Performance Characteristics of Gravity-Assisted Potassium Heat Pipes

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Experiments with potassium-stainless steel gravity-assisted heat pipes were performed. Performance limitations due to entrainment or flooding of the liquid return flow are compared with analytical model predictions. The effect of heated pool height was investigated, and problems with surface wetting are discussed. A comparison between entrainment limits for smooth- and textured-walled heat pipes was made, and a minimum internal surface texturing depth is suggested.

Nomenclature

A_v = vapor flow area
E_t = entrainment parameter
g = gravitational acceleration
h_{fg} = latent heat of vaporization
Q_E = dimensionless power
δ = surface texturing depth
δ^* = reference surface texturing depth
λ = characteristic wavelength
ρ_g = vapor density
ρ_f = liquid density
σ = surface tension

Introduction

TERRESTRIAL applications of nuclear power supplies require reactor operating temperatures of 500-600°C. The higher limit corresponds to systems with thermoelectric power converters, whereas the lower limit corresponds to organic Rankine cycle converters. Heat transfer from the reactor or heat source to the power converter can be accomplished using vertical gravity-assisted heat pipes. Typical lengths are 2-4 m with 1.3-m heated zones. The heat pipe's outside diameters range from 3.8 to 6.0 cm. Tubing can be either stainless steel or zirconium-niobium alloy. Because of the operating temperature and the adverse radiation environment, potassium is the most suitable working fluid.

Heat-pipe startup characteristics are of interest because the heat-pipe liquid inventory that forms a pool in the bottom of the evaporator section is located outside the heated zone. Location of the pool outside the heated zone is required to prevent slugging of the working fluid that may occur during startup. In this case, slugging refers to a nonstationary state of the working fluid where slugs of liquid, with a characteristic dimension equal to the heat-pipe diameter, are periodically ejected from the pool, traverse some distance toward the condenser, and disappear into the liquid film along the heat-pipe wall. The ejected liquid returns to the pool via the film and the process can be repeated. The slugging is usually caused by flash vaporization of the working fluid within the pool, and is frequently observed with liquid metals. The relatively large neutron absorption cross section of potassium may induce neutronic instabilities in the reactor if slugging of the working fluid occurs.

Previous experimental investigations[1,2] at Los Alamos National Laboratory using potassium in gravity-assisted heat pipes have concentrated on complex internal liquid flow passages. These passages have included graded screen wicks and spiral flow channels or gutters. Test results have indicated axial heat-flux limits due to entrainment of 1.0 kW/cm². This paper reports on the efforts to develop gravity-assisted potassium heat pipes with simplified wick structures formed by knurling that are also capable of attaining axial heat fluxes of 1.0kW/cm².

Theory of Gravity-Assisted Heat-Pipe Operation

The basis for the performance goal of 1.0kW/cm² is derived from an analytical model[3] of gravity-assisted heat-pipe performance based on experimental data.[4] The analytical model is based on the principle of providing a protected liquid return path for the liquid condensate. "Protected" in this sense refers to inhibiting the tendency of the counterflowing vapor to interact with the liquid film located on the wall of the heat pipe, and thus impede its return to the evaporator region. This interaction, if severe enough, results in liquid entrainment by the vapor or flooding in the heat pipe condenser. In effect, this prevents the liquid from returning to the evaporator, thus interrupting the circulation of the working fluid. The evaporator then dries out, and the power transport within the heat pipe stops. This condition defines a heat-pipe performance limit.

Mechanical roughening of the heat pipe's inner wall has been shown to be very effective in inhibiting the liquid-vapor interaction. Knurling to depths of 0.2-0.5 mm has been employed on the inner heat-pipe wall to create the desired effect. The mechanical process is relatively simple, and the depth of cut can be conveniently varied. The analytical model relates the heat-pipe entrainment limit to the depth of the surface roughness. In particular, it has been found that the entrainment limit is proportional to the square root of the knurl depth as follows:

$$Q_e = \sqrt{2\pi} E_t^{1/2} (\delta/\delta^*) \tag{1}$$

where Q_e and E_t are dimensionless correlating parameters defined by

$$Q_e = \frac{q/A_v}{\rho_g h^{1.5}{}_{fg}} \tag{2}$$

and

$$E_t = \frac{\sigma}{\rho_g h_{fg} \delta} \tag{3}$$

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The depth of surface texturing is given by δ, and δ^* is a reference depth with a value of 0.074 cm. Using Eq. (1) with Eqs. (2) and (3), the maximum axial heat flux is given by

$$\frac{q}{A_v} = \frac{\sqrt{2\pi}}{\delta^*} h_{fg} (\sigma \rho_g \delta)^{1/2} \tag{4}$$

