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of the
University of California
LOS ALAMOS • NEW MEXICO

Quarterly Status Report on the
Space Electric Power R and D Program
for the Period Ending April 30, 1968
Part I

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HEAT PIPE SYSTEMS

Annular Return Heat Pipes

Introduction

Very high heat-transfer rates can be achieved with a heat pipe by using a composite wick that provides a large capillary force for fluid circulation and a low-impedance flow path for liquid return. This has been demonstrated most effectively in some recent experiments with simple heat pipes consisting of two cylindrical tubes. An inner tube of fine porosity forms a circular passage for vapor, and an outer container tube separated from the porous tube by a gap provides an annular flow path for liquid return. Tests with Na have shown conclusively that capillary forces are developed in the porous tube when the annulus is completely filled with liquid and closed at each end of the system. This result has also been confirmed by using K as the working fluid. Construction techniques and heat-transfer results are described in the following paragraphs.

Construction

Two porous tubes, 1.17-cm o.d. x 1.14-cm i.d. x 137-cm long, were constructed for the experiments. Each tube was made by wrapping a single piece of 400-mesh, stainless-steel screen around a Cu tube until eight layers were obtained. The structure was placed in another Cu tube and drawn through a die to compress the screen layers. The Cu was removed and the screen tube was heated in a vacuum to 1000°C to bond the structure. This method produced thin, rigid tubing with very fine pores and relatively smooth walls.

Stainless-steel tubes, 1.38-cm o.d. x 1.20-cm i.d. x 138-cm long, were used as containers. The porous tubes were placed loosely in the containers with no provision for centering because radial clearance was only 0.15 mm. Enough liquid was added to each heat pipe to fill the annulus and to saturate the porous tube. Na was added to one system and K to the other by vacuum distillation. Both systems were then sealed and heated uniformly in a vacuum to allow the liquid to wet the wick structure and the container.

Fig. 1. Annular return heat pipe for heat-transfer measurements.

Heat-Transfer Results

Heat-transfer experiments were first conducted with the Na heat pipe; the experimental arrangement is shown in Fig. 1. Heat was added with a 14-cm long induction coil near one end of the system. Short sections of the pipe were insulated on each side of the heat-input zone so that wall temperatures could be measured accurately in these locations. Heat was removed from the remainder of the pipe (110 cm) by conduction through a gas gap to a water calorimeter. The use of different mixtures of Ar and He in the gap allowed heat-pipe temperature variations at a fixed heat input, or heat input variations at a fixed heat-pipe temperature.

The Na heat pipe was first tested before the annulus was closed at each end. In this test, capillary forces are developed in the annulus rather than in the porous tube, and the system could not be started in the calorimeter. It could be operated in air, however, in a horizontal position, but ceased to function when the heated end was elevated a few centimeters. The test showed that a capillary force of about 1×10^4 dynes/cm² was obtained. This agrees closely with the capillary force estimated for the annulus. When the ends of the annulus were closed, capillary forces were developed in the porous tube, and the system could be operated in a vertical position with heat input near the top. It was estimated that the vertical operation required capillary forces of at least 1×10^5 dynes/cm².

Fig. 2. Behavior of heat pipe with Na in startup.

Fig. 3. Trans-sonic velocity conditions in a heat pipe.

The method of closing the annulus is indicated in Fig. 1. Heavy-wall tubes were pressed into each end of the porous tube during heat-pipe assembly and the outer container was rolled in near each end of the system, without opening the heat pipe.

The heat pipe with its annulus closed was returned to the calorimeter, and startup was accomplished without difficulty although sonic vapor limitations were encountered. A sonic

limiting curve for the system is shown by the dashed line in Fig. 2. The results of a typical startup test are plotted to show how the evaporator exit temperature follows the limiting curve until hot vapor reaches the end of the condenser. Although this took place at an exit temperature of $\sim 560^{\circ}\text{C}$, it can occur at other temperatures, depending on the length and the environment of the condenser.

