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Experimental and analytical study of a loop heat pipe at a positive elevation using neutron radiography

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ABSTRACT

An experimental and analytical study has been conducted of a loop heat pipe's steady state operating conditions at a positive elevation, which refers to when the condenser is higher than the evaporator. A unique trend of the steady state operating temperature as a function of evaporator heat load at a positive elevation was observed in the experimental data. A gravity-assisted operating theory was proposed and explained in detail. In addition, the proposed hypothesis was validated by neutron radiography, a non-destructive visualization tool. When the LHP is operated at a positive elevation, it can operate in the capillary-controlled mode, which means the system is driven by pressure gain from both surface tension and liquid head, or in the gravity-controlled mode, which means the system is driven only by the pressure gain from the liquid head. A pressure–temperature diagram illustrating the thermodynamic states of the circulating fluid was presented when the system is operating in a gravity-controlled mode. Experimental temperature data were presented for a loop heat pipe operating at 25.4, 76.2, and 127.0 mm positive elevations. Lastly, predicting results from an analytical model with the newly added features at a positive elevation were compared with the experimental results obtained at a 76.2 mm positive elevation. The model prediction and the experimental data agree well, which means the operating mechanisms were understood and captured in the model. This is the first study of a loop heat pipe focusing on a positive elevation, which unveils the unique temperature trend at low heat load operating conditions.

1. Introduction

Loop heat pipes (LHPs) were invented at the Urals Technical University in Russia in 1971 and patented in the United States in 1985 by Maidanik et al. [1]. LHPs were first developed to solve thermal management problems in space, especially on satellites [2]. After successfully demonstrating the heat transport capability and reliability in space applications, LHPs started gaining worldwide attention in the late 1980s [2–4]. Since then, numerous studies focusing on improving the efficiency and robustness of the system and understanding its operating characteristics have been conducted [5–13]. With the rapid development of nanotechnology, micro-scale LHPs are being developed and tested to meet the needs of thermal control in various applications, such as computer chips [14–19]. To effectively utilize our natural resources to generate energy, effective management of heat and power is crucial. Thus LHPs will play an increasingly important role in a variety of energy-related applications in the future [20].

As its name suggests, LHPs are closed-looped two-phase heat transfer devices that utilize evaporation and condensation to transport heat. Surface tension developed in a porous material is the main source of the pumping force used to circulate the fluid. A LHP consists of five key components: an evaporator, a reservoir, a condenser, a liquid line, and a vapor line. A schematic diagram of a typical LHP with a detailed cross-sectional drawing of the evaporator is shown in Fig. 1.

When heat is applied to the evaporator wall, it is conducted radially into the primary wick. The liquid at the outer surface of the primary wick is vaporized and collected in the vapor channel. The vapor carries the heat applied to the evaporator as it flows through the vapor line to the condenser. In the condenser, where the heat is rejected, the vapor is recondensed to liquid. The liquid then flows through the liquid line back to the evaporator. In the evaporator/reservoir assembly, the liquid line is referred to as the bayonet, which directs the liquid all the way to the closed end of the

