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WORKING FLUID

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CONSTRUCTION AND TESTING OF CERAMIC FABRIC HEAT PIPE WITH WATER WORKING FLUID

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Abstract

A prototype ceramic fabric/titanium water heat pipe has been constructed and tested; it transported 25 to 80 W of power at 423 K. Component development and testing is continuing with the aim of providing an improved prototype, with a 38- μ m stainless steel liner covered by a biaxially-braided Nextel (trademark of the 3M Co., St. Paul, Minnesota) sleeve that is approximately 300- μ m thick. This fabric has been tested to 800 K, and its emittance is about 0.5 at that temperature. Advanced versions of the water heat pipe will probably require a coating over the ceramic fabric in order to increase this emittance to the 0.8 to 0.9 range.

INTRODUCTION

Both the Air Force and NASA future spacecraft thermal management needs span the temperature range from cryogenics to liquid metals. Many of these needs are changing and poorly-defined and will remain so until goals, technology, and missions converge. Nevertheless, it is certain that high-temperature (about 800 K, with 100 to 1000-kW heat rejection) and medium-temperature (about 450 K, with 10 to 500-kW heat rejection) radiator systems will have to be developed that offer significant improvements over current designs. This paper addresses the lower temperature and heat regimes in a comprehensive fabric heat pipe development program. The intent of this program is to unambiguously demonstrate fabric heat pipe performance potential and identify areas for optimization.

PURPOSE OF PROPOSED WORK

The purpose of the fabric heat pipe work discussed here is twofold: (1) to construct and test a non-optimized heat pipe with a water working fluid, and (2) to obtain various fabrics and other material and test them on a subcomponent level. Both tasks aim at a proof-of-concept, and will demonstrate our current knowledge of fabric radiator components. The water heat pipe being built at Pacific Northwest Laboratory (PNL) employs ceramic fabrics in the structural and wicking components.

The approach taken in this study is to design and test a simple, easily-constructed and modified device. Because wicking poses the greatest uncertainty, it is desirable to test a variety of wicks, consisting of: the corrugated foil alone; foil plus a thin homogeneous wick, allowing the rugose foil to act as manifold grooves; foil plus arteries; and last and most complex, foil plus wick plus arteries.

TEST FABRIC HEAT PIPE DESIGN

An "ideal" fabric heat pipe would use thin fabric/foil construction throughout (see Figure 1). The test heat pipe is a metal/fabric hybrid, with thick end pieces (see Figure 2). One end piece is permanently attached; the other one is screwed in very tightly. The advantage of having a removable end piece is that various wicks can be tested and removed, through the use of a suitable jig. Other end piece designs being considered are illustrated in Figure 3. Any homogeneous wicking material employed would be pressed against the foil with a helical spring. Both the wick and the wall material consist of a biaxially braided aluminoborosilicate fabric tube. Copper is the preferred metal, for the end pieces and for the foil. Copper and ceramic fibers have both been successfully employed with water in the past (Dunn and Reay 1982).

FIGURE 1. "Ideal" Fabric Heat Pipe - All Seamless Construction

FIGURE 2. Test Heat Pipe Design

FIGURE 3. End Piece Option Details.

Fill and testing are accomplished as follows. After thorough surface cleaning and sizing removal at the heat pipe innards, an inert gas at atmospheric pressure is introduced until it displaces the air originally present. The proper amount of clean water is then injected via the fill tube, and the heat pipe sealed. Testing takes place in air, at ≤ 473 K; the pressure in the heat pipe then is about 1.55 MPa (225 psia) and the inert fill gas occupies only a negligibly small fraction of the volume. To reduce the noncondensable gas (air) fraction even further, initial heating with the fill tube partially open to permit steam venting has been instituted. After testing and prior to shutdown, this fill tube is again opened to permit pressure equalization and to prevent collapse of the central portion and stress failure of the foil at the ends.

FABRIC HEAT PIPE CONSTRUCTION AND TESTING

A non-optimized ACF heat pipe was built using currently-available materials. This heat pipe was intended to demonstrate limited operation only, as well as to provide a learning tool. It was constructed as follows:

o Outer liner	430- μ m (17-mil) thick biaxially-braided Nextel fabric
o Metal liner	200- μ m (8-mil) Titanium alloy
o Wick	ca. 250- μ m (10-mil) Nextel, held in place with 100-mesh stainless steel
o End fittings	standard swagelok
o Working fluid	water
o Dimensions	titanium is 0.016-m (5/8-in) OD x 0.9-m (36-in) long
- evaporator	0.229-m (9-in) (wrapped with electrical heating tape; titanium surface maintained at 423 K)
- adiabatic section	0.25 m
- condenser	variable; typically full remaining length in reflux mode, and about 0.25 m in adverse tilt (- 5 or - 10 degrees) mode. Heat rejection is to ambient air.