Steady-state operating conditions were investigated with the system at a heat input rate of 6.4 kW, the maximum that could be delivered with the 14-cm long induction coil. Temperature measurements were made at several axial locations to determine variations in the static vapor pressure for different vapor flow conditions. Four of these conditions are represented in Fig. 3. Curve A shows a condition in which the vapor velocity is subsonic everywhere in the system. The velocity is zero at the beginning of the evaporator (Point 1). In the evaporator, mass is added and the vapor is accelerated until it reaches a maximum value at the evaporator exit (Point 2). When the vapor enters the condenser (Point 3), mass is extracted and the vapor is decelerated. The deceleration results in recovery of static pressure (Points 3-8). Whenever the vapor velocity is subsonic in the entire system, changes in the condenser pressure are transmitted to the evaporator so that its pressure also changes. Curve-B shows a condition where the vapor velocity is sonic at the evaporator exit and subsonic elsewhere.

The power input to the evaporator is the same for Curves A and B, but the condenser cooling environment is different. When the pressure in the condenser is decreased further, the evaporator pressure conditions remain constant. This is shown in Curves C and D. It is also seen that the vapor velocity does not immediately decelerate when mass is extracted. Instead, the velocity increases in a portion of the condenser (Points 3-4), followed by a more abrupt pressure recovery (Points 4-5).

Tests at higher heat inputs were conducted with the Na heat pipe by using a 40-cm long induction coil. The length of the pipe in the

High-Temperature Heat Pipe

Indium as Working Fluid

An evaluation has been completed of a Re heat pipe with W screen and In fluid. This pipe was fabricated from Re sheet, rolled, and seam welded. The cost of Re screen was so great that it was decided to make the wick structure from 100-mesh W screen. The heat pipe was operated at 1950°C, and the test was terminated for evaluation after 1000 h.

The external appearance of the heat pipe after the test was good. Upon disassembly it was found that almost complete mass transport of the W wick structure and the W-Re reaction layer had occurred in the condenser section, as well as thinning-down of the Re wall (Fig. 5a). Metallographic analysis revealed an extensive buildup of Re in the evaporator section of the pipe (Fig. 5b). In addition, electron microprobe examinations showed the presence of a reaction layer on the inner surface of the heat pipe (Figs. 5b and 6a). This layer contained two phases, a metallic Re-W phase which is difficult to differentiate optically from the Re metal, and a darker In-containing phase. Indium was not detected in the Re metal or in the Re-W phase, and Re and W were not detected in the In phase. Diffusion of W into the Re past the reaction layer was not observed.

The results of the test show that interdiffusion of Re and W did take place at 1950°C after 1000 h of operation and that In was able to penetrate this interdiffusion layer (Fig. 6b). The detection limits for In in Re and W and for Re in In are estimated to range between 0.1 and 1%. Because of the observed mass transport, it is concluded that Re and W are soluble in In at a rate below the measurable range. The interdiffusion of W and Re is a contributing factor for this mass transport.

Silver as Working Fluid

A Re pipe, also with a W screen and with Ag as the working fluid, was tested for 373 h at

Fig. 4. Comparison of sonic limits in Na and K heat pipes.

calorimeter was 90 cm. In one of these tests, the evaporator overheated at an exit temperature of 740°C and at a heat-transfer rate of 9.3 kW. In another test, overheating occurred at an exit temperature of 800°C and at a heat-transfer rate of 9.3 kW. In another test, overheating occurred at an exit temperature of 800°C and at a heat-transfer rate of 12 kW. Both of these limitations may have been due to the fact that the available capillary force was not strong enough to balance the pressure losses in the liquid and vapor phases. Since the liquid cannot be separated from the wick by gravity only, the heat pipe will be rotated in future experiments to measure the centrifugal force required for such separation.

