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Abstract

A survey of space-power related liquid metal heat pipe work at Los Alamos National Laboratory is presented. Heat pipe development at Los Alamos has been on-going since 1963. Heat pipes were initially developed for thermionic nuclear-electrical power production in space. Since then Los Alamos has developed liquid metal heat pipes for numerous applications related to high temperature systems in both the space and terrestrial environments. Some of these applications include thermionic electrical generators, thermoelectric energy conversion (both in-core and direct radiation), thermal energy storage, hypersonic vehicle leading edge cooling, and heat pipe vapor laser cells. Some of the work performed at Los Alamos has been documented in internal reports that are often little-known. A representative description and summary of progress in space-related liquid metal heat pipe technology is provided followed by a reference section citing sources where these works may be found.

INTRODUCTION

On July 24, 1963, George Grover made the following entry into his laboratory notebook: "Heat transfer via capillary movement of fluids. The "pumping" action of surface tension forces may be sufficient to move liquids from a cold temperature zone to a high temperature zone (with subsequent return in vapor form using as the driving force, the difference in vapor pressure at the two temperatures) to be of interest in transferring heat from the hot to the cold zone. Such a closed system, requiring no external pumps, may be of particular interest in space reactors in moving heat from the reactor core to a radiating system. In the absence of gravity, the forces must only be such as to overcome the capillary and the drag of the returning vapor through its channels."

Thus began heat pipe research at Los Alamos. Later that year Grover submitted the results of "heat pipe" experiments with water and sodium as working fluids to the *Journal of Applied Physics* (Grover et al., 1964). The sodium heat pipe, 90 cm long with a 1.9 cm O.D., operated at 1100 K with 1-kW heat input. This paper reviews the 28 years of space power-related liquid metal heat pipe research that has been conducted at Los Alamos since the invention of the heat pipe.

THERMIONIC REACTOR PROGRAM APPLICATIONS

Early research in heat pipes conducted at Los Alamos was directed to applications in space-based thermionic energy conversion systems operating in excess of 1500 K. Heat pipes were considered for heating thermionic emitters, for cooling thermionic collectors, and for the ultimate radiation of heat to space. Fluids and materials were tailored to this temperature regime. Experiments with a Nb-1%Zr heat pipe, with lithium operating at 1573 K, 207 W/cm^2 evaporator radial heat flux; a 1.95 kW/cm^2 axial heat flux, and an Ag-Ta operating at 2273 K, 410 W/cm^2 evaporator radial heat flux; and a 4 kW/cm^2 axial heat flux are reported in Deverall and Kemme (1964). The results of early thermionic-related heat pipe fluid-wall compatibility and life test studies with systems of In-W at 2173 K for 75 hours, Ag-Ta at 2173 K for 100 hours, Cs-Ti at 673 K in excess of 2000 hours, Na-stainless steel at 1073 K for 500 hours, and Li-Nb-1%Zr at 1373 K for 4300 hours are summarized in Grover et al. (1964), Deverall and Kemme (1964), Grover et al. (1965), Cotter et al. (1965), and Ranken and Kemme (1965). A study characterizing both potassium and sodium heat pipes with various wick structures and a treatment of the limitations to heat pipe start-up and operation is contained in Kemme (1966).

Development of Heat Pipe Theory

A number of early Los Alamos papers have presented general quantitative principles of heat pipe operation. Cotter (1965) presented an overview of heat pipe start-up and steady-state heat pipe operation. He discussed the capillary and the boiling limits to heat pipe operation and considered the operating characteristics of heat pipes with multicomponent fluid. A set of analytical steady-state equations describing the flow of vapor in the vapor space was also included. Transient modes of heat pipe start-up and failure are described in Cotter (1967). A general treatment of the sonic, entrainment, capillary, and boiling limits in liquid metal heat pipes are given in Kemme (1968), Kemme (1969), and Deverall et al. (1970). These papers consider various wick structures including arteries, open channels, screens, concentric and crescent annuli. Deverall et al. (1970) also gives a characterization of start-up failure modes due to externally imposed boundary conditions and the presence of noncondensable gas in liquid metal pipes. They provided experimental and quantitative results of sonic limitation to the start-up of mercury heat pipes and experimental and qualitative descriptions of evaporator entrainment, condenser freeze-out, and capillary failure. Several computer codes have been developed to quantitatively model various aspects of both steady-state (analytically based) Woloshun et al. (1988), and transient (numerically based) Costello et al. (1987) heat pipe operation. HTPIPE, the current Los Alamos steady state heat pipe performance analysis program, has been verified extensively with experiment. Some recent efforts have attempted to correlate entrainment in gravity-assist potassium heat pipes Merrigan et al. (1987) and predict boiling limits in potassium heat pipes with annular gap wicks Woloshun et al. (1990b). A thermochemical corrosion model using a free energy minimization routine coupled to a hydrodynamic model of liquid metal heat pipe system is described in Merrigan and Feber (1985) and Feber and Merrigan (1987).