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Nomenclature

A_w	cross-sectional area in the radial direction of liquid portion in the primary wick, m^2
f	Darcy friction factor
g	standard acceleration of gravity, m s^{-2}
h	height between the evaporator and the condenser, m
k_{eff}	effective thermal conductivity of primary wick, W m^{-1} K^{-1}
L_{wick}	length of primary wick, m
$\dot{m}$	mass flow rate of the system, kg s^{-1}
ΔP_{bay}	pressure drop in the bayonet, N m^{-2}
ΔP_c	pressure drop in the condenser, N m^{-2}
ΔP_{cap}	pressure gain from the surface tension across the evaporating menisci, N m^{-2}
ΔP_{grav}	pressure drop/gain from the gravitational head, N m^{-2}
ΔP_{ll}	pressure drop in the liquid line, N m^{-2}
ΔP_{total}	Total pressure drop of the system, N m^{-2}
ΔP_{vc}	pressure drop in the vapor channel, N m^{-2}
ΔP_{vl}	pressure drop in the vapor line, N m^{-2}
ΔP_{wick}	pressure drop of liquid flow through the primary wick, N m^{-2}
$\dot{Q}_{app}$	total heat load applied to the evaporator, W
$\dot{Q}_{r-a}$	heat loss/gain of the reservoir from the ambient, W
$\dot{Q}_{sc}$	amount of subcooling brought back by the liquid in the liquid line to the reservoir, W
$\dot{Q}_{hl}$	heat leak from the evaporator to the reservoir, W
$\dot{Q}_{hl,a}$	axial heat leak from the evaporator to the reservoir, W
$\dot{Q}_{hl,r}$	radial heat leak from the evaporator to the reservoir, W
R	local radius of the meniscus in the primary wick, m
r_{in}	inner radius of the primary wick, m
r_{out}	outer radius of the primary wick, m
$\Delta T_{ac.wick}$	temperature difference across primary wick, K
T_{amb}	ambient temperature, K
T_{evap}	evaporator wall temperature, K
T_{res}	reservoir temperature, K
T_{sink}	sink temperature, K
T_{ssot}	steady state operating temperature of the LHP, K
TL_{out}	liquid temperature at the end of the liquid line before entering the reservoir, K
TC_{out}	liquid temperature at the exit of the condenser, K
$(UA)_{LHP}$	overall heat transfer coefficient of a LHP, W K^{-1}
x	thermodynamic vapor quality
r	radial coordinate, m
κ	wick permeability, m^2
λ	latent heat of vaporization, J kg^{-1}
μ	fluid viscosity, N s m^{-2}
θ	contact angle, rad
ρ	density, kg m^3
σ	surface tension, N m^{-1}

Subscripts

g	vapor phase
l	liquid phase
1ϕ	single phase
2ϕ	two phase

Superscripts

—	mean value

evaporator. After the liquid exits the bayonet into the evaporator core, most of the liquid wets the primary wick and the secondary wick. The excess liquid goes back to the reservoir through the non-wick flow path. This completes the flow circulation cycle in an LHP. The primary wick in the evaporator is the divider between the vapor channel and the liquid core. The primary wick is usually made of sintered metal with very fine pores (on the order of 1 μm) to increase the pumping capability of the system. Unlike the primary wick, the secondary wick resides in both the evaporator core and the reservoir. It physically connects the evaporator and reservoir to prevent the primary wick from drying out when the heat load is extremely high. The secondary wick usually has greater pore size (on the order of 100 μm) than the primary wick. The detailed design and specification of primary and secondary wicks have significant influence on the performance of a LHP and are usually proprietary.

Because the evaporator and the condenser are separated by smooth and flexible transportation lines, the pressure drop for the liquid returning to the evaporator is much less than that in a traditional heat pipe. Along with the high pumping capability provided by the primary wick with a very fine pore size, LHPs can be operated against gravity efficiently. This also allows the heat source and the heat sink to be at different locations within a reasonable distance (on the order of meters), while the system still functions properly with minimal temperature differences. Another unique design of LHPs is that the evaporator and the reservoir are physically connected. This design not only prevents the primary wick from drying out but also allows vapor to exist in the evaporator core. Excess liquid and vapor inside the evaporator core can flow back to the reservoir following the non-wick flow path. Therefore, the reservoir is always under two-phase saturated condition. With all these features, LHPs are passive, robust, self-starting, reliable, and highly efficient heat transport devices.

With more and more terrestrial applications, the performance of LHPs with the presence of gravitational force has become increasingly important. Most of the existing studies in the literature on LHPs focus on their behavior when operating at an adverse elevation, which means that the condenser is below the evaporator, or at zero elevation [20–22]. It was generally assumed that the behavior of a LHP operating at a positive elevation is similar to that at an adverse or zero elevation. However, after conducting a series of tests of an ammonia LHP operating at different elevations, it was observed that a LHP operating at a positive elevation and one operating at an adverse elevation behave differently when the evaporator heat load is small. This paper presents a thorough discussion of the steady state operating theories at positive elevation conditions.

In this study, neutron radiography was employed as a visualization tool to qualitatively verify the proposed gravity-assisted operating theory. In order to produce a neutron radiograph, a continuous supply of free neutrons is directed onto the object being observed. The object modifies the neutron beam by scattering or absorbing the radiation, and the beam reaching the detector has an intensity pattern representative of the structure of the object. Neutron imaging is an ideal tool to visualize the internal fluid of a LHP [23], because the fluid (ammonia) has a high neutron attenuation, while the shell of the test LHP (aluminum) is nearly transparent to thermal neutrons. In addition, the two-phase flow in the tube can also be easily observed because of the density difference between liquid and vapor phases.