This equation has been verified experimentally[4] using sodium, mercury, water, acetone, and toluene as heat-pipe working fluids. Recently, additional experiments have been conducted at Los Alamos National Laboratory using potassium as a heat-pipe working fluid. The following section discusses these experiments.

Potassium Heat-Pipe Experiments

Experiments have been carried out on three heat pipes with knurled internal walls. A summary of the dimensions of each heat pipe is given in Table 1. The heat pipes are designated NWS-1, NWS-2, and NWS-5. All of the heat pipes were heated with induction coils and cooled with a water-jacketed calorimeter. Heat-pipe temperature was controlled with a gas-filled gap between the heat-pipe condenser and calorimeter. A controlled mixture of helium and argon gas was maintained in the gap to provide a variable thermal conductance between the heat pipe and the heat sink. The power carried by the heat pipe was determined from the flow rate and temperature rise of the cooling water in the calorimeter. The NWS-1 and -2 heat pipes have similar external dimensions and are shown schematically in Fig. 1. Thermocouples were attached to the heat-pipe wall as shown in Fig. 1. The NWS-5 heat pipe shown in Fig. 2 has a much shorter condenser for the purpose of creating a larger radial Reynolds number, Re_r, in the condenser. Values of Re_r as large as 100 are expected in the heat-pipe condenser if an organic Rankine cycle vaporizer is used. However, condenser radial heat fluxes are lower if thermoelectric converters are used; this condition is represented by the NWS-1 and -2 heat pipes. The NWS-1 and -2 heat pipes differ internally from each other by having 0.05 and 0.028 knurl depths, respectively.

Heat pipes NWS-1 and -2 were filled by liquid transfer of the working fluid, i.e., liquid potassium was transferred by gas pressurization from the potassium cask to a fixed-volume fillpot and then to the heat pipe. By contrast, the NWS-5 heat pipe was filled by distillation. Evidence of poor wetting characteristics that resulted in degraded performance was observed in both the NWS-1 and -2 heat pipes. The NWS-5 heat pipe, which was filled by distillation, exhibited better per-

Table 1 Heat-pipe dimensions

Heat pipe	Evaporator length, cm	Condenser length, cm	Outside diameter, cm	Knurl depth, cm
NWS-1	60	60	3.8	0.051
NWS-2	60	60	3.8	0.028
NWS-5	36	20	2.5	0.020

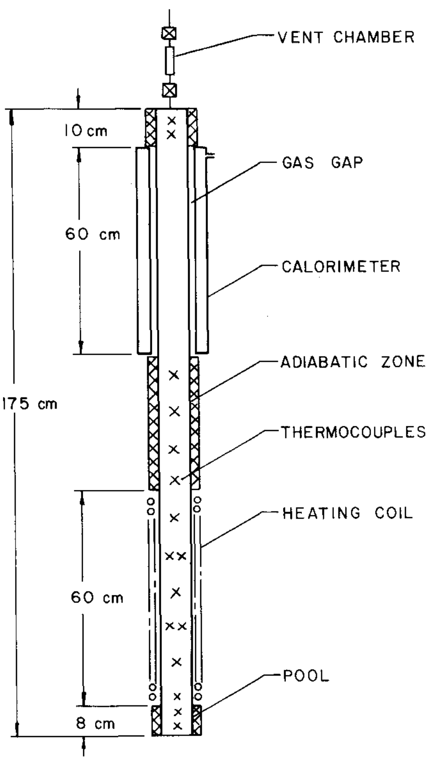

Fig. 1. Potassium heat-pipe test schematic (NWS-1 and NWS-2).

