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Research Paper

Experimental heat transfer analysis of a cryogenic nitrogen pulsating heat Pipe at various liquid fill ratios

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HIGHLIGHTS

- A nitrogen based PHP has been operated at temperatures between 77 K and 80 K.
- Various fill ratios below 40% and heat loads below 4.5 W have been applied.
- A minimum startup heat load of 2 W is required to operate the PHP successfully.
- Results show a maximum thermal conductivity of 70 kW/m/K at a fill ratio of 20%.

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ABSTRACT

The experimental results of extensive testing of a cryogenic Pulsating Heat Pipe (PHP) using nitrogen as the working fluid operating between 77 K and 80 K is presented. Fifty-two different test runs were analyzed over a range of different fill ratios, heater input powers, and orientations in order to map thermal performance as a function of the system operating parameters. The temperature difference between the evaporator and condenser section were obtained using platinum resistance thermometers (PRTs), and a pressure transducer was used to record the fluid's pressure oscillations. As opposed to other N_2 pulsating heat pipes which use less than 16 parallel tubes, this experimental PHP consists of 40 parallel tubes. The PHP was operated at different liquid fill ratios ranging between 10% and 40% and heat loads between 1 W to 4.5 W. Results show that the PHP's temperature difference between section are small and resulted in high effective thermal conductivities up to 70,000 W/m/K at fill ratios around 20%. Also, it was shown the PHP stopped oscillating at heat loads below 1.5 W but operated successfully above 2 W. Results from experiments conducted in both horizontal and vertical orientations show that gravity has a significant effect on the thermal performance of the PHP even with a high number of turns.

1. Introduction

1.1. Motivation

Devices such as MRIs use liquid cryogens to cool down their superconducting magnets (SCM). Cryocoolers are used in these systems to minimize any boil-off of the cryogens, but still the cost per year of refilling the MRIs are an important factor to consider. For example, as shown in Fig. 1, 22% of helium was consumed solely for MRI magnets in 2011 [1]. Currently, liquid helium costs around \$9.5 per liter but can reach as high as \$22 per liter [1]. General Electric (GE) allocated 6 million liters per year to service its MRI magnets at hospitals and other sites in 2012 [2]. Generally, another disadvantage is that a cryocooler cannot alone cool down an entire SCM system or any extensive surface area since its cooling region is localized.

For these reasons companies are focusing on effective alternative cooling mechanisms such as pulsating heat pipes (PHPs) that may be connected to a single cryocooler and distrubute its cooling power, maintain a uniform temperature distribution, mitigate hot spots and thermal gradients.

Space agencies such as NASA are also interested in absorbing heat loads from multiple locations and rejecting heat to one cryocooler. Potential space applications are:

- Cooling heat shields of large cryo-propellant tanks at multiple locations which would replace current systems which utilize magnetic stir-bars to distribute heat loads throughout the cryogen. For proposed manned missions to Mars, large amounts of liquid cryogens will be necessary in order to travel the 67.8 million mile round-trip to the red planet. Current systems which utilize extreme insulation and stir-bars would be vastly ineffec-

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Nomenclature

A_c	total cross-sectional area (m^2)
D_{crit}	critical diameter (m)
f_{liq}	fill ratio (–)
g	acceleration due to gravity (m/s^2)
k	thermal conductivity (W/m-K)
L	length (m)
N	number of parallel tubes (–)
N_{total}	total mass in moles
P	pressure (Pa)
$\dot{Q}$	heat load or power applied (W)
R	gas constant (J/mole-K)
T	temperature (K)
$\bar{T}$	average temperature (K)
V	volume (m^3)
σ	surface tension (N/m^2)
ρ	density (kg/m^3 or $mole/m^3$)
$\bar{\rho}$	average density (kg/m^3 or $mole/m^3$)
μ	uncertainty

Subscripts

amb	ambient condition
cond	condenser section
evap	evaporator section
eff	effective
final	final value of a variable
PHP	part of PHP
P	pressure
Q	heat load
T	temperature
tank	part of supply tank
l	liquid phase
v	saturation phase
gas-lines	part of gas lines
sat	saturation

