CONF-740705--1

Performance Tests of Gravity-Assist Heat Pipes
with Screen-Wick Structures*

by

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Submitted for Presentation at the
AIAA/ASME Thermophysics and Heat Transfer Conference
Boston, Massachusetts
July 15-17, 1974

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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Introduction

Because most heat-pipe research to date has been directed towards space applications, the force of gravity has been regarded primarily as a difficulty to be overcome in the testing of heat pipes for gravity-free operation. However, there are a number of real and potential terrestrial applications where gravity can be used to enhance the return of liquid from the condenser to the evaporator section of a heat pipe and, under the right operating conditions, to increase the heat-transfer capability of the device. Little is known about the subject of gravity-assist heat pipe operation other than that it is a considerably more complex phenomenon than generally supposed. This paper describes the initial part of an investigation that is directed generally towards understanding this phenomenon and specifically toward determining optimum designs and ultimate heat-transfer limits for the gravity-assist mode.

An immediate application of the gravity-assist heat pipe involves its use as a temperature controller for irradiation experiments in the Experimental Breeder Reactor (EBR-II).¹ For this reason initial tests have been done with sodium working fluid, and heat-pipe dimensions and operating regimes suitable for this type of application. Wick designs have been kept relatively simple in an attempt to gain knowledge from more readily diagnosable configurations before moving to more exotic designs with higher potential performance.

Test Structures and Apparatus

A wick consisting of layers of woven-wire screen is often termed a homogeneous wick because it is assumed to have uniform porosity. This assumption was made to calculate performance limits for a reference-design heat pipe, 22 mm o.d. by 540 mm long with a wick consisting of six layers of 100-mesh screen. It was further assumed that the pressure drop through this wick structure was twice as great as that through a wick with pores forming a number of straight axial tubes. Experience has shown that these assumptions are fairly realistic for wicks made from individual layers of screen just contacting each other. It has also been found that heat-transfer limits are lower than calculated when the screens are compressed, whereas higher limits are obtained with loose screen layers.

In an effort to achieve higher heat-transfer limits than those calculated, four prototype heat pipes with slightly different wick structures were tested. A list of the heat pipes and a description of the wick structures are given in Table I. The general test arrangement and apparatus are shown in Fig. 1.

Heat-pipe fabrication features and test results are described in the following sections.

TABLE I. HEAT PIPE TEST STRUCTURES

<u>Heat Pipe No.</u>	<u>Screen Structure</u>	<u>Wick Type</u>
XG1	6 layers 100 mesh	Individual layers
XG2	6 layers 100 mesh	Spiral-wrapped
	2 layers 250 mesh	
XG3	6 layers 100 mesh	Spiral-wrapped (Expanded)
	2 layers 250 mesh	
XG4	5 layers 100 mesh	Spiral-wrapped
	2 layers 250 mesh	

Gravity-Assist Test - Heat Pipe XG1

The two basic types of wick structures that have been tested to date are shown schematically in Fig. 2. Although spiral-wrapped layers are more easily fabricated, individual layers were used in Heat Pipe XG1 because this fabrication method closely approximates the conditions assumed in the heat-transfer calculations. The layers were arranged on a mandrel and spot-welded at several points to fix their position. This screen assembly was placed in an oversized container tube, the diameter of which was then reduced so that the container wall contacted the outer screen layer. The mandrel size was selected so as to achieve a final configuration of loosely packed screen layers, with the inter-layer regions serving as channels of relatively low impedance for the return flow of the liquid.

After sodium addition, heat-transfer limits were obtained for Pipe XG1 as a function of the temperature at the evaporator end of the system. The limits obtained for horizontal and vertical (gravity-assist) operation are compared with the reference-design calculations in Fig. 3. The reference-design curves were computed for the homogeneous wick of uniform pore distribution described earlier. As expected, the reduction of return-flow impedance by the interlayer channels of XG1 resulted in performance limits greater than calculated for both horizontal and vertical operation at most operating temperatures.

After the test, the horizontal data point at 1023 K was used to determine the actual flow characteristics of the wick. (Above 1000 K the vapor density of sodium is sufficiently high that the vapor pressure drop is negligible compared to the liquid pressure drop for this pipe design.) Calculated curves based on these characteristics are shown as finely dashed lines in Fig. 3 for horizontal and vertical operation.