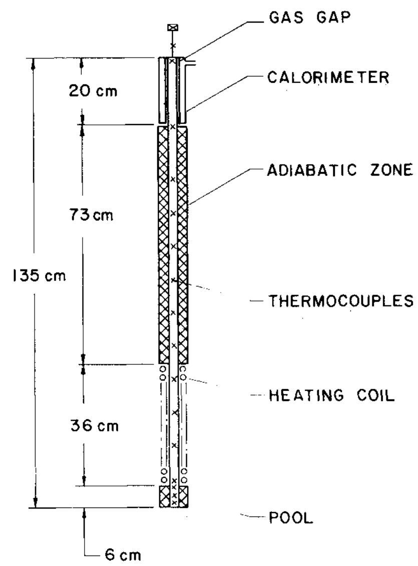

Fig. 2 Potassium heat-pipe test schematic (NWS-5).

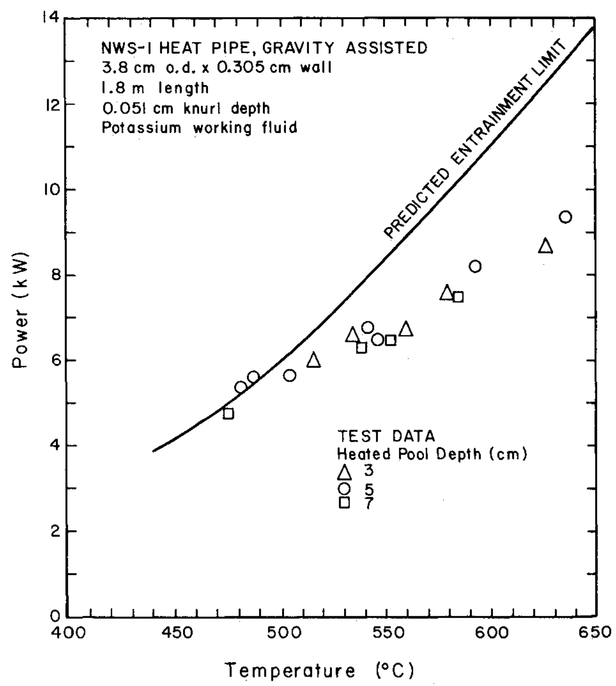

Fig. 3 NWS-1 heat-pipe test data.

formance and closely matched the predictions of the entrainment model given by Eq. (4). The effect of incomplete wetting on the heat-pipe performance is evident in the following discussion of results.

Failure of the NWS-1 and -2 heat pipes to achieve their predicted performance is believed to be caused by incomplete wetting due to impurities present in the potassium working fluid. Distillation of potassium into the heat pipe, as was done with the NWS-5 heat pipe, provided much better wetting and performance results, consistent with the analytical model.

Satisfactory startup behavior was observed with all three heat pipes. A heated pool depth of 5 cm appears to be optimum for these heat pipes. Some slugging in the NWS-5 heat pipe was observed at a heated pool depth of 8 cm. The better wetting characteristics of the NWS-5 heat pipe apparently result in higher superheats.

Limits on the Surface Texturing

The entrainment limit correlation[3] for a smooth-walled tube is given by

$$Q_e = \sqrt{2\pi} E_{t_\lambda}^{1/2} \tag{5}$$

where the characteristic length in the entrainment parameter is defined as

$$\lambda = \left[\frac{\sigma}{(\rho_f - \rho_g)g}\right]^{1/2} \tag{6}$$

Comparing Eqs. (1) and (5) will give a relationship between λ and δ that defines a minimum depth for the surface texturing on the inside wall of the heat pipe, or

$$\delta_m = \delta^{*2}\left[\frac{(\rho_f - \rho_g)g}{\sigma}\right]^{1/2} \tag{7}$$

but δ^* is a constant; therefore, δ_m is only a function of the properties of the working fluid. Equation (7) is plotted as a function of temperature for several heat-pipe working fluids in Fig. 7. For a given operating temperature and working fluid, Fig. 7 gives the minimum depth of surface texturing required for an improvement in heat-pipe performance over the corresponding smooth-walled case. For potassium at 500°C, the minimum depth is 0.016 cm. Equation (7) suggests that there is a minimum depth of internal surface roughness below which a smooth internal surface may be better. Whether or not the textured surface yields lower entrainment limits than the smooth surface for values of $\delta < \delta_m$ has not been experimentally verified. In general, there are severe constraints on the orientation of smooth-walled heat pipes. These heat pipes are restricted to operation near vertical orientation.

