavitation inception as NPSH approached zero. Figure 22 shows NPSH values slightly below zero for the 1200 and 1300°F runs. This probably represents experimental error in pressure or temperature measurement.

An additional argon-pressure method test was made in which the potassium level in the metering tank was lowered from its normal operating level of about 10 in. to a level of about 3 in. This test was to determine whether additional gas entrainment would occur that might in turn affect cavitation inception. No change in NPSH at cavitation inception was observed.

Fig. 20. Stainless Steel Pump Cell and Discharge Temperatures for Pump Inlet Temperature of 1000°F.

Fig. 21. Stainless Steel Pump Cell and Discharge Temperatures for Pump Inlet Temperature of 1200°F.

Fig. 22. Cavitation Inception for the Stainless Steel Pump When Using the Argon-Pressure Method.

Cavitation-inception data taken with the vapor-pressure method are shown in Fig. 23 for operating temperatures of 1200 and 1300°F. The pump developed undiminished head at negative suction head and, in this respect, performed similar to the refractory-metal pump (see Fig. 16). It was not possible to obtain a thermal gradient in the loop large enough to cause cavitation inception. Comparison of Figs. 22 and 23 shows that cavitation inception was markedly affected by the presence of argon in the system.

A test was run with the vapor-pressure method to demonstrate that the pump would operate stably for extended periods with a negative net suction head. During this test, the metering-tank temperature was held constant at 1185°F, and the line leading to the pump inlet was heated to 1300°F to reduce the suction head to a negative value. The pump then operated for 120 hr at 1300°F inlet temperature, 44-lb/hr flow rate, and a suction head of -4.1 psi. The potassium in the 3/8-in.-OD, 0.065-in.-wall inlet line was in the turbulent flow regime ($R_n = \sim 8100$), and the liquid sustained tensile forces for periods of about 30 sec as it approached the pump inlet. Figure 24 indicates the temperatures, the tensile forces in the liquid, and the elapsed travel time through the inlet line during the 120-hr run. The values of tensile force shown have been corrected for changes in static head of liquid at the different points along the pump inlet line. After 120 hr of operation, several attempts were made to induce cavitation by increasing the flow rate. Stepwise increases were made to more than 100 lb/hr by opening additional parallel restricting orifices in the loop piping; also, the stator voltage was varied from 250 to 450 v several times to induce cavitation, but the pump pressure rise indicated no loss in hydraulic performance. A final attempt to induce cavitation was made by cooling the metering tank to 1090°F and heating the pump inlet temperature to 1410°F so that the suction head was -13.2 psi, but the pump did not cavitate.

Two additional cavitation-inception runs were made with an argon partial pressure of about .5 psia in the metering tank. In these tests, NPSH was reduced by heating the liquid in the pump inlet line rather than using the usual argon-pressure method of withdrawing the argon from above

Fig. 23. Cavitation Inception for the Stainless Steel Pump When Using the Vapor-Pressure Method.

Fig. 24. Conditions of Stainless Steel Pump During 120-hr Run with Liquid in Tension When Using Vapor-Pressure Method.

the liquid surface in the metering tank. (The procedure for reducing NPSH was, therefore, similar to that used in the 120-hr extended run, which was described in the preceding paragraph.) In these two runs with argon partial pressure, the pump cavitated when the NPSH was lowered to about zero. This performance seemed to indicate that the presence of argon was, indeed, more of a factor in cavitation inception than was the technique of reducing NPSH by heating of the inlet line. Postrun examination of the data for these two runs showed that one thermocouple, located 14 in. upstream of the pump inlet, indicated temperatures 80 to 90°F higher than the pump inlet thermocouple. This high temperature may have been due to an above-normal power supply voltage on one of the electric trace heaters. It is not known what effect, if any, this "hot spot" had on the cavitation inception of the pump.

The thermocouples in wells at the metering tank and at the pump inlet and discharge were removed after all tests were completed and calibrated to insure that accurate temperature measurements had been made during the tests.

It was concluded that the stainless steel pump would be suitable for the intended Rankine-system boiler feed service because of its ability to function at low values of NPSH. The NPSH required to suppress cavitation varied greatly between the two methods of NPSH reduction, and this confirmed previous cavitation-inception experience with the refractory-metal pump.

Conclusions

Both the refractory-metal and the stainless steel helical induction pumps are well suited for potassium Rankine-system boiler feed service because of their ability to provide full hydraulic performance at very low values of NPSH.

Comparison of the NPSH measured for both pumps when using the two methods of reducing NPSH (Figs. 14, 16, 22, and 23) indicates differences both in value and kind. The vapor-pressure method provides a lower value of NPSH than the argon-pressure method and also indicates that the potassium liquid sustains tensile forces. Results from the argon-pressure

method indicate that argon, entrained or in solution in the potassium, provides nucleation sites for cavitation that are absent or very much reduced in the vapor-pressure method of testing.

The double-helix pump cell configuration of the refractory-metal pump has a slow thermal response to transients in both system flow resistance and applied voltage and requires several minutes to achieve a new thermal equilibrium, particularly at low flow rates. Because the pump performance is temperature dependent, the instantaneous hydraulic behavior during a transient is different from that at thermal equilibrium, as shown by a comparison of Figs. 10 and 11 with Figs. 7 and 8. Thus, although the shape of the pump performance curves at thermal equilibrium shown in Figs. 7 and 8 would indicate unstable pump flow at low flow rates, the data of Figs. 10 and 11 prove conclusively that stable flow can be maintained with ordinary control equipment

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