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Research paper

Experimental investigation on the operating characteristics of a dual compensation chamber loop heat pipe subjected to acceleration field

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HIGHLIGHTS

- The DCCLHP operating performance is studied experimentally in acceleration field.
- Acceleration effects have notable impacts on the DCCLHP performance in some cases.
- Temperature fluctuation and reverse flow phenomenon are observed in the tests.

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ABSTRACT

High power and high local heat flux electronic devices employed in aircraft and spacecraft sustain the high acceleration condition in maneuvers and take-off stage. Loop heat pipe (LHP) are promising in dissipating high heat load to meet the increasing cooling needs. This article presents an experimental investigation on the operating characteristics of a dual compensation chamber loop heat pipe (DCCLHP) under elevated acceleration conditions. A centrifuge with a 2 m-long arm is used to provide the acceleration up to 7 g with four different acceleration directions. The heat load applied on the evaporator ranges from 80 W to 300 W. The typical performances in terrestrial were obtained and the influence of the different acceleration direction and magnitude on the operating characteristics was analyzed. Experimental results show that the change of the vapor–liquid distributions induced by the acceleration force results in some specific operating characteristics of the DCCLHP. The operating temperature becomes lower as the effect of the acceleration force improves the liquid returning. The operation of the DCCLHP demonstrates the sensitive behavior to the acceleration direction at small heat load and insensitive behavior at large heat load. It was also found that the acceleration magnitude can alter the operating mode. A number of unstable phenomena are observed under both terrestrial gravity and elevated acceleration conditions.

1. Introduction

With the development of packing technology and miniaturization, the electronic devices with high power level and large component density are widely used in avionics and space applications. Their thermal management, however, has become a critical issue because of the high heat load and hot spots. It is recognized that the typical cooling techniques for avionics, such as conduction and forced or natural convection, cannot meet the cooling needs. Therefore, there is an urgent demand to seek new cooling techniques or design concept to keep the components within the temperature limits [1–4].

Loop heat pipes (LHPs) could become one of the most effectively used cooling methods to prevent thermal failure. LHPs use the evaporation and condensation of a working fluid to transfer the heat and the capillary forces developed in the fine porous wicks to circulate the fluid [5,6]. The advantages of the accurate temperature control capability, long distance heat transport capability and flexibility in installation make themselves successfully apply in thermal control system of spacecraft [7–9]. As a two-phase heat

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Nomenclature

a	radial acceleration, m/s^2
A	area, m^2
c	specific heat capacity, J/(kg K)
g	gravitational acceleration, 9.81 m/s^2
G	thermal conductance, W/k
I	output current, A
L	distance, m
m	mass flow rate, kg/s
Q	heat load, W
r	pore radius, m
T	temperature, K
U	output voltage, V
Δp	pressure difference, Pa
λ	thermal conductivity, W/(m K)
θ	contact angle, arc degree
σ	surface tension, N/m^2
CC	compensation chamber
CCM	constant conductance mode
DCCLHP	dual compensation chamber loop heat pipe
LHP	loop heat pipe
RTD	resistance temperature detector
VCM	variable conductance mode

Subscripts

cw	cooling water
dV	Voltage drop loss
e	evaporator
in	at inlet
loss	heat loss
mcap	maximum capillary pressure
out	at outlet
r	radial
sink	sink
total	total
w	wick
τ	tangential

transfer unit, the LHP operation embodies a variety of dynamical responses due to the complex interactions of the numerous thermodynamics forces, interfacial forces and viscos forces. When the operating condition varies, the operating temperature will change during the transient state [10–12]. However, the aboard electronic devices always suffer from a variety of acceleration forces when the fighter aircraft maneuvers and combats. The operating performance of the conventional LHP with a single compensation chamber (CC) will be influenced by the orientation of the evaporator and compensation chamber under the terrestrial gravity and acceleration environments [13–15].

During literature surveys it was found that there were limited research investigated the acceleration effects on the conventional LHPs. Ku et al. [16,17] experimentally studied the startup and operating characteristics of a miniature aluminum-ammonia LHP to examine the effects of the varying acceleration. Several different situations were considered, including the LHP startup before the acceleration was applied and vice versa, several acceleration profiles were obtained with the value of radial acceleration a_r from 0 g to 4.8 g and varying heat loads. Their results presented that the steady-state acceleration forces significantly influenced the liquid–vapor distributions in the LHP and temperature oscillation.

Fleming et al. [18] conducted an experimental study to investigate the behavior of a titanium-water LHP under the standard and elevated acceleration fields over the heat load ranges at the evaporator 100–600 W and at the compensation chamber 0–50 W with radial acceleration 0–10 g. It was found that the radial acceleration made the dry-out conditions occur more readily at a low heat input ($Q < 400$ W) while make the evaporator wall superheat turns higher when compared that with $a_r = 0$ g. The acceleration force changed the fluid distribution within the LHP and resulted in the operating temperature increases over those at $a_r = 0.1$ g in all instances, but the results obtained by Ku et al. [17] showed that the acceleration could either increase or decrease the operating temperature of LHP.

Yerkes et al. [12] experimentally investigated the transient performance of a titanium-water LHP subjected to a sine wave acceleration field with the radial acceleration value ranging from 0.5 g to 10 g and with frequency from 0.01 Hz to 0.1 Hz. They found that the acceleration driven forces complimented the thermodynamic forces which improved the LHP dynamical performance and also countered the thermodynamic forces in some cases. It resulted in immediate total failure of the LHP to operate, delayed total failure, or stable operation but in degraded condition. Whether the LHP operated prior to or started up after an acceleration functions can induce various LHP dynamical performance characteristics.

Based on the conventional LHP with a single compensation chamber, the dual compensation chamber loop heat pipe (DCCLHP) was developed by configuring two CCs on the two ends of the evaporator to solve the problem of the liquid supply difficulty for the primary wick under terrestrial gravity. Wolf and Bienert [19] investigated the temperature control characteristics of the LHPs with a single compensation chamber and dual compensation chambers. It was found that the LHP exhibited two operational modes, characterized by either constant conductance mode (CCM) or variable conductance mode (VCM). Gerhart et al. [20,21] verified that the DCCLHP operated normally when the evaporator and CCs were at different positions and presented different experimental results. Lin et al. [22–25] carried out some studies on the start-up behavior, operating characteristics, operating instability and visualization. They presented a detailed analysis in understanding the operating mechanism.

It appears from the previous investigations that there are only limited reports on the operating performance of DCCLHP. To the best of the authors' knowledge, however, compared with the conventional LHP, both theoretical and experimental investigations on the DCCLHP have been far from complete and there is still much room to be enhanced in this area. There is also a lack of available experimental data concerning the operating characteristics of the DCCLHP under acceleration fields. As such, the present research work is aimed to address the operating characteristics of the DCCLHP subjected to various heat loads and radial acceleration forces. In the current study, both transient and steady-state performances of the DCCLHP are studied under terrestrial gravity and acceleration conditions. Four different directional acceleration configurations at different acceleration magnitudes and heat loads are applied in the study.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

A new experimental test apparatus was constructed to determine the operating performance of a DCCLHP under elevated