Experimental Results

The performance limits for all three heat pipes were obtained using the same method. The applied heat load was increased in small increments until hot spots appeared in the evaporator wall indicating a local dryout condition. These hot spots, which were located near the center of the heated zone, were evident both visually and by thermocouple measurement. In most instances, just prior to the development of a hot spot in the evaporator, the working fluid pool level suddenly decreased, indicating a significant drain of liquid from the pool. This was interpreted as liquid holdup in the condenser. As a further indication of flooding, the hot spots were quenched from above when the input power was decreased after the dryout occurred. It would appear that the held-up liquid was then able to return to the evaporator, quenching the hot spot in transit. Since a dryout of the heat-pipe evaporator results in a visible hot spot, the progress of the liquid film due to its quenching effect can be conveniently observed.

Figure 3 shows the performance limits of NWS-1 as a function of evaporator exit temperature. The data are for three different heated pool depths. Heated pool depth corresponds to the distance that the evaporator heating coil extends into the liquid pool from above. If the coil does not extend into the pool, the heat pipe will be difficult to start. If the heated pool depth is too large, slugging of the working fluid may occur during startup. The slugging occurs due to the liquid metal's ability to support a large superheat. No slugging was evidenced with either the NWS-1 or -2 heat pipes. The depth of the heated pool has some influence on the limiting heat-pipe performance, as shown in Fig. 3. Note that the performance data for the NWS-1 heat pipe falls substantially below the predicted values.

Results from the NWS-2 heat pipe are shown in Fig. 4. This heat pipe has a shallower knurl but only a slightly lower performance than the NWS-1 heat pipe. Both heat pipes

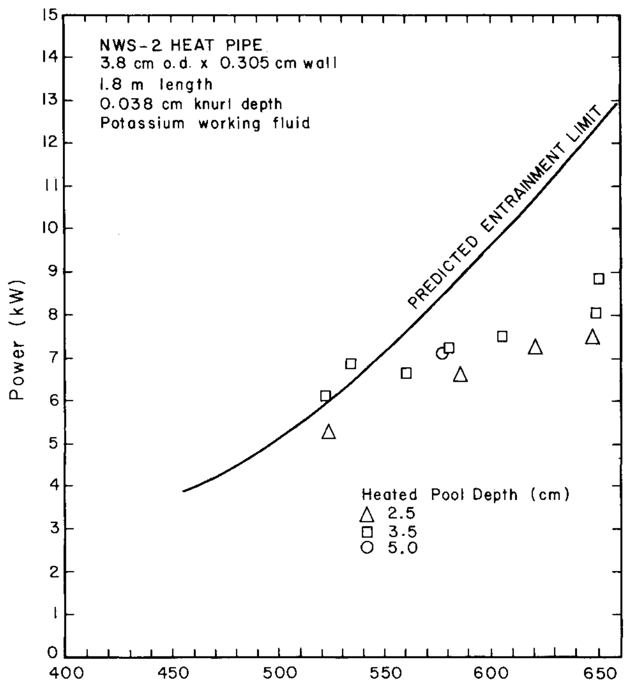

Fig. 4 NWS-2 heat-pipe test data.

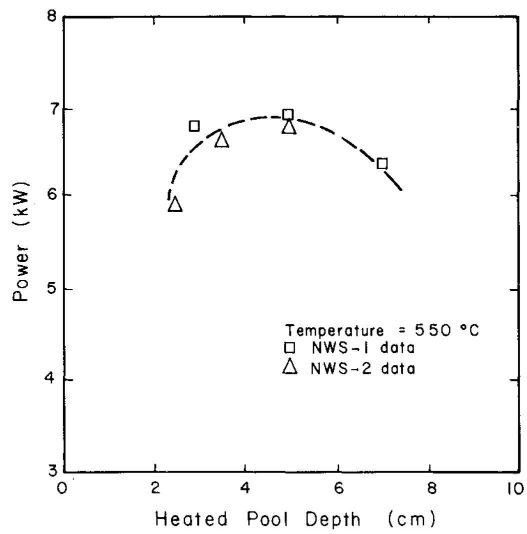

Fig. 5 Influence of pool depth on heat-pipe performance.

