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for SAFE-30 Reactor Prototype

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Sodium Heat Pipe Module Test for the SAFE-30 Reactor Prototype

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Reliable, long-life, low-cost heat pipes can enable safe, affordable space fission propulsion and power systems. Advanced versions of these systems can in turn allow rapid access to any point in the solar system. Twelve stainless steel-sodium heat pipe modules were built and tested at Los Alamos for use in a thermohydraulic simulation of a fission propulsion and power source. These modules were delivered to NASA Marshall by August 2000 and were assembled and tested in a prototypical configuration during September 2000. The construction and test of one of these modules is described. In the startup described in this paper, the heat pipe transitioned from the free-molecule flow regime to the viscous- to the radiation-limited heat-transport modes.

Heat Pipe Module Construction

A cutaway drawing of a heat pipe module with its four cartridge heaters is shown in Figure 1. Characteristic module dimensions are given in Table 1. The heat pipe envelope consisted of a 304 stainless steel seamless tube having a 2.54-cm OD and a 1.65-mm thick wall. The end caps were identical in composition. A crescent annular wick was fabricated from 304 L stainless steel screens that had been chemically cleaned and vacuum fired at 1025 K for several hours. The annular wick consists of one support layer of 100-mesh screen, three capillary pumping layers of 400-mesh screen, and two liquid flow layers of 60-mesh screen. This configuration chosen to simplify construction, insure robustness, and to minimize axial pressure drop in the liquid region. The annular wick was fabricated by wrapping the screen layers around a copper rod drawn to 1.73-cm OD. The outer layer of screen was retained around the rod by wire-to-wire spot welds at approximately 2-mm intervals along the trailing edge of the screen. After wrapping, the copper rod was slid out of the wick assembly. The 0.17 cm thick wick assembly formed a rigid tube. Final dimensions of the wick were 1.74-cm ID and 2.07-cm OD for a wick thickness of 0.17-cm. The evaporator end of the wick tube was closed with a fitted stainless steel plug and mechanically retained with a nickel wire wrap. The annular wick was checked for maximum pore size in an ethyl alcohol bath using helium as a pressurizing gas. Tests verified that the pore radius was less than 47 microns.

The condenser end cap was tig welded to a fill stem. The end caps were tig welded to the tube body. Each weld was inspected and leak tested. The heat pipe interior was vacuum fired at 10^{-5} torr and 1025 K for several hours. The heat pipe was filled with 77 kPa argon and its fill stem seal with a compression fitting. The sealed heat pipe was delivered to a commercial vendor where four 43-cm long, 2.54 cm OD fuel tubes were brazed to the evaporator end of the heat pipe forming the module assembly. Braze occurred at 10^{-5} torr and 1325 K over an eight minute period. After braze the module was shipped back to Los Alamos. The inside of the module was vacuum fired for several hours at 10^{-6} torr and 1073 K.

Figure 1. Cutaway view of stainless steel-sodium heat pipe module.

The heat pipe was then distillation filled with 145 g of DuPont NIAPURE sodium. The charge quantity was calculated to provide filling of the wick void volume, annulus volume, and surface cavities; and some excess for liquid expansion and dimensional uncertainty. At the conclusion of the fill a copper chill block was used to form a plug of sodium in the fill stem. Following distillation the heat pipe was brought to 1073 K over its entire length inside a furnace open to atmosphere for 48 hours. This step permitted the sodium to wet the heat pipe's internal surfaces. Qualification testing consisted of bringing the module's evaporator exit to 950 K in air with four-43 cm long, 1.9-cm diameter cartridge heaters. Before shipment to NASA Marshall the sodium inventory was transferred to the condenser end of the module. The condenser end of the heat pipe was stripped of oxide. The fill stem was severed from the module body inside an argon atmosphere, exposing solid sodium. An end cover was electron beam welded to the condenser end, sealing the module.

Table 1. Heat Pipe Module Dimensions

Item	Value
Heat Pipe Length	120 cm
Evaporator Length	43 cm
Condenser Length	77 cm
Heat Pipe Outside Diameter	2.54 cm
Heat Pipe Inside Diameter	2.21 cm
Wick Outside Diameter	2.07 cm
Annular Gap Thickness	0.07 cm
Wick Inside Diameter	1.74 cm
Wick Thickness	0.17 cm
Effective Pore Radius	47 micron
Module Weight After Distillation	3785.6 g
Module Tare Weight	3640.3 g
Sodium Transferred to Module	145.3 g
Wet in Temperature	875 K
Wet in Time	49.5 hrs

Test Procedure

On arrival at Marshall the sodium inventory that had been solidified at the condenser end was melted and moved toward the evaporator end of the heat pipe. The oxide layer that had formed on the outside module surface during test at Los Alamos was removed by bead blasting. The module was rested horizontally on a stainless steel frame and placed inside a vacuum chamber so its evaporator and two fuel tubes could be viewed through a quartz glass on the side of the chamber. Unoxidized cartridge heaters were inserted in each fuel tube, wired in parallel, and connected to a voltage controlled AC power supply. Power to the module was found by measuring the terminal voltage and total current through a shunt. Type C thermocouples were spot welded at three locations on the fuel tubes and at five axial locations along the heat pipe length. Figure 2 shows the thermocouple placement used during this test.