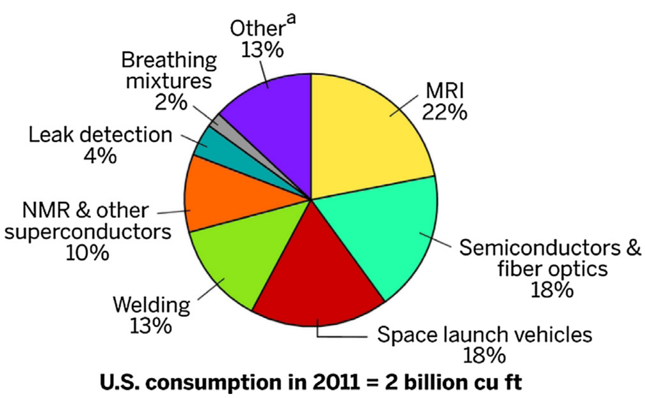

Fig. 1. Helium Consumption 2011.. Source [1]

tive for missions of such magnitude. Thus, NASA is interested in pulsating heat pipes as the core component of a revolutionary thermal management system. Data indicate that the PHPs have operated successfully, however further investigation is required to understand how these systems behave under various operating conditions.

- In addition, PHPs could be used to cool infrared (IR) optics which are currently used in detectors. IR detectors need to be at cryogenic temperatures and instead of using copper straps to connect these detectors to a cryocooler PHP's could transfer the heat with lower system mass because the work at much higher effective thermal conductivities.

Results from this PHP apparatus were published in a previous paper [10], however results of further testing are reported in this paper. In the previous published paper [10] the data was collected when the PHP valve was open, as shown in Fig. 2; therefore the PHP's capillary tubing, gas-lines and supply tank were directly connected to each other. With the PHP valve open the experiments were able to verify that cryogenic PHPs can be successfully operated in this form, however the paper did not show if the PHP operates in an optimal behavior by having the valve closed. A main advantage of operating the PHP with the valve open is if the cryocooler and relief valve malfunctions. In such a case, the PHP's

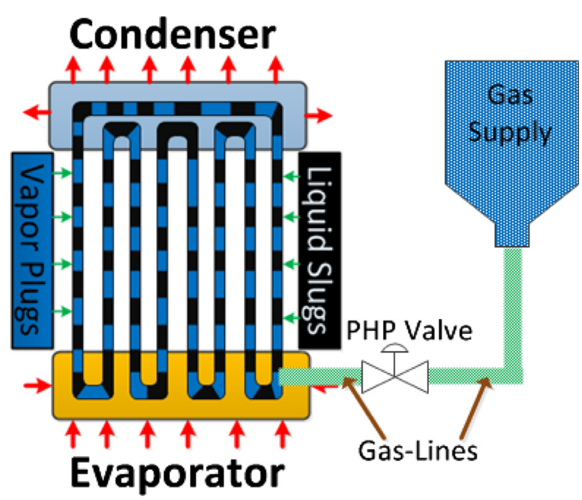

Fig. 2. Simple PHP schematic of a pulsating heat pipe.

pressure would equilibrate with the supply tank. This valve open case resulted in fill ratios between 27% and 46% and achieved a maximum effective thermal conductivity of 35,000 W/m-K at a heat load of 3.5 W and fill ratio of 27%. The data presented and analyzed in this paper is for the case when the valve is closed. An extensive set of 52 test runs were performed. In contrast to only 4 test runs with the valve open. For cases where the valve is closed, the PHP had higher effective thermal conductivities. The pulsating heat pipe described in this work consists of 40 parallel tubes with an inner diameter of 0.5 mm and an adiabatic length of 80 mm when valve is closed. Most of the experiments were conducted at lower fill ratios in order to achieve higher effective thermal conductivities since high fill ratios resulted in lower thermal performance.

In order to achieve a slug/vapor flow it is necessary that the surface tension forces be larger than the gravity forces. This criterion leads to, a critical diameter of the tube, D_{crit} [1]

$$D_{crit} \leqslant 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$