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Fractal Loop Heat Pipe performance testing with a compressed carbon foam wick structure

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HIGHLIGHTS

- Use of compressed foam as a wick structure in a prototype Loop Heat Pipe.
- COTS (commercial off the shelf) materials fabricated and used for Loop Heat Pipes.
- Heat flux performance for a Loop Heat Pipe up to 70 W/cm^2 using water.
- Heat flux performance comparable to that with use of sintered glass wick structures.

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ABSTRACT

This study investigates heat flux performance for a prototype wick structure fabricated from compressed carbon foam when used with a Loop Heat Pipe (LHP) containing a fractal-based evaporator design. The prototype wick structure geometry was based on a previous soda lime glass wick structure designed and manufactured by Mikros Manufacturing Inc., for use with the Fractal Loop Heat Pipe (FLHP). The compressed carbon foam wick structure was manufactured by ERG Aerospace Inc., and machined to specifications comparable to that of the initial soda lime glass wick structure. Machining of the compressed foam as well as performance testing were performed at the United States Naval Academy's School of Engineering. Heat input to the FLHP was supplied via cartridge heaters mounted in a copper block. The copper heater block was placed in intimate contact with the evaporator. The evaporator had a circular cross-sectional area of 0.88 cm^2. Twice distilled, deionized water was used as the working fluid. Thermal performance data was obtained for three different Condenser/Subcooler temperatures under degassed conditions (P_{sat} of 10.5 kPa at 23 °C). The compressed carbon foam wick structure demonstrated successful start-ups in each of the test cases performed and had a maximum heat flux of 70 W/cm^2.

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1. Introduction and background

Over the past two and a half decades, Loop Heat Pipes (LHPs) have successfully flown on several NASA Goddard Space Flight Center (GSFC) instruments such as GLAS (Geo-Laser Altimeter Science), EOS-AURA's TES (Tropospheric Emissions Spectrometer) and the SWIFT Gamma Ray Burst observatory. LHPs have been established throughout the aerospace industry as reliable and robust heat acquisition/transport devices and are standard flight hardware in contemporary thermal control system (TCS) design for space flight platforms. Nonetheless, while LHPs are common place in the space community, they have yet to attain widespread use for ground applications in the private and university sectors in the United States. This is primarily due to the high costs associated with the manufacturing and/or fabrication of LHP components. Notwithstanding design details and safeguards associated with space qualification, the standard price for a space flight qualified LHP in the United States presently is approximately $1.0 M. Since cost is a primary criterion for spacecraft design on all levels (including TCS architecture), cost efficient thermal control techniques that meet technical performance requirements are highly sought after.

A review of LHP literature shows there have been numerous studies performed to gain insight into the performance and operational characteristics of LHPs. Previous studies examining LHP performance and operational characteristics have investigated start-up [1–9], shutdown [1], steady state operation [1–4,7,8], working fluid distribution [2,3,10], and hysteresis phenomena

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Nomenclature

Area	area (cm^2)
CC	compensation chamber
LHP	loop heat pipe
P	pressure (kPa)
PPI	pores per inch
T	temperature (°C)
TC	thermocouple
TM	thermistor
k	thermal conductivity (W/m-K)
h_{fg}	enthalpy of vaporization (kJ/kg)
$\dot{q}''$	heat flux per unit area (W/cm^2)
$\delta\dot{q}''$	uncertainty (W/cm^2)
x	thermocouple distance (mm)
δ	error
Δ	difference

Subscripts

cond,avg	condenser/subcooler average
int	heat flux probe/evaporator interface
k	conductivity
sat	saturation
surf	surface
T	temperature
x	thermocouple distance

[1,2,11]. Other topics investigated include analytical modeling [1,12–15], temperature oscillations [2,3,9], miniature (or small) LHP performance characteristics [4,8,16], and space flight hardware performance reviews [16,17]. In addition, there have also been several works written that provide a comprehensive overview of LHP operational characteristics [1,18,19]. In each of the aforementioned experimental studies, as well as throughout the comprehensive experimental LHP literature database to date, there have been several types of wick structure materials used. Standard wick materials used have included fine pore sintered metals such as nickel [4–6,8,9,14,16,20], titanium [21,22] and stainless steel [23,24]. Also, alternate materials such as porous silicon [13], polystyrene [25], polyethylene [7,26] and silica glass [27–29] have been incorporated into LHPs for use as wick structures at an ever increasing rate over the past decade.

