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Effect of non-condensable gas on the operation of a loop heat pipe

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ABSTRACT

Non-condensable gas (NCG) is one of the main causes affecting the thermal performance and lifespan of the two-phase heat transfer devices. In this work, the effect of NCG on the operating performance of an ammonia–stainless steel loop heat pipe (LHP) was experimentally investigated. Nitrogen was selected as NCG, and the steady-state operating characteristics of the LHP with NCG was systematically studied for different NCG inventories, heat loads applied to the evaporator, heat load cycles and heat sink temperatures. Experimental results reveal that NCG elevates the operating temperature of the evaporator, and the more NCG exists, the higher the operating temperature of the evaporator and the larger the heat load range corresponding to the variable conductance mode. Meanwhile, the effect of NCG is notable for a smaller heat load or lower heat sink temperature. The increase of the operating temperature attributes to that NCG breaks the original energy/pressure balance of the components of the LHP, which leads to further change of heat and mass transfer as well as the redistribution of the working fluid in the loop. With NCG in the LHP, the temperature hysteresis is a common phenomenon for different heat load cycles. In addition, unique temperature oscillation was observed in the experiments, and it may be associated with the frequent repeated processes of the generation/collapse of the bubbles in the evaporator core.

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1. Introduction

Loop heat pipes (LHPs) are two-phase heat transfer devices that utilize the evaporation and condensation of a working fluid to transfer heat, and the capillary forces developed in fine porous wicks to circulate the working fluid [1,2]. Compared with conventional heat pipes, they have many advantages such as large heat transfer capacity, long distance heat transport, flexible thermal link as well as strong anti-gravity capability, which have been traditionally utilized to address the thermal management problems of spacecraft, and successfully applied in many space tasks [3–7]. However, some unfavorable phenomena such as the operating temperature rise, startup difficulty and operation failure happened in several LHPs during their runtime [8–10], and the reliability and lifespan issues have become the main challenges to promote extensive applications of LHPs.

Similar to the situation in conventional heat pipes, the non-condensable gas (NCG) is considered as one of the main causes for the decreased reliability and limited lifetime of LHPs. NCG is the gas in the two-phase heat transfer devices that cannot be condensed to liquid during the operation and always remains in the gas state. Generally, NCG consists of nitrogen, light hydrocarbons, carbon dioxide and other gaseous materials. NCG is mainly generated by the chemical reactions among the impurities which are introduced into the loop during the machining, cleaning and charging processes, container wall, wick material and the working fluid. Besides, some NCG (mainly air) will be adsorbed by the wick or the container material and diffuses gradually with the circulation of the working fluid over the system's lifetime. Depending on NCG's amount and distribution in the loop, NCG can cause the increase of the operating temperature, difficulty in startup process and heat transfer performance degradation in the condenser and evaporator. With continuous accumulation of NCG, the thermal performance of LHPs gradually degrades until complete failure. As the LHPs onboard are not allowed to repair on orbit, the adverse effects of NCG on LHPs are cumulative and irreversible.

So far, the issue of NCG for LHPs has been investigated by some researchers, which are summarized briefly as follows.

1.1. NCG distribution in the LHP

Joung [11] found there existed a constant difference between the measured CC pressure and the calculated saturation pressure corresponding to the CC temperature over the tested heat load range, and concluded that such pressure difference was due to the existence of NCG in the CC. Randeep [12] observed oxidization phenomenon on the inner wall of the CC and on the liquid absorbing surface of the wick in a flat LHP, which indicated that the major NCG storage in both gaseous state and solid metal absorption form

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Nomenclature

C_p	specific heat capacity (J/kg K)
E	energy (J)
G	thermal conductance (W/K)
$\dot{m}$	mass flowrate (kg/s)
n	number of moles
P	pressure (Pa)
Q	heat load (W)
R	universal gas constant (J/mol K)
T	temperature (K)
V	volume (m^3)

Subscripts

amb	ambient
CC	compensation chamber
Cond	condenser
cont	container
EV	evaporator
int	liquid/vapor interface
LL	liquid line
l	liquid-phase
load	heat load
leak	heat leak
loss	heat loss
NH_3	ammonia
NCG	non-condensable gas
return	returning fluid
sink	heat sink
sub	subcooling
VL	vapor line

occurs in the CC. However, the CC is not the only part where NCG existed. Nikitkin [13] measured the operating temperatures of a LHP corresponding to eight hydrogen injections, and found that the saturation temperature for the post-injection was always higher than that for the next pre-injection even though both measurements were made at the same NCG inventory. The results indicated that the saturation temperature gradually dropped with time, and the authors hypothesized that the NCG was dissolved in the working fluid and/or adsorbed by the wick and envelope material.

1.2. Effect of NCG on the steady-state performance

In Refs. [13–16], the steady-state behaviors of LHP at a given NCG inventory were experimentally investigated. The results showed that the saturation temperature of LHP increased with the NCG inventory. Moreover, the measured saturation temperatures were higher than the predicted values only considering the NCG partial pressure assuming that all NCG accumulated in the CC, indicating that the additional effect existed i.e. the heat leak from the evaporator to the CC. Cullimore and Baumann [17] simulated the effect of NCG on the thermal performance of the condenser with SINDA/FLUINT software. The model considered the mechanism for degraded heat transfer due to the existence of NCG such as liquid film blockage and diffusion-limited condensation. The calculated results showed that a small amount of NCG (1% of the total mixture in the condenser) could lead to a significant drop of heat transfer performance of the condenser.

1.3. Effect of NCG on startup behavior

Because of the partial pressure of NCG in the CC, a larger temperature gradient across the evaporator wick would be required to circulate the working fluid along the loop, thus a longer time and higher temperature rise of the evaporator was required to initiate the startup. Such theoretical analysis was consistent with both the experimental results [12,13] and modeling results [18]. Especially, a failed startup may occur at a small heat load condition. However, if some NCG located in the vapor grooves of the evaporator, the startup might be easy to initiate as it facilitated the evaporation of the working fluid there [14,19].

Essentially, the change of the thermal performance caused by NCG lies in the breaking of the original energy/pressure balance of the components of the LHP. The existing studies mostly focus on the partial pressure of NCG in the CC, but little attention has been paid to the variation of the heat and mass transfer in the whole system. In addition, most experiments were conducted under the laboratory environment, so the heat transfer between the LHP and the ambient cannot be absolutely neglected. Such unavoidable heat losses may affect both the steady-state and startup