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PERFORMANCE CHARACTERISTICS OF GRAVITY-ASSISTED, POTASSIUM HEAT PIPES

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Abstract

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-walled 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 to 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 to 4 m with 1.3-m heated zones. The heat pipe 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. 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 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 potassium, gravity-assisted heat pipes with simplified wick structures formed by knurling that are also capable of attaining axial heat fluxes of 1.0 kW/cm².

Theory of Gravity-Assisted Heat Pipe Operation

The basis for the performance goal of 1.0 kW/cm² is derived from an analytical model³ of gravity-assisted heat pipe performance that has been 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, which is located on the wall of the heat pipe, and thus impede its return to the evaporator region. This interaction, if severe enough, results in entrainment of the liquid by the vapor or flooding in the heat pipe condenser. Mechanical roughening of the heat pipe inner wall has been shown to be very effective in inhibiting the liquid-vapor interaction. Knurling to depths of 0.2 to 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:

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

where Q_e and E_t are dimensionless correlating parameters defined by

$$Q_e = \frac{q/A_v}{\rho_g h_{fg}^{1.5}} \quad (2)$$

and

$$E_t = \frac{\sigma}{\rho_g h_{fg} \delta} \quad (3)$$

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

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

This equation has been verified experimentally⁴ using sodium, mercury, water, acetone and toluene as heat pipe working fluids. Recently, additional experiments have been conducted at Los Alamos 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 all with knurled internal walls. A summary of the dimensions of each of the heat pipes is given in Table I. 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 flowrate and temperature rise of the cooling water in the calorimeter. The NWS-1 and NWS-2 heat pipes have similar external dimensions and are shown schematically in Fig. 1. Thermocouples were attached to the heat pipe wall and their locations are also shown in Fig. 1. The NWS-5 heat pipe that is shown in Fig. 2 had 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

Table 1. Heat Pipe Dimensions

Heat Pipe	Evaporator Length (cm)	Condenser Length (cm)	Outside Diam (cm)	Knurl Depth (cm)
NWS-1	60	60	3.8	0.051
NWS-2	60	60	3.8	0.038
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).

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 and this condition is represented by the NWS-1 and NWS-2 heat pipes. The NWS-1 and NWS-2 heat pipes differ internally from each other by having 0.05 cm and 0.011 cm knurl depths respectively.

Heat pipes NWS-1 and NWS-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 NWS-2 heat pipes. The NWS-5 heat pipe, which was filled by distillation, exhibited better performance and closely matched the predictions of the entrainment model given by (4). The effect of incomplete wetting on the heat pipe performance is evident in the discussion of results that follows.

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 hold-up 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 heldup liquid was then able to return to the evaporator, quenching the hot spot in transit.

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 doesn't 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 because of the liquid metal's ability to support a larger superheat. No slugging was evidenced with either the NWS-1 or NWS-2 heat pipes. The depth of 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.

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

Results from the NWS-2 heat pipe are shown in Fig. 4. This heat pipe had a shallower knurl but only a slightly lower performance than the NWS-1 heat pipe. Both heat pipes demonstrated performance limits below the entrainment model predictions. Figure 5 combines results from both NWS-1 and NWS-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 this diameter heat pipe.

Figure 6 shows the results for the NWS-5 heat pipe that 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 noncondensable gas was

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

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

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

present in the heat pipe and it appears to have a degrading effect on the measured performance. Also some slugging was evident during startup at the larger heated pool depths.

Failure of the MWS-1 and MWS-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 MWS-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 MWS-5 heat pipe was observed at a heat pool depth of 8 cm. The better wetting characteristics of the MWS-5 heat pipe apparently results in higher superheats.

Limits on the Surface Texturing

The entrainment limit correlation³ for a smooth-walled tube is given by

$$Q_e = \sqrt{2\pi} E_t^{1/2} \lambda \quad (5)$$

where the characteristic length in the entrainment parameter is defined as

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

Comparing (1) with (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

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

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. Generally there are severe constraints on the orientation of smooth-walled heat pipes. These heat pipes are restricted to operation near vertical.

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

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