Figure 2. Thermocouple placement on fuel tubes and heat pipe during test.

The chamber was brought to 10^{-5} torr pressure. Power was increased to the module in 80 W increments at five minute intervals. Figure 3 shows the total electrical power to the module versus time. The total hemispherical emittance of the bead-blasted module was about 0.4, estimated from values found in the literature and from consistency in module temperature and power data taken during test. Total radiation heat transfer from heat pipe condenser surface was about 700 W at 900 K. The fuel tube surfaces ran 75 K hotter than the heat pipe. From the area ratio, total radiation heat transfer from evaporator tubes was about 1800 W. Thermal power was rejected from the heat pipe condenser by radiant exchange to the water cooled vacuum chamber surfaces surrounding it. Wall temperature data were used to make an estimate of condenser power throughput. The net radiant energy rate between condenser surface and its surroundings is:

$$\dot{q}_{rad} = \sigma \epsilon \pi d_o \sum_{i=1}^{N_c} (z_{i+1} - z_i) \left(\frac{T_{i+1}^4 + T_i^4 + T_{i+1}^3 T_i + T_i^3 T_{i+1} + T_{i+1}^2 T_i^2}{5} - T_\infty^4 \right) \quad (1)$$

Note that the unity coefficient in the $T_{i+1}^2 T_i^2$ term in Equation (1) corrects Equation (9) in Reid et al. (1999) which had a coefficient of 2 leading the same term.

The wall temperature at locations along the pipe during the startup is shown in Figure 4. The slope of the temperature versus time profile at the first thermocouple location increased from near zero at 1800 s to 13 K/minute 3600 s. The slope of the temperature versus time profile diminished as continuum flow was approached locally. Except for the 10 cm long condenser pool, the heat pipe became isothermal at 850 K 2 hours into the startup. Power was increased to the heat pipe until it reached 900 K at the evaporator exit. The heat pipe surface temperatures agreed within 5°C along the active length.

Figure 3. Upper curve: total electrical power to module versus time. Lower curve: estimated condenser heat rejection rate versus time.

Figure 4. Surface temperatures measured during a 3-hour frozen startup to 900 K. Distance in legend is measured from the evaporator end cap.

Figure 5 compares condenser heat rejection rate to the steady-state sonic and viscous limits at various temperatures near the evaporator exit. The solid triangles represents startup data. The open inverted triangles represent measurements made during shutdown.

As the evaporator temperature increased, the vapor density and the axial pressure gradient in the core region became sufficient to move vapor into the heat pipe condenser. The condenser heat rejection rate follows the viscous heat transport limit up to 750 K. Above this temperature, the heat pipe was isothermal along its active length. Radiation coupling between the heat pipe and its surroundings limited the heat rejection rate from the condenser. In the radiation-limited mode, there was a reduction in the slope of the heat rejection rate versus temperature curve. The condenser power curve continued in the radiation-limited mode up to a peak 660 W throughput at 900 K.

Figure 5. Heat rejection rate versus temperature near the evaporator exit .

Heat Pipe Start Up Simulation

A routine that gives some transient response characteristics for an alkali metal heat pipe was written using a one-dimensional lumped capacitance differential formulation of the energy equation. This routine is very similar to a procedure described by Silverstein (1992). The heat transfer rate between the evaporator and condenser is described by analytical expressions for the viscous, sonic, and condenser coupling heat transfer limits. This routine does *not* predict transient heat pipe failure modes which are best handled by first principle heat pipe codes such as HPTAM (Tournier, 1996) or THROHPUT (Hall, 1994). Such failure modes require the continuity and momentum equations for adequate description. Heat pipe operation near the capillary limit is also not considered by this routine. This is not a restrictive shortcoming: capillary limited operation is not typically a serious concern during liquid metal heat pipe frozen startup.

This routine divides the heat pipe into a number of axial lumped capacitance nodes. The evaporator is treated as a single node. The condenser can be divided into an arbitrary number of nodes, which in practice, might correspond to temperature measurement locations. The effects of heat capacity in the heat pipe wall and wick, radiation to the

environment, and heat transport into the condenser by heat transfer limiting mechanisms are considered. Heat of fusion effects during startup are also considered.

This routine is compact and can be easily incorporated into a system code. With appropriate relations for the viscous, sonic, and condenser coupling limits this routine can also compute the one-dimensional startup response of heat pipes with noncylindrical geometry. Figures 4 and 5 compare the startup response predicted by the routine to the module start up temperature data presented in this paper.

NOMENCLATURE

$\dot{q}_{rad}$	radiative emissive power
σ	Stefan-Boltzmann constant
ε	emittance
d_o	heat pipe outside diameter
z	axial position
T_i	heat pipe surface temperature
T_∞	temperature surrounding module
N_c	total number of condenser segments

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