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TITANIUM WATER HEAT PIPES FOR SPACE FISSION POWER COOLING

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For future space transportation and surface power applications, NASA Glenn Research Center (GRC) is currently investigating a small fission power system (Kilopower system), which operates at powers in range of 1 to 10kWe. The Kilopower system uses alkali metal heat pipes to transport heat from the nuclear reactor to the Stirling convertors to produce electricity and titanium water heat pipes to remove the waste heat from the convertors to the radiators. In a recent NASA SBIR Phase II program, Advanced Cooling Technologies, Inc. (ACT) developed the titanium/water heat pipes. These water heat pipes are featured with bi-porous wick in the evaporator, and screen-groove hybrid wick for the rest of the pipe, that allow the kilopower system to function under four different conditions: (1) in space where there is no gravity (2) on ground during testing with slight adverse gravity orientation (3) on planetary surface in gravity-aided orientation (4) and during launch, in the against-gravity orientation. This paper presents the development of the titanium water heat pipes for Kilopower waste heat rejection, including the hardware design, fabrication and thermal performance experimental validation.

I. INTRODUCTION

NASA Glenn Research Center is developing a small scale nuclear fission power reactor as demonstration unit, which aims to provide roughly 1 kW of electric power for future space transportation and surface power applications (Ref. 1). The Kilopower system utilizes alkali metal heat pipes to transfer thermal energy from the nuclear reactor to Stirling convertors to produce electricity. The waste heat from the convertor's cold end needs to be removed and rejected to space efficiently. Under a Small Business Innovation Research (SBIR) program, Advanced Cooling Technologies (ACT), Inc. developed titanium water heat pipe radiators for Kilopower system waste heat rejection (Ref. 2). The thermal management system shown in Fig. 1 consists of Ti-H_2O heat pipes attached to radiator panels. Each heat pipe is designed to carry at least 250 W of waste heat at a temperature of 400K and to function under the following conditions:

1. Space operation with zero-gravity.
2. Ground testing with a slight adverse (<0.5°) gravity orientation to estimate micro-gravity performance.
3. Operation with gravity-aided orientation (i.e. thermosyphon).
4. Restart after exposure to launch conditions.

The Ti-H_2O heat pipe consists of two portions: a screened semi-annular evaporator and an approximate 1m-long grooved titanium tube as adiabatic and condenser sections. In a previous paper (Ref. 2), the development of a full-length prototype was reported. Its heat transfer capability and freeze-thaw startup performance were validated. This paper presents the development of the final deliverables that will be further tested at NASA Glenn Research Center.

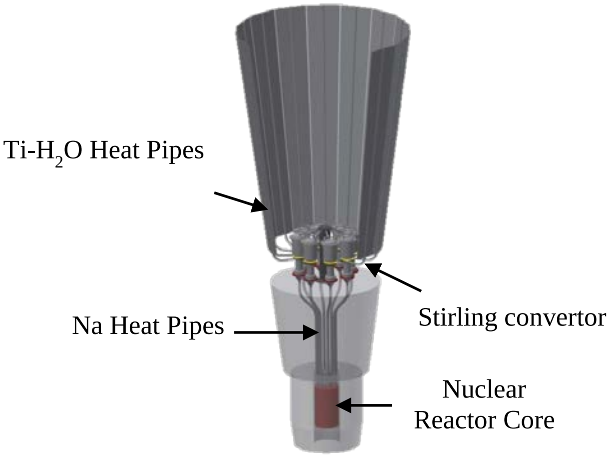

Fig. 1. Kilopower nuclear fission system and the thermal management system (Ref. 1)