Because the wicking height of sodium in 100-mesh screen is ~ 500 mm, only enough sodium was added to XG1 to fill this length of wick in the temperature range of 950 to 1000 K. The creation of a pool of sodium at the bottom of the heat pipe during vertical operation was thus avoided, but, because of the relatively high volume-expansion coefficient of sodium, this meant the wick was not completely full at lower temperatures. The lower horizontal limits shown in Fig. 3 at temperatures below 950 K probably resulted from the partially filled wick.

Although vertical limits appeared unaffected by liquid deficiency at lower operating temperatures, a few small hot spots were observed in the heated section. Because it is well known that liquid will fill small pores in a wick at the expense of larger pores, it was assumed that the hot spots were caused by vapor forming in the relatively large dimpled pockets produced by the spot-welding process. Further evidence of vapor pockets was obtained at higher operating temperatures where the hot spots grew suddenly whenever a heat-transfer limit was reached.

When the heat-transfer capability of a heat pipe is limited by formation of vapor bubbles in the wick structure, performance will substantially decrease with increasing temperature.² Ordinarily, this boiling or superheat limitation is initiated by vapor-bubble nucleation at a site between the heat-pipe wall and the wick that is not completely filled with liquid. Because alkali metals generally fill all potential nucleation sites, superheat limits are seldom encountered with these fluids. However, as shown in Fig. 3, vertical tests of XG1 at temperatures above 1020 K indicated that superheat limits can occur in heat pipes if portions of the wick in the heated section are not completely filled with liquid.

Gravity-Assist Test - Heat Pipe XG2

The wick for Heat Pipe XG2 was fabricated by spiral-wrapping a single piece of 100-mesh screen around a mandrel of the same size used for XG1. The width of the screen was adjusted so that six layers were obtained. Because

this type of fabrication forms a step at the heat-pipe wall (See Fig. 2) a piece of 250-mesh screen was wrapped over the 100-mesh screen in an attempt to fill the void created by the step, and thus to prevent the superheat limits encountered earlier. This screen structure was placed in an oversized container the diameter of which was then reduced as described for XG1.

Although this structure should have been compressed more than the wick in XG1, it was found to be tightly compressed only on one side of the pipe. On the other side the layers were quite loose, and distinct channels were seen between some layers.

The results of heat-transfer limit tests with this eccentric wick are compared with reference-design calculations in Fig. 4. The high limits achieved during horizontal operation reflect the low flow impedance provided by the spaces between layers. As with XG1, a high temperature data point (1050 K) was used to determine the actual flow characteristics of the wick. Calculated curves based on these flow characteristics are shown as dashed lines in Fig. 4. The curve for the horizontal test limits fits the experimental data very well over the entire test-temperature range because this heat pipe contained sufficient liquid to fill the wick at all operating temperatures.

As indicated in Fig. 4, vertical test limits were always lower than calculated. Because it was suspected that the channel spaces may not have remained filled during vertical operation, a series of heat-transfer-limit tests were made at different heat-pipe inclination angles. During these tests the heat-pipe temperature was maintained at 1020 K, and the channels were positioned so that they extended along the bottom portion of the pipe when it was in the horizontal position. The results of these tests are presented in Fig. 5. The linear increase in performance with gravity head as the heat-pipe angle was varied from $+30^\circ$ with the evaporator up, to -30° with the evaporator down, indicates that the channels remained filled with liquid in this range. The leveling-off performance for tilt angles below -30° suggests that the channels began to empty as the gravity head was further increased.

One additional test was made at -30° with the channels positioned along the top portion of the heat pipe. In this position the gravitational force and differential capillary forces on the liquid both tend to remove liquid circumferentially from the channels to the finer pore structure at the bottom of the pipe and the performance of the pipe is substantially reduced, as shown by the open-circle data point in Fig. 5.

Gravity-Assist Test - Heat Pipe XG3

Heat Pipe XG3 contained the same amount of screen as XG2, but the fabrication procedure was different. The container tube was first drawn to its final size over a mandrel covered with two spiral-wrapped layers of 250-mesh screen. This procedure produced a container tube lined internally with very tightly compressed screen. Six layers of 100-mesh screen were then spiral-wrapped around a copper tube whose outer diameter was somewhat smaller than the diameter of the mandrels used for the earlier heat pipes. A series of tapered plugs were then drawn through the copper tube to expand the screen against the container structure.