COMPATIBILITY AND LIFE STUDIES

Understanding of materials compatibility and corrosion problems is essential to the proper design and long term operation of liquid metal heat pipes. Deverall (1970) presented life test data on a 12-inch-long, 0.75-inch-OD Hg-Stainless Steel system operating at 603 K for 10,000 hours. In these tests the maximum heat flux was 1.06 kW over a 2.25-inch evaporator region. Magnesium was used as an oxygen getter to clean the surface, promoting wetting. Titanium was used as an inhibitor to reduce stainless steel corrosion. Kemme et al. (1978) report test results from a number of liquid metal heat pipes including a 7.3 m long, 45 mm i.d., Hg-Stainless Steel heat pipe operating up to 27 kW at 650 K in a vertical gravity-assist mode.

Ceramic heat pipes were developed for use in high temperature heat recovery in process heat furnace recuperators Keddy and Ranken (1979), Merrigan and Keddy (1982), and Merrigan et al. (1981). Operation of sodium heat pipes in air at temperatures in excess of 1200 K was accomplished using SiC as a shell material and a chemical vapor deposit tungsten inner liner for protection of the ceramic from the working fluid. Throughput was about 2-kW with a 19-mm-ID pipe with repeated start cycles having temperature rise rates in excess of 1.2 K/s.

Merrigan (1985) provides the results of a 1700 hour test of a Li-Mo heat pipe operating at 1500 K with an axial heat flux of 11 kW/cm^2 and an evaporator radial heat flux of 70 W/cm^2. Lundberg and Merrigan (1984), Lundberg and Feber (1984), and Lundberg (1987) present the results of tests with cladded Na-Mo-UO_2 combinations operating at around 1400 K for up to 28,432 hours and Li-Mo operating at 1700 K for 25,216 hours before failure. Corrosion mechanisms were attributed to the transport of impurities such as Ni, O, C, Si, and N into the evaporator region. These transport mechanisms were then modeled theoretically. Oxygen-induced corrosion in potassium heat pipe is described in Lundberg (1987). A thermochemical corrosion model for both Mo-alkali metal systems and Nb-alkali metal systems is described in Merrigan and Feber (1985) and Feber and Merrigan (1987). On going compatibility tests of K-Nb-1%Zr heat pipes operating at around 850 K are summarized in Sena and Merrigan (1990).

The results of a 45,036 hour test with a Na-Mo-TZM heat pipe operating at 1400 K is presented in Lundberg (1987). Data on K-Ni, K-Ti, Li-Ta, Li-Nb-1%Zr, and Li-Mo systems are also given. This paper also reviews liquid metal heat pipe lifetime and compatibility tests conducted at Los Alamos and elsewhere.

SPACE POWER RELATED APPLICATIONS

Orbital Heat Pipe Experiment

The first orbital heat pipe was flown aboard an Atlas-Agena launch vehicle in April 1967. The heat pipe was a simple 12-inch-long water-stainless steel system described in Deverall and Kemme (1965), Deverall et al. (1967a), Deverall and Salmi (1967), Deverall et al. (1967b), and Grover et al. (1968). The experiment ran successfully for 51 hours before the satellite's battery voltage became too low for signal transmission. The experiment demonstrated that the absence of gravitational forces does not affect heat pipe performance.

SPAR and SP-100 Reactor Programs

The LANL SPAR reactor program was the predecessor of the current DOE SP-100 program. The SPAR system was based on thermoelectric conversion with the heat pipes coupled directly into the reactor core. This design posed a number of technological challenges, not the least of which was the need for two or more bends of nearly 90^o in the heat pipe to go around the reactor's radiation shield. The SPAR program produced a number of significant advances in liquid metal heat pipe technology in the areas of fabrication, axial and radial power density, and startup methods. A general overview of space reactor related heat pipe technology issues is provided in Merrigan (1985).

The fabrication and bending of Li-Mo heat pipes with annular screen wicks is described in Lundberg and Martinez (1980). These pipes were bent and successfully operated at 1

kW/cm^2 axial heat flux between 1400 and 1700 K. The construction, testing, and performance correlation of a number of artery Na-Mo heat pipe designs operating in the 1450 K range is reported in Merrigan et al. (1982). Similar tests were performed with a Li-Mo TZM compacted artery heat pipe design at 1500 K in Merrigan et al. (1983a) and Merrigan et al. (1983b). These tests demonstrated axial power levels up to 19 kW/cm^2 and radial heat fluxes in the evaporator up to 300 W/cm^2. A study examining the suitability of Mo-13%Re for reactor heat pipe operation is given in Merrigan and Lundberg (1983).