II. HEAT PIPE DEVELOPMENT

II.A. Evaporator

Two evaporator configurations were designed to accommodate the interface with the Stirling convertor in two different modes. The first evaporator (shown in Fig. 2(a)) directly interfaces with the Stirling convertor's cold end. Waste heat enters the evaporator through its inner cylindrical surface. The second evaporator (Fig. 2(b)) interfaces with Stirling convertor via a Cold Side Adapter Flange (CSAF). In this case, waste heat released by the Stirling convertor conducts through CSAF and enters the evaporator from the flat bottom surface. Both evaporators have a bi-porous wick design inside the envelope: (1) a fine screen mesh provides capillary pumping from the grooved section to the heating surface of the evaporator (2) a stack of coarse screen, which is called "accumulator", stores the entire liquid inventory while the heat pipe is not operating (i.e. launch). Fig. 3 and Fig. 4 show the arrangement of primary wick and accumulator within an evaporator. To minimize liquid flow path through the screen portion, the grooved tube was extended into the evaporator and directly attached to the primary wick as shown in Fig. 3.

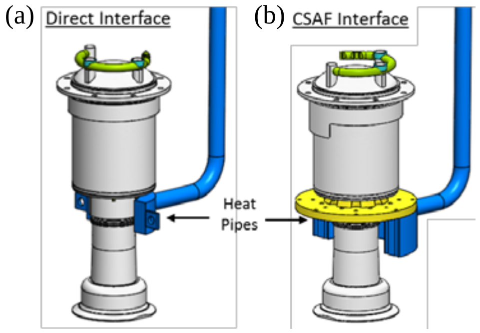

Fig. 2. Two Ti-H_2O evaporator designs (a) directly interfaced (on cylindrical surface) with the Stirling Convertor (b) interfaced (flat) via CSAF

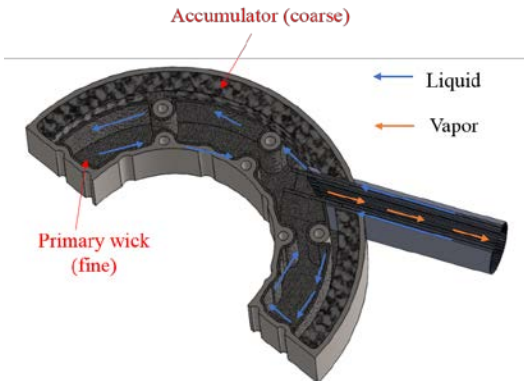

Fig. 3. Bi-porous screen arrangement and working fluid path within a CSAF evaporator

Fig. 4. CSAF evaporator

II.B. Groove Section Design

The groove design was optimized based on an upgraded one-dimensional groove mathematical model, that considered the meniscus geometry variation along the groove. The foremost objective of this optimization was the heat transport capability, while secondary objectives included high accuracy assessment of total mass, liquid volume and thermal conductance. The finalized groove profile shown in Fig.5a was fabricated by Electrical Discharge Machining (EDM). To validate the design, a 48-inch groove heat pipe was fabricated and tested. The heat transfer capability was measured at 100, 120 and 140°C and at 0.26, 0.5 and 0.76 inch against gravity orientation. Experimental results showed good agreement with the model predictions (Ref. 2).

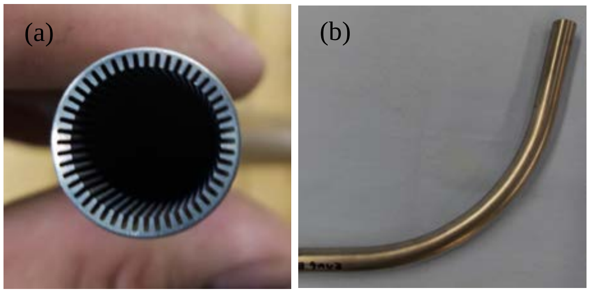

Fig. 5 Ti-H_2O heat pipe groove section (a) optimized groove geometry (b) grooved pipes after salt bending.

II.C. Heat Pipe Bending

As Fig. 2 shows, the pipes had to be bent at 90° to interface with Stirling convertor. A regular bending process would introduce local stresses that would lead to pipe deformation, weakening and grooves damage. During this research, a novel and reliable salt bending procedure was developed. Using salt particles as the medium for local stress spreading, a smooth bending profile with minimum changes in cross-section geometry was be obtained (see Fig. 5(b)).