Below 1000 K the performance limits of this pipe in horizontal operation were somewhat higher than for XG2, probably because of the relatively large channel formed by the step near the heat-pipe wall (refer to Fig. 2). Above this temperature performance fell off with increasing temperature. This loss of heat-transfer capability was even more pronounced for vertical operation, as shown in Fig. 6, in which the performance limits of XG3 and XG1 are compared. Note the expanded heat-transfer-rate scale. The initial dip and subsequent recovery of performance for XG3 is not understood, but the decrease of performance of both XG1 and XG3 above 1020 K follows the behavior predicted for superheat limitations resulting from vapor formation in voids in the wick structure. This phenomenon is particularly critical when the void exists between the wick and the heat-pipe wall (through which the heat enters the evaporator). Once a vapor pocket forms adjacent to the heat-pipe wall, the only means by which working fluid can reach the wall at this location (to cool it by evaporation) is by film flow across the wall surface. However, this film flow does not occur at a sufficient rate to provide the necessary cooling, and the portion of the wall in contact with the vapor pocket heats up. The use of two layers of fine screen immediately adjacent to, and in very close contact with, the heat-pipe wall in XG3 (and other experimental pipes) was designed to eliminate this effect by providing sufficient capillary pumping action at the wall surface to keep it cool despite the presence of oversize voids in the main wick. It is suspected that in the case of XG3 the fine screen layers were overcompressed in the drawing process (in an attempt to ensure that no gaps existed between these layers and the heat-pipe wall) so that the porosity remaining in the fine screen liner was insufficient to provide the requisite pumping action. Hence, superheating hot spots formed at the step between the fine screen layers and the spirally-wound main wick.

Gravity-Assist Tests - Heat Pipe XG4

Identical fabrication procedures were used for XG2 and XG4, but the wick in XG4 consisted of five layers of 100-mesh screen instead of six. Figure 7 shows that vertical heat-transfer-limit curves are similar for each pipe, but Pipe XG4 with its larger vapor passage performed better at most operating temperatures despite its smaller wick. This behavior suggests that an interaction between high-velocity vapor and returning liquid was decreasing the performance of each pipe. The decrease was greater with XG2 because the vapor velocity was greater as a result of its smaller vapor passage.

A more obvious example of interaction between vapor and liquid is indicated in Fig. 8. This figure shows the vertical and horizontal limits obtained with XG4. This heat pipe contained a slight excess of working fluid, which formed a puddle along the bottom of the pipe during horizontal operation at temperatures above 1020 K. Because the puddle provided an additional flow path for liquid return, heat-transfer limits were somewhat higher at these temperatures. At lower temperatures the vapor velocity was sufficient to move the puddle toward the condenser end of the pipe, thus reducing its effectiveness.

Additional heat-transfer-limit tests were made with XG4 to verify the effect of puddle position on heat-pipe performance. In these tests, the heat-pipe temperature was maintained at 1020 K and pipe inclination was varied so that the puddle position was affected by gravity instead of by vapor velocity. The results of these tests are shown in Fig. 9. The step in performance which occurs close to 0° tilt angle as the evaporator is being lowered represents the contribution of puddle flow. (When the evaporator is above horizontal the excess liquid remains in the condenser.)

Conclusions

The foregoing tests with sodium heat pipes operating in the gravity-assist mode show that superheat limitations are a major factor to be overcome in wick design and wick fabrication methods. Oversize voids adjacent to the heat-pipe wall tend to become the loci of vapor pockets which block heat transfer through the wick and seriously reduce performance, particularly at relatively high working-fluid vapor pressures. In general, wick imperfections, which may be inconsequential or even beneficial under gravity-neutral operating conditions, are likely to have a performance-limiting effect for gravity-assist operation.

Some of the tests also indicate that the performance of gravity-assist heat pipes may be limited by interactions between vapor and liquid. Tests are now being conducted with helical baffles which should provide protected flow paths of low impedance for the returning liquid.

References

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2. T. P. Cotter, "Heat Pipe Startup Dynamics," Proc. IEEE Thermionic Conversion Specialist Conference, Palo Alto, Calif. (1967).

Fig. 1. Gravity Assist Test Arrangement

Fig. 2. Different heat pipe screen wicks.

Fig. 3. Comparison of experimental and calculated performance of XGI.

Fig. 4. Comparison of experimental and calculated performance of XG2.

Fig. 5. Effects of heat pipe inclination angle and channel position on XG2 test limits.

Fig. 6. Comparison of XG1 and XG3 vertical test results.

Fig. 7. Comparison of XG2 and XG4 vertical test results.

Fig. 8. XG4 test results compared with calculations based on wick flow characteristics.

Fig. 9. Effects of heat pipe inclination angle and puddle flow on XG4 test limits.