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CONF-870585--2

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TITLE: PERFORMANCE CORRELATIONS FOR HIGH TEMPERATURE POTASSIUM HEAT PIPES

LA-UR--87-1000

DE87 007456

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SUBMITTED TO: Sixth International Heat Pipe Conference
Grenoble, France
May 25-28, 1987

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PERFORMANCE CORRELATIONS FOR HIGH TEMPERATURE POTASSIUM HEAT PIPES

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ABSTRACT

Potassium heat pipes designed for operation at a nominal temperature of 775K have been developed for use in a heat pipe cooled reactor design. The heat pipes operate in a gravity assist mode with a maximum required power throughput of approximately 16 kW per heat pipe. Based on a series of sub-scale experiments with 2.12 and 3.2 cm diameter heat pipes the prototypic heat pipe diameter was set at 5.7 cm with a simple knurled wall wick used in the interests of mechanical simplicity. The performance levels required for this design had been demonstrated in prior work with gutter assisted wicks and emphasis in the present work was on the attainment of similar performance with a simplified wick structure. The wick structure used in the experiment consisted of a pattern of knurled grooves in the internal wall of the heat pipe. The knurl depth required for the planned heat pipe performance was determined by scaling of wick characteristic data from the sub-scale tests. These tests indicated that the maximum performance limits of the test heat pipes did not follow normal entrainment limit predictions for textured wall gravity assist heat pipes. Test data was therefore scaled to the prototype design based on the assumption that the performance was controlled by an entrainment parameter based on the liquid flow depth in the groove structure. This correlation provided a reasonable fit to the sub-scale test data and was used in scale up of the design from the 8.0 cm² cross section of the largest sub-scale heat pipe to the 25.5 cm² cross section prototype. Correlation of the model predictions with test data from the prototype is discussed.

NOMENCLATURE

- A = Flow area
- D = vapor space diameter
- d = groove depth
- d_E = liquid depth in groove
- E_T = entrainment parameter
- g = gravitational constant
- h_{fg} = latent heat of vaporization
- N = number of grooves in heat pipe circumference
- Q_E = dimensionless heat flow
- Q = heat flow
- ρ = density
- σ = surface tension
- ϕ = helix angle of grooves
- μ = dynamic viscosity

SUBSCRIPTS

- ℓ = liquid
- g = vapor

INTRODUCTION

Over the past several years a development program has been conducted at Los Alamos National Laboratory on a compact nuclear power source (CNPS) intended for use in remote, inaccessible locations where fossile fuel supplies are difficult to obtain and maintenance costs are high. As a result of these requirements the CNPS system design emphasizes simplicity and passive operation. The basic system configuration, shown in Fig. 1 incorporates a graphite moderated reactor coupled to an organic Rankine cycle conversion system through the use of heat pipes. The heat pipe coupling provides a passive means of heat transfer from the reactor core to the organic Rankine boiler. Routing of the organic Rankine loop directly through the reactor

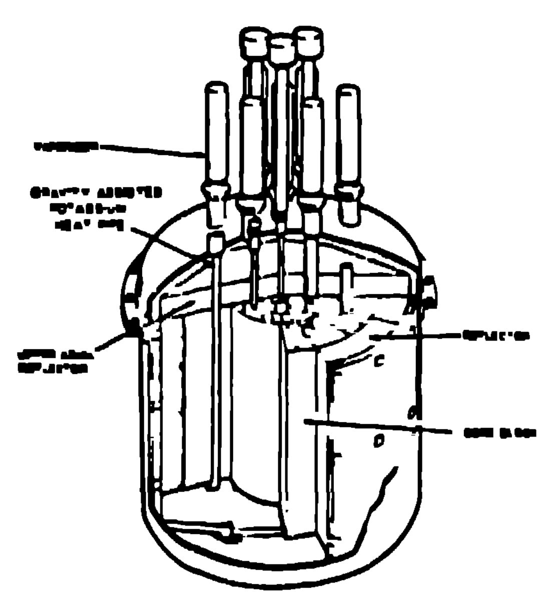

Fig. 1 CNPS reactor showing heat pipes used for transfer of heat to toluene boilers