The K heat pipe performed better at lower operating temperatures than the one with Na (Fig. 4). This advantage is ascribed exclusively to the higher vapor pressure of K. It is expected, however, that capillary force and liquid-flow limitations will be encountered at heat-input rates below those obtained with Na. If this is so, these limitations can be overcome by providing a tube with finer pores, or by the use of a slightly wider annulus.

Fig. 5a. **Condenser** section of Re heat pipe ($\sim 37\times$).

Fig. 5b. **Evaporator** section of heat pipe ($\sim 56\times$).

Fig. 5c. Section of heat pipe showing voids in Re wall ($\sim 75\times$).

Area Examined

Fig. 6a. Photomicrograph of reaction layer at inner surface of Re heat pipe ($\sim 160\times$).

Fig. 6b. X-ray intensity distribution of Re in examined area ($\sim 560\times$).

Fig. 6c. X-ray intensity distribution of W in same area ($\sim 560\times$).

Fig. 6d. X-ray intensity distribution of In in same area ($\sim 560\times$).

Fig. 7. Intensities of Re, W, and C x-rays near inner surface of Re heat pipe.

2000°C. The test was terminated due to a leak near the seam-weld area in the condenser section. Metallographic evaluation in the immediate vicinity of the leak did not disclose the reason for the failure. But, microscopic examination of the Re wall in both the In and Ag pipes showed widely dispersed voids or inclusions in the metal. Some of these voids are seen clearly in Figs. 5c and 6c. These voids were probably introduced during fabrication of the Re sheet and are suspected to be the cause of failure of this heat pipe.

Electron-microprobe examination again disclosed that an interdiffusion between W and Re had occurred on the inner surface of the heat pipe (Fig. 7). The W content was particularly high for 10-12 μ at the extreme inner surface. Carbon was also detected, possibly introduced into the pipe by either the inclusions open to the inside of the pipe or by hydrocarbon vapor during vacuum assembly of the heat pipe. All of the Ag had evaporated when the leak occurred, and none was therefore detected during examination.

To determine the true compatibility of Re with In and Ag, the W must be eliminated entirely from the heat pipes. A pseudo-wick structure is being prepared to replace the W screen in the next evaluation.

Total Hemispherical Emissivity Measurements by the Heat-Pipe Method

The heat pipe appears to offer a distinct possibility for determining the total hemispherical emissivities of surfaces. If a heat source is located inside a heat pipe, the heat input to the system is accurately known. All of the heat input must be radiated from the external surface of the heat pipe, and if the surface is isothermal, the total emissivity can be determined. The heat pipe, with its two-phase fluid flow, has this ability to maintain isothermal conditions over large areas and provides a simple, accurate method for emissivity measurements. By using various heat-pipe containers and by plating or spraying the containers with different materials, the emissivities of numerous materials can be established. The total emissivities of several different surfaces have been determined over a wide temperature range using a variety of heat-pipe sizes and operating fluids. The results indicate that accurate, absolute measurements can be made by this method.

Phenyl Ether Life Test

A $1\frac{1}{4}$ -in. o.d. by 12-in. long stainless-steel heat pipe, containing phenyl ether as the working fluid, has been operated at 300°C for 3200 h to determine the stability of phenyl ether at this temperature. At the end of the period, a slight difference in operating characteristics was noted as indicated by the temperature distribution along the length of the pipe. The temperature at the condenser end of the pipe dropped about 4°C, indicating the possible presence of some noncondensable gas. The test was terminated at this point and the heat pipe is now being examined by neutron radiography.

Publications

- "Small Out-of-Pile Thermionic Converter," LA-3813.
- "Total Hemispherical Emissivity Measurements by the Heat Pipe Method," LA-3881-MS.
- "Look at Nuclear Thermionic Systems," Astronaut. Aeron., 6, NC. 1, 50 (1968).

THERMIONIC POWER SYSTEMS

The results obtained in the work on Thermionic Power Systems are classified and are described in the Space Electric Power Report, Part II, LA-3942-MS (Confidential).