A demonstration of the operation of a flexible Na-stainless steel heat pipe operating at 1100 K is described in Merrigan et al. (1984). This heat pipe was flexed repeatedly through angles of 180 degrees both at room temperature and at its operating temperature. The start-up, shut-down, restart, and peak power of an annular Li-Mo heat pipe operating at 1500 K was characterized in Merrigan et al. (1985) and Merrigan et al. (1986). Maximum power throughput in the tests was 36.8 kW, corresponding to a power density of 23 kW/cm^2 for a 1.4 cm diameter vapor space. The evaporator heat flux was approximately 150 W/cm^2 over an evaporator length of 40 cm at peak power.

The current DOE SP-100 reactor design uses K-Nb-1%Zr heat pipes at over 750 K as a part of its main radiator. Numerous alternative radiator designs have been proposed to reduce the weight of the existing baseline design. One of these alternative designs is a K-Ti radiator consisting of 360, D-shaped, 5.2-m long, 3 kW heat pipes operating at 775 K. The construction and testing of prototypes of these K-Ti heat pipes is described in Girrens et al. (1980), and Girrens (1982).

Experimental lifetime performance studies are currently in progress (Sena and Merrigan, 1990) with six of eight originally operating K-Nb1%Zr heat pipes between 850 and 950 K. These pipes have been operating in excess of 10,000 hours at axial heat fluxes of over 180 W/cm^2. The operation of a K-Nb-1%Zr heat pipe operating with radial heat fluxes in the evaporator region of up to 147 W/cm^2 at 925 K is described in Woloshun et al. (1990a).

Thermal Energy Storage

The organic Rankine cycle solar dynamic power system was a candidate to provide the Space Station with constant power during both insolation and eclipse. This system incorporates thermal energy storage canisters within the vapor space along with an organic fluid heater tube used as the condenser region of the heat pipe. Potassium heat pipes in Keddy et al. (1987), Keddy et al. (1988a), and Keddy et al. (1988b) were developed to absorb and transfer solar energy within the receiver cavity operating between 725 and 775 K. A heat pipe assembly incorporating LiOH energy storage was fabricated and tested at a nominal design input of 4.8 kW and a maximum input of 5.7 kW.

Hypersonic Vehicle Leading Cooling

The cooling requirements for the wing and engine ducting leading edges of the proposed National Aerospace Plane (NASP) exceed the limits of demonstrated heat pipe technology. A Li-Mo heat pipe operating with tip temperatures in excess of 1900 K, was operated at tilt angles between 10 and 90 degrees from the horizontal with radial heat fluxes between 800 and 550 W/cm^2, in an investigation of NASP heat pipe applications by Merrigan and Sena (1989). Both radio frequency (rf) plasma jet and direct rf induction heating methods were used. The higher heating rates were achieved with using direct rf induction with a concentrator.

Gas-Controlled Liquid Metal Heat Pipes

Rankine (1990) describes tests performed on a total of 29 Neon-filled stainless steel heat pipes having either Na or K as a working fluid. The heat pipes varied from 10.3 to 28.0 mm in diameter and 194 to 540 mm in length. Heat transport capacity varied from 500 to over 5000 W. The operating temperature ranged from 850 K to 1100 K. These pipes were used as temperature control units for materials irradiation capsules tested in the EBR-II reactor. Unpublished work conducted for the Rockwell Dynamic Isotope Power Subsystem (DIPS) program involved construction and testing of neon-gas-controlled, Li-Stainless steel heat pipe operating between 1030 and 1230 K having a maximum axial heat flux of 230 W/cm^2.

Heat Pipe Vapor Cells

Laser beams with various specific wavelengths can be generated using metal vapor atmospheres in heat pipes. Gas loaded heat pipes with transparent window have been used to produce these atmospheres. Experiments with a stainless steel vapor cell containing a Hg-Xe mixture with a typical centerline temperature of 586 K are described in Deverall and Phillips (1976) and Deverall (1977). The principle objectives of these tests were to determine the effect of heat pipe diameter, buffer-gas density, and convection on the stability of the gas-vapor interface. A neon buffered sodium heat pipe cell Kemme and York (1978) was constructed and successfully operated at 970 K. Unfortunately, this effort failed to produce the desired sodium lasing action and the program was terminated. More recent studies have used Pb-Ar mixtures in alumina and tungsten-tantalum heat pipes Merrigan et al. (1990) and Reid et al. (1990) with quartz windows at around 1573 K to produce a Raman shift between the UV and the blue. The objective of this last program was to produce an airborne or space-based submarine communication system.

SUMMARY

High temperature space-power has been the principle emphasis in heat pipe work at Los Alamos since its invention there 28 years ago. Recent heat pipe work at Los Alamos has involved performance testing of typical space reactor heat pipe designs to power levels in excess of 23 kW/cm^2 axially and 800 W/cm^2 radially. Flexible heat pipes intended for use in deployable space radiators have been tested with continuous operation during 180° bends. Mass transport/corrosion chemistry models have contributed significantly to the understanding of liquid metal heat pipe failure modes and to the prediction of operating life. Controlled life-tests have demonstrated successful heat pipe operation at temperatures above 1700 K for over 45,000 hours.

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