core is not possible because of radiolytic decomposition problems with the toluene used as a working fluid in the ORC. The toluene working fluid also determines the operating temperature of the system through the limits established by thermal decomposition of the working fluid. The upper temperature limit for long term operation of the toluene in the cycle is 645 K. With allowance for temperature drops through the heat pipe condenser section and toluene boiler walls, the corresponding operating temperature of the heat pipes is 775 K. A lower temperature would be preferable, however, concerns for the power limits of the potassium heat pipes prevented the use of a lower heat pipe operating temperature. In the final design a gas gap thermal resistance was positioned between the heat pipe condenser region and the toluene boiler surface in order to ensure the 130 K temperature difference between the components.

The nominal design value of 775 K for the operating temperature of the potassium heat pipes was based on the expectation that their limiting performance in terms of axial power density would be established by entrainment of the working fluid in the counter flowing vapor [1]. Entrainment predictions for the heat pipes were based on correlations developed at Los Alamos for textured wall heat pipes operating in gravity assist mode [2,3]. In order to minimize the nuclear fuel load of the reactor the heat pipes were intended to operate at comparatively high power density. The primary heat pipe design factor affecting the reactor fuel load was the neutron absorption of the heat pipe wall material. Original design studies for the system were based on the expected use of a ferrous alloy for the heat pipe envelope. Initial tests were conducted using a 300 series stainless steel. This material, while having demonstrated compatibility with the potassium working fluid, has a comparatively high neutron absorption cross section. Therefore, a zirconium-niobium alloy used in Canadian reactor designs was investigated as an alternative. Compatibility of these alloys with both the potassium working fluid and the reactor core graphite was demonstrated in test. These tests included the operation of a potassium heat pipe at a power throughput of 2 kw in a helium atmosphere with a graphite heater surround. This test was operated for more than 12,000 hours with no evidence of degradation of the heat pipe performance or materials. The heat pipe used for this life test was a sub-scale design because of the availability of the envelope material. The performance of this heat pipe, designated HWS-VI, is discussed in the experimental program section of this paper.

As the design of the power system evolved the thermal power level of the reactor core was established at 125 kw for a 25 kwe electrical power output of the system. The design employed 12 heat pipes, each conducting a nominal power of 10.4 kwt to the ORC system during normal operation. Because of concerns for the safe operation of the system in a degraded mode and the design requirement for unattended operation in remote locations the reactor core was designed for operation with failed heat pipes or failed toluene boiler elements that would effectively eliminate one or more heat pipes from the heat transfer path.

Thermal modeling of the reactor core under failed heat transfer element conditions gave values for the required heat transfer capability of each of the core heat pipes under conditions in which one or more had failed. The worst-case operating condition for a single heat pipe was found to be 1.310 times the nominal heat load with an increase in heat pipe operating temperature of 65 K [4]. This operating temperature increase was of interest because of the expected increase in power limit of the heat pipe with temperature.

EXPERIMENTAL PROGRAM

At the start of the experimental portion of the program a number of sub-scale heat pipes were tested to establish the expected performance of the knurled wall, gravity assist, potassium heat pipes in the operating temperature range of 500 to 600 K. The knurl patterns and depths as well as the tube diameters used in some of these tests were established by the availability within the laboratory of knurled wall heat pipes used in an earlier test program. Two of these existing heat pipes (HWS-I and HWS-IV) were emptied, cleaned, and refilled with potassium. Performance data taken with these heat pipes indicated that some phenomena other than that predicted by textured wall heat pipe entrainment models was establishing their performance limits. Tests were conducted with variation in the fill quantity of the heat pipe as well as with screen and wire inserts intended to delay the onset of entrainment. As these heat pipes had been operated in a prior test program with organic working fluids, the possibility of surface contamination leading to changes in the wetting characteristics of the material was considered [5]. However, as the test program continued it became apparent that the limiting axial throughput of the test heat pipes was too consistent to be explained by changes in surface wetting characteristics. An alternative hypothesis considered was that the behavior of the heat pipes was dependent on the liquid return flow pressure gradients as previously discussed [6,7].