This heat pipe was filled with clean deionized water; after it was ascertained that the wick was fully saturated, about 20 % more water was added. Testing yielded reasonable performance. In the reflux mode, the heat pipe rejected about 50 W, and the condenser section was nearly isothermal over its full length, at near 373 K (measured on the outside of the fabric sleeve). Tilt angle, from vertical to horizontal, had a minimal effect on heat throughput. Later tests, with better purging of non-condensable gases from the heat pipe and better measurements of power and temperature, indicated about 80 W power handling.

When operated against gravity, with a slight tilt raising the evaporator above the condenser, performance degraded significantly. Heat rejection dropped to about 25 W and only a short section of the condenser was near 373 K; also, evidence of wick dryout in the evaporator is indicated by near - 473 K readings at the end farthest from the condenser. These data show that, as anticipated based on heat pipe code runs, the homogeneous wick is unable to pump sufficient liquid against a gravity head and a more sophisticated wick will need to be incorporated into a high-performance fabric heat pipe.

While attempting to run a long-term reflux test, we encountered a dry-out problem. We believe this was caused by seepage of water/steam past the end fittings. The temperature attained by the thermocouple at the evaporator end farthest from the condenser was about 975 K.

A more advanced version of a ceramic fabric heat pipe is being constructed using carbon-overbraided tubes, with densified ends. During the densification process, the tubes were heated to about 1175 K and held there for 4 hours.

The thermal expansion coefficient mismatch between the stainless steel foil liner and the carbon resulted in longitudinal crimping in the foil. This densification process will need to be modified in the future - a lower temperature (about 975 K) should work as well. Only the ends will be exposed to this temperature. We intend to use at least one of the crimped tubes to construct a prototype water heat pipe for use until a Nextel-overbraided heat pipe can be constructed.

COMPONENT TEST AND DEVELOPMENT

A number of aluminoborosilicate fabric sleeves have been tested at various temperatures within a small vacuum chamber. These sleeves were not coated with a high-emittance layer that we had previously used and reported on (Antoniak et al. 1989); the effective emittance then was about 0.70. Thus, the results below are indicative of inherent aluminoborosilicate fabric emittance. Note that the effective emittance includes a contact resistance between the heated mandrel (where the temperature was actually measured) and the fabric, and conduction through the fabric itself. This contact resistance was a function of braid type (with the triaxial braid and the thinner biaxial braid relatively loose on the mandrel) and temperature.

TABLE 1. Effective Emittance of Various Nextel Fabric Sleeves.

Fabric/Item	Temperature (K)	Radiated Power (W)	Effective Emittance	Comment
Painted mandrel	792	368	0.95	without fabric
400- μ m triaxial	799	115	0.27	high contact resistance
425- μ m biaxial	798	198	0.49	low contact resistance
Same	763	153	0.45	
Same	722	119	0.43	to
Same	663	82	0.40	
200- μ m triaxial	797	145	0.35	
Same	425	13	0.29	high contact resistance

Permeation tests have been performed on 38- μ m samples of a fine-grain stainless steel foil, with grain size averaging about 10 μ m. Leak detectors show no permeation using ammonia at about 900 kPa (130 psi) and hydrogen at about 3.45 MPa (500 psi), at a leak detection sensitivity of 10^{-15} m³/s. These tests were done at room temperature, and lasted about 3 weeks each. An e-beam welding apparatus will soon be used to construct tubes with this stainless foil strip. The weld will be an overlapping seam type, with a very small amount of overlap that should have a negligible effect on mechanical properties. Essentially any length tubes can be constructed in this manner, and water heat pipes representing near-optimal mass will be made with this material.

CONCLUSIONS

Good progress has been made in the development and testing of a fabric/foil water heat pipe. Preliminary heat pipe and component-level tests indicate that the goal of a survivable, low-mass (2 to 3 kg/m²) heat pipe space radiator is achievable.

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