II.D. Heat pipe assembly

After bending, grooves were aligned and multiple sections were joined together through electron beam welding. To ensure a smooth connection between screened evaporator and groove sections, an advanced hybrid joining technique was employed. The final product is shown in Fig. 6. A total of 7 heat pipes were designed and fabricated, consisting of 4 full-length pipes with CSAF interface evaporator, 2 full-length pipes with direct interface evaporator and an additional half-length pipe with direct interface evaporator for shock and vibration testing. The working fluid amount for each pipe is listed in TABLE I.

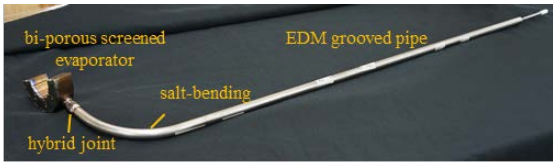

Fig. 6. Titanium water heat pipe with CSAF interface evaporator

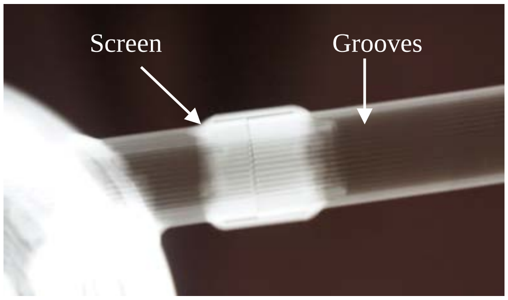

Fig. 7. Screen-groove hybrid joint x-ray image (opaque white: screen region)

TABLE I. Specifications of deliverable Titanium water heat pipes

Number	Evaporator Type	Pipe Length (inch)	Fluid Charge (ml)
A	CSAF	44.50	33.00
B	CSAF	44.50	33.00
C	CSAF	51.25	36.63
D	CSAF	51.25	36.63
E	Direct	44.50	31.94
F	Direct	44.50	31.94
G	Direct	24.00	20.94

III. THERMAL PERFORMANCE TEST SETUP

The test setup for the hybrid heat pipe was designed so that little to no changes were required between the tests. The hybrid heat pipe was mounted to a tilt table and instrumented with T type thermocouples. Power was applied to the heat pipe by an aluminum heater block mimicking the Stirling convertor cold ends. Cooling at the grooved section was provided by multiple aluminum blocks with coolant passages for nitrogen. To simulate heat pipe performance in micro-gravity, the orientation of heat pipe was slightly tilted so that the evaporator was slightly higher (< 0.2 inch) than the condenser section.

Fig. 8. Titanium water heat pipe thermal performance test apparatus

IV. THERMAL PERFORMANCE TEST RESULTS

IV.A. Prototype test results

A full-length prototype, which has a similar CSAF evaporator design was first tested. Fig. 9 shows the evaporator ΔT (T_{evap}-T_{sat}) with increased heat flux. The slope of the curve represents the thermal conductance of the evaporator. Fig. 9 (a) shows that the heat pipe at gravity-aided orientation has the highest thermal conductance. At low heat flux situation (<13 W/m^2), thermal conductance in gravity-aided orientation is lower than the against gravity case, which mainly due to the liquid paddle formation inside the evaporator. Fig. 9 (b) shows the effect of vapor saturation temperature on thermal conductance. It shows that heat pipe at higher working temperature (150°C) has higher thermal conductance because of the working fluid thermal/fluid properties enhancement. ACT also performed a freeze-thaw test. The prototype showed a smooth start-up from frozen conditions (Ref. 2).