In all, four sub-scale heat pipes with simple knurled walls were tested prior to fabrication and test of a prototype heat pipe. In addition to the heat pipes taken from the prior, organic heat pipe investigations, a smaller heat pipe (HWS V) previously operated with sodium was cleaned, refilled and tested, and a new heat pipe of zirconium niobium alloy was fabricated, primarily for material compatibility tests, but also for performance verification. Physical parameters for these four heat pipes are summarized in Table 1.

Test results for these heat pipes are given in Figs. 2 through 5. Predictions for entrainment limited performance based on textured wall heat pipe correlations [3] are also shown on the figures. It is apparent that the textured wall entrainment prediction is not applicable at higher temperatures

TABLE I

Heat Pipe Designation	ID (cm)	Knurl Depth (cm)	Helix Angle (°)	Evaporator Length (cm)	Adiabatic Length (cm)	Condenser Length (cm)	Number of Grooves
I	3 2	0 051	30	60	35	60	53
IV	3 2	0 028	30	60	55	60	134
V	2 12	0 020	45	36	73	20	105
VI	3 2	0 051	30	80	88	30	53

CORRELATION OF SUB-SCALE TEST DATA

In the initial attempts to determine the phenomena limiting the heat pipe performance, numerical values for liquid and vapor pressure gradients within the heat pipes were calculated. As the radial Reynold s numbers for the test limit conditions were on the order of 100 the axial velocity profiles were calculated using Busse's numerical corrections to Poiseuille flow [8]. The viscous pressure loss for flow of liquid in the grooves was based on relations for the axial pressure gradient in grooves in terms of the hydraulic diameter of an individual groove defined in terms of cross sectional area and wetted perimeter [9]. Interfacial shear was estimated based on a fourth order polynominal approximation for the evaporator axial velocity profile. These numerical evaluations indicated that the pressure balance in the heat pipe was dominated by the gravitational terms.

Equating the pressure gradient for flow in the grooves to the gradient of the hydrostatic head gave the following relationship for the depth of liquid flow in an individual groove.

$$d_E^{4} = \left(\frac{\delta}{A_g}\right) \frac{\mu_\ell Q^2}{\rho_\ell^{2}\, g\cos\phi\, h_{fg} N} \qquad (1)$$

where the interface radius of curvature is assumed infinite.

Numerical values for the groove flow depths at the test limits based on measured parameters for the wick structures are summarized in Table 2, for a common temperature of 778 K. The values show that the groove structure of the NWS-V heat pipe is overfilled at the mass flow rates equivalent to the demonstrated test limits. This may explain why this heat pipe most closely followed the textured wall entrainment limit prediction model.

In order to correlate the data for these heat pipes use was made of the dimensionless heat flow and entrainment expressions used in prior gravity assisted heat pipe correlations [2]. In this application the entrainment parameter was modified to use a characteristic length based on the calculated depth of flow in the grooves under operating conditions and the liquid density used in the dimensionless heat flow expression, giving:

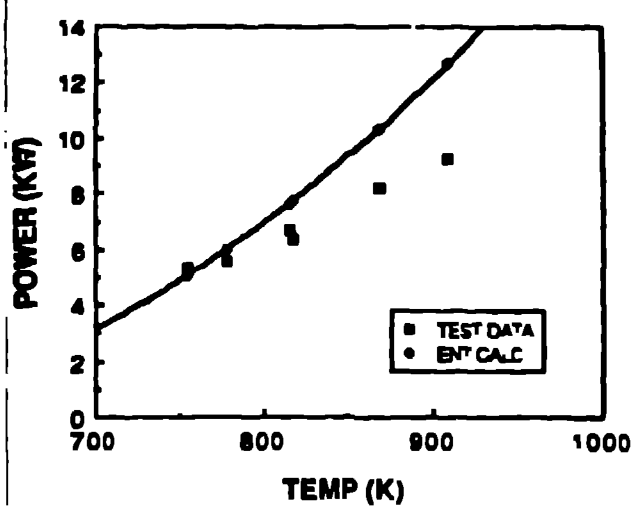

Fig 2 Performance data and textured wall entrainment predictions for sub-scale heat pipe I