In the work by Singh et al. [8], a miniature LHP (mLHP) was designed and fabricated for microprocessor cooling applications. The evaporator was a novel flat plate design which had a thickness of 5 mm with the compensation chamber positioned on the sides of the evaporator (yet within the same plane). The loop was made of copper and had a sintered nickel wick with 75% porosity. The radius for the pores in the nickel wick structure was 3–5 μm. Water was used as the working fluid. In the horizontal orientation the loop demonstrated a heat flux of 50 W/cm^2. The overall thermal resistance for the mLHP during operation varied 1.5–5.23 °C/W.

In the study by Riehl and Siqueira [7] two LHPs with slightly different evaporator geometries were fabricated and performance tested using high grade acetone as the working fluid. Both LHPs used Ultra High Molecular Weight (UHMW) polyethylene wick structures. Each wick structure had a pore radius of 6 μm and a porosity of 50%. Both loops successfully demonstrated a heat transport capacity upwards of 80 W. The overall thermal resistance of the loop over the heat loads tested varied 0.2–1.3 °C/W. Extended life tests by the authors resulted in successful start-ups with no temperature overshoot or evaporator dry-out.

Wu et al. [25] investigated LHP performance when using a polystyrene wick structure. The LHP itself was made of stainless steel. Ammonia was used as the working fluid. The wick structure was fabricated using the salt leaching method in order to tailor the wick to have high porosity and low thermal conductivity. Multiple porosities and pore radii were fabricated and tested. The best thermal performance was demonstrated with the wick structure having a porosity of 80% and a pore radius of 5.9 μm. LHP testing with these wick features successfully demonstrated a transport capacity of 320 W. At this heat load the overall thermal resistance was 0.234 °C/W.

NASA Goddard Space Flight Center (GSFC) has been actively pursuing cost efficient fabrication techniques and materials for LHPs since the mid-2000s. One previous area of interest has been evaporator technology. Using funds provided by NASA GSFC's Small Business Innovative Research program, Mikros Manufacturing Inc. successfully developed the FLHP (Fractal Loop Heat Pipe) in 2006. The FLHP included a high heat flux evaporator made by diffusion bonding multiple fractal layers with variable feature sizes. The overlay and bonding of the fractal layers resulted in the creation of small channels internal to the evaporator (see Capillary Evaporator patent [27]). The previous study by Silk and Myre [28] investigated heat flux performance for the FLHP as a function of condenser/subcooler sink temperature combination using water as the working fluid. The wick structure was made of sintered fused silica glass with an average pore size (primary wick) ranging 8–10 μm. The maximum heat flux performance observed was 75 W/cm^2. The overall thermal resistance observed at this heat flux level was 0.7 °C/W. Hysteresis testing showed negligible variation of the heat flux during the heating and cooling cycle. In addition, no failed start-ups occurred during testing.

The present work emphasizes the use of carbon foam as a wick structure in Loop Heat Pipes. Foam is a COTS (commercial off the shelf) material available in multiple material types (e.g., copper, aluminum, graphite, silicon carbide) and is capable of being machined with standard tooling. As such, validation of heat flux and/or temperature control performance with LHPs using foam materials as wick structures is another step towards reducing standard LHP fabrication costs. The reduction of LHP fabrication costs directly corresponds to the overall cost of a given space flight instrument's TCS (Thermal Control System) when incorporating LHPs into the architecture. The present work emphasizing compressed carbon foam as a viable wick structure is a continuation of NASA GSFC's effort to identify alternative, cost efficient construction techniques, methodologies and materials for LHP components that result in reduced LHP costs and greater transfer of the technology to the University and Private sector.

2. Test set-up and procedure

The experiments were conducted using an FLHP system. The FLHP evaporator is a novel design that is atypical of the axial grooved evaporator configuration used in most LHPs. As shown in Fig. 1, the evaporator structure is made from several layers of photoetched copper that have fractal like square passageways when laminated on top of one another (see Fig. 1a and b for example fractal stack-up passageway). The multiple fractal layers are diffusion bonded together. The evaporator's cylindrical cross-section is machined out of the multi-layer composite structure and integrated into the closed fluid loop (photo shown in Fig. 2). The FLHP system tested (schematic shown in Fig. 3) consisted of an evaporator, vapor line, condenser, subcooler, liquid return line and compensation chamber. The initial primary and secondary wicks