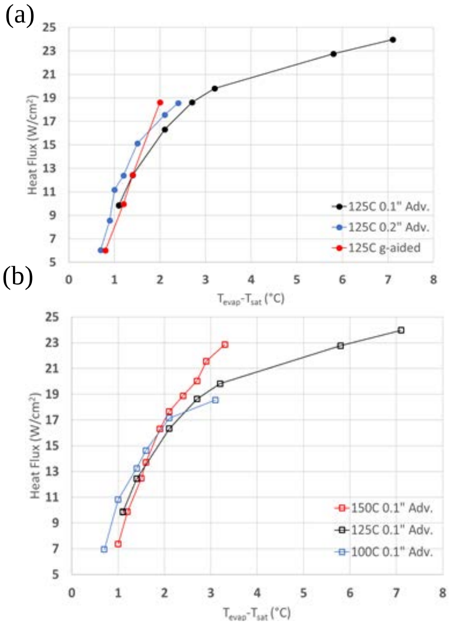

Fig. 9. Ti-H_2O heat pipe prototype evaporator ΔT (T_{evap}-T_{sat}) vs. heat flux (a) orientation dependency (b) working temperature dependency

IV.B. Deliverable test results

After prototype testing, the deliverable heat pipes were tested on the same test apparatus in against gravity orientation at a small angle (<0.1°). Fig. 10 shows the temperature variation at different locations of the heat pipes with increased heat inputs. Fig. 10(a) shows the behavior of the longest pipe with CSAF evaporator (heat pipe "C"). Fig. 10(b) shows the behavior of the short pipe with direct interface evaporator (heat pipe "F"). Both heat pipes demonstrated great isothermality and the capability to transport the required power (250W) at the working temperature of 125°C (400K). Based on the 250W power, the overall thermal conductance of the heat pipes that was calculated from the plots is 25 W/°C.

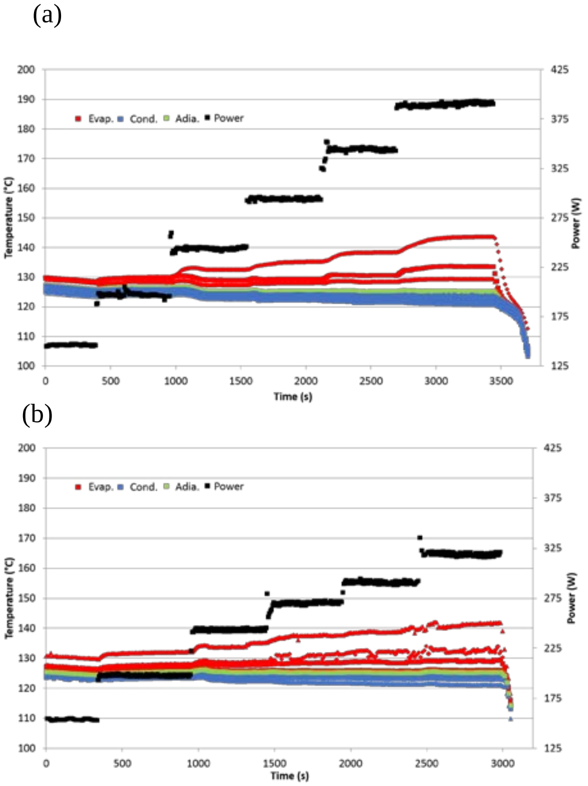

Fig. 10. Deliverable Ti-H_2O heat pipes thermal performance (a) CSAF evaporator (b) Direct interface evaporator

V. CONCLUSION

To reject the waste heat generated from small nuclear system in space, ACT have developed titanium water heat pipes with innovative hybrid wick structure. Under the SBIR program, 7 heat pipes with different evaporator designs were developed. Several technical challenges were overcome during the program, including EDM grooved pipe bending, screen-groove hybrid joint etc. Thermal performance of heat pipes was tested and the results showed that all heat pipes were capable of transferring required power at a small angle of against gravity orientation at working temperature of 400K. Next, ACT will focus on attaching aluminum fins to the groove section using S-bonding technologies and investigating the radiation cooling performance in a thermal vacuum chamber.

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