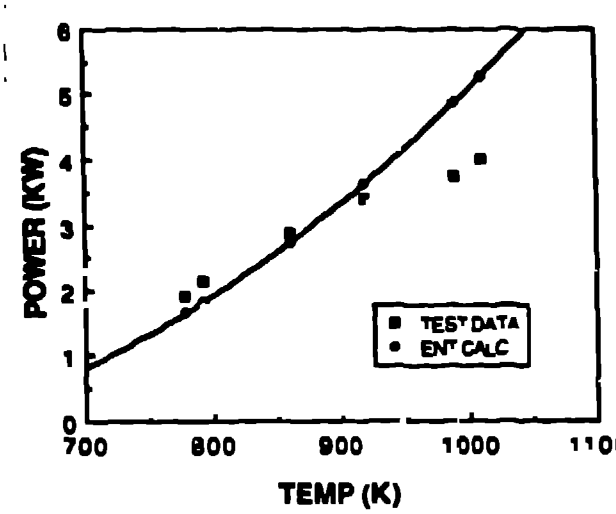

Fig 4 Performance data and textured wall entrainment predictions for sub-scale heat pipe V

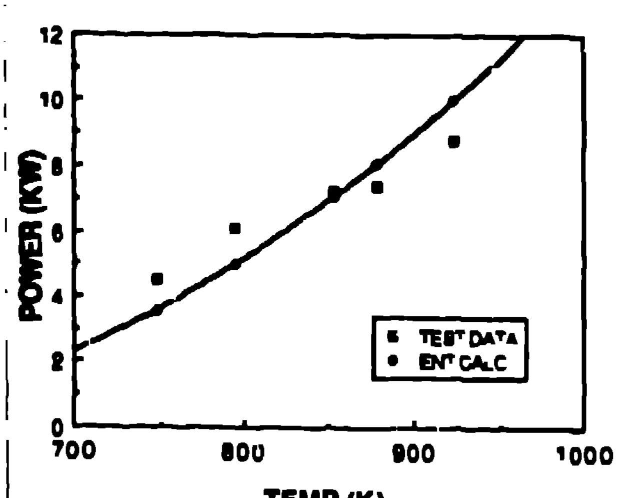

Fig 3 Performance data and textured wall entrainment predictions for sub-scale heat pipe IV

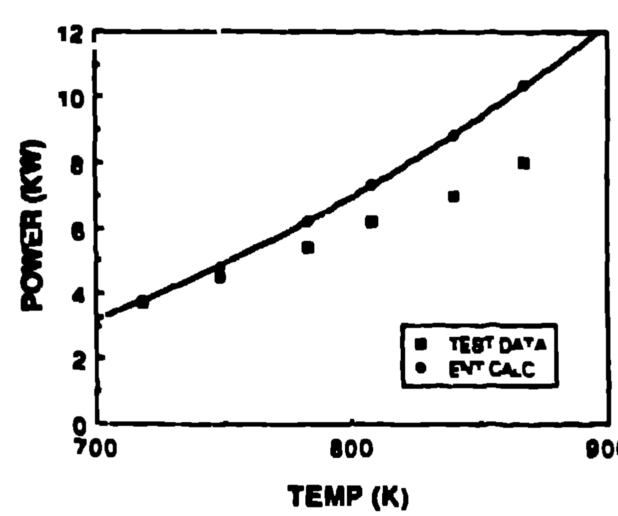

Fig 5 Performance data and textured wall entrainment predictions for sub-scale heat pipe VI

$$Q_E = \frac{(q/A_g)}{\rho_g h_{fg}^{1.5}} \quad . \tag{2}$$

$$E_T = \frac{\sigma}{\rho_g\, h_{fg}\, d_E} \quad . \tag{3}$$

where d_E is as defined in equation (1)