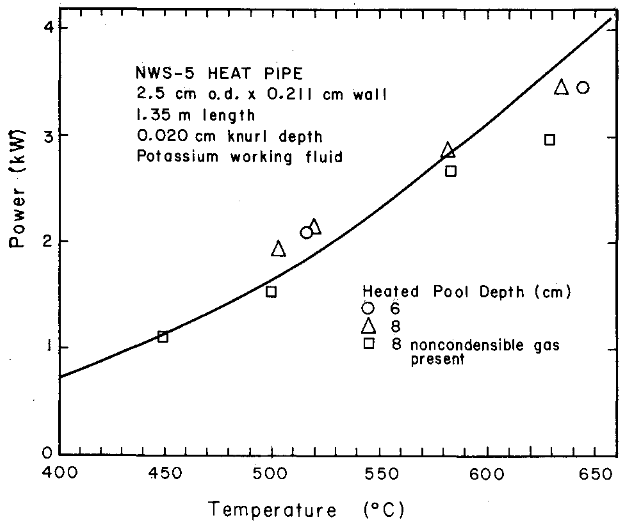

Fig. 6 NWS-5 heat-pipe test data.

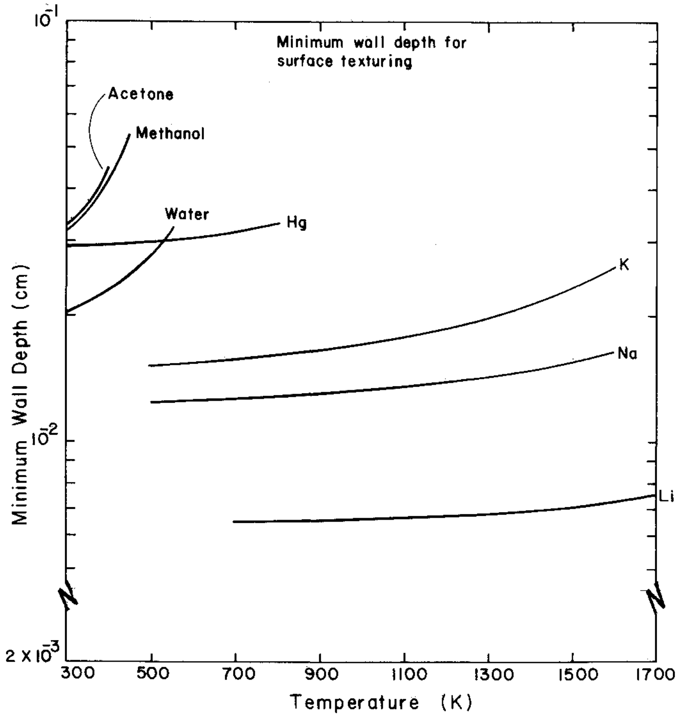

Fig. 7 Minimum wall depth of surface texturing for various working fluids.

demonstrated performance limits below the entrainment model predictions. Figure 5 combines results from both the NWS-1 and -2 heat pipes to show the influence of heated pool depth on heat-pipe performance. A heated pool depth of 5 cm is nearly optimum for a heat pipe of this diameter.

Figure 6 shows the results of the NWS-5 heat pipe, which was the smallest of the heat pipes tested. The knurl depth was also the shallowest at 0.020 cm. This heat pipe was filled by distillation, and the measured performance limits agree well with the entrainment model prediction. The heated pool depth in this heat pipe was varied between 6 and 8 cm, with little effect on performance. Initially some noncondensible gas was present in the heat pipe, which appears to have a degrading effect on the measured performance. The origin of the noncondensible gas is unknown. Also, some slugging was evident during startup at the larger heated pool depths.

Conclusions

Results of this investigation indicate that impurities in the potassium working fluid have a detrimental effect on the entrainment or flooding limit in gravity-assisted heat pipes. This is based in large part on the good agreement between the test data and the entrainment model for heat pipe NWS-5, which appeared to be free of contamination. However, the authors are not convinced that this is the only explanation for the discrepancy between the potassium heat-pipe test data and the entrainment model. Since Deverall and Keddy[1] have experienced anomalous behavior with potassium heat pipes in the past, it remains to be determined if another mechanism for a performance limitation is present. Such a limit could be dependent on the liquid flow characteristics and suggests an extension of the existing theory[3] to include this possibility. The use of potassium as a heat-pipe working fluid could create unique operating conditions not previously encountered with this type of heat pipe.

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