Data from the sub-scale heat pipe tests were plotted in terms of Q_E versus E_T as indicated in Fig. 6. A numerical fit to the data gave the relationship:

$$Q_E = 6.02 \times 10^{-7}\, E_T^{-0.297} \quad . \tag{4}$$

TABLE 2
DEPTH OF LIQUID FLOW IN GROOVES AT 778 K

Heat Pipe	d_E (cm)	d_E/d
I	0 04814	0.741
IV	0 03000	1 08
V	0 0256C	1.200
VI	0 03490	0.680

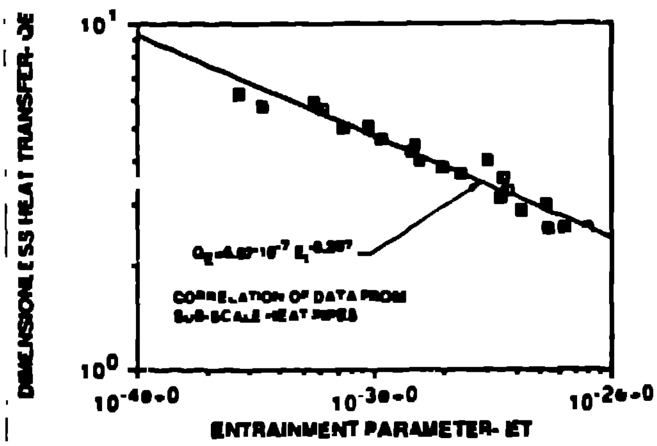

Fig 6 Dimensionless power versus entrainment parameter for sub-scale heat pipes

The form of the resulting relationship is similar to that used for correlation of entrainment data for smooth wall heat pipes although different in exponent and in the basis for the characteristic dimension used in the entrainment parameter Justification for using this form which is normally explained on the basis of domination of the heat pipe behavior by vapor inertia considerations [10]. in the present case where, on the basis of the calculated pressure gradients, that does not appear to be true, is based on consideration of the effect of surface curvature on the flow resistance for the liquid in the grooves As the pressure gradient for the liquid is strongly dependent on the flow cross section any local pressure difference between the liquid and vapor will lead to rapid increase in the gradient and presumably to flow interruption

Design of the Prototype Heat Pipe

Using the relationships developed from the sub-scale tests the prototype heat pipe dimensions were established at 6 35 cm outside diameter and 5 73 inside diameter Knurl depth was set at 0.089 cm with a 60° included angle knurl having a helix angle of 30° This knurl depth was conservative in the sense that the predicted depth of flow in the knurls under design conditions was approximately half of the knurl depth Both this design margin and that of the heat pipe diameter were incorporated because of the range of extrapolation of the data from a vapor space area of approximately 8.0 cm to more than 25.0 cm^2

DESCRIPTION OF THE PROTOTYPE TEST HARDWARE

A 3 meter long heat pipe was fabricated from 6 35 cm outside diameter cold drawn C-1018 steel tubing having a wall thickness of 3.14 mm End closures were machined from stock of the same material. The interior surfaces of the steel tube were knurled to provide a network for uniform distribution of the potassium condensate. The knurling process produced pyramidal structures about 0.89 mm high in a triangular array. Individual grooves in the pattern followed a helix with a lead angle of 30 degrees After knurling the pattern into the tube the peaks of the pyramids were cut back by a honing process to eliminate possible contamination from trapping of the lubricants used in the honing process Additional cleaning processes for the tube included a sulphuric acid bath and water wash, followed by an alcohol rinse The knurled tube was then vacuum fired at 1090 K for 100 hours to remove all volatile contaminants. The end caps and fill tube were welded to the knurled tube and the final assembly leak checked with a 10^{-10} atm/cm^3/sec. leak detector

A potassium charge of 457 g was vacuum distilled into the heat pipe assembly. This amount was based on the calculated working inventory at temperature plus a surplus of approximately 100% The filled heat pipe was wet-in for 72 hours at 875 K in a horizontal position. To ensure that all of the knurled surface received complete wetting the heat pipe was rotated 60 degrees per hour through the final 8 hours of the wet-in-period

Test Set-up and Operation

The potassium heat pipe was set-up for test in a vertical orientation with an induction coil 113 cm long placed 13 cm from the lower end as indicated in Fig 7. A water cooled calorimeter, 61 cm in length, was positioned at the top of the heat pipe with a space of 5 cm between the end of the calorimeter and the heat pipe condenser end. The adiabatic region of the heat pipe, approximately 113 cm long was insulated to minimize heat loss Copper-constant thermocouples were placed along the length of the assembly by welding to the surface of the heat pipe Heat was introduced into the evaporator region of the pipe by an induction coil using an operating frequency of approximately 300 khz The temperature of the heat pipe was controlled with a gas filled gap between the calorimeter and the heat pipe condenser region A controlled mixture of helium and argon gas was used to vary the gap conductance The power throughput of the heat pipe was determined from the flow rate and temperature rise to the water in the calorimeter

Performance limits of the test heat pipe were obtained by increasing the heat input power in small increments and simultaneously adjusting the gas mixture to maintain a constant operating temperature Power was increased in this fashion until a hot spot appeared in the evaporator region of the heat pipe indicating a performance limit Recovery of the heat pipe was accomplished by reducing the input power level When the power was reduced the hot spots were observed to reduce in temperature in a manner consistent with reflooding with liquid

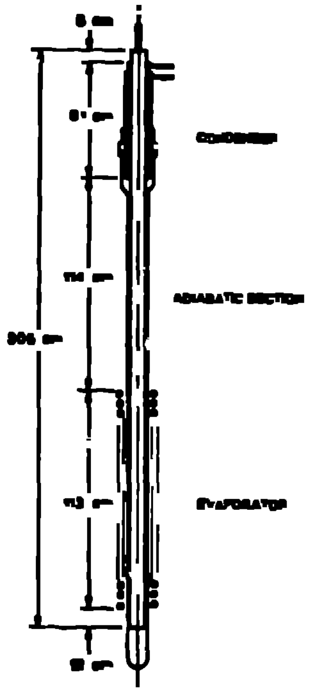

Fig. 7 Experimental set-up for test of prototype for heat pipe

from above The experimental performance limits established for the heat pipe as a function of temperature are shown in Fig 8, together with the predicted limits from the sub-scale grooved surface entrainment extrapolation The temperature used for correlation of the data is the evaporator exit temperature

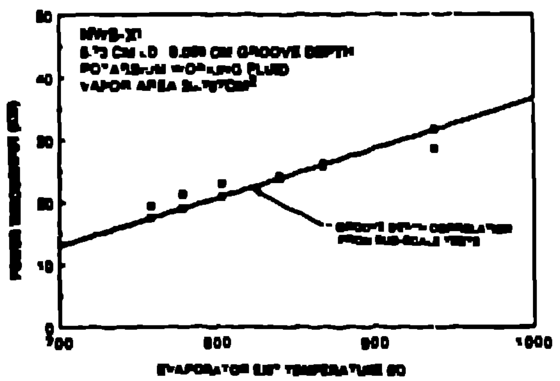

Fig 8 Comparison of sub-scale prediction and prototype heat pipe test data

DISCUSSION OF TEST RESULTS

As with the sub-scale heat pipes, the textured wall entrainment prediction using the texture depth of the knurls as the critical dimensional parameter does not agree with the test data at higher temperatures The entrainment correlation developed from the sub-scale heat pipe tests provides a reasonable fit to the higher temperature test data In retrospect it appears possible to reduce both the knurl depth and vapor space diameter of the production heat pipes as the design margin of the present design configuration is approximately 25% at 775 K.

It is also apparent from the test data that the textured wall entrainment correlation applies to the present situation in a range of operating condition at lower temperatures between the sonic limit and the groove depth limit.

Conclusions

Test data from a total of five heat pipes operating vertically in gravity assist mode have been correlated with a relationship based on an entrainment parameter characterized by the operating depth of liquid in the groove structure. The final expression for the correlation, incorporating the data from the prototype heat pipe, is

$$Q_E = 6.59 \times 10^{-7} \, E_v^{-0.284} \quad (5)$$

where the definition of the terms is as before

This correlation defines an operating range in existence at operating conditions above the range of the prior textured wall heat pipe correlations The point of transition between the limits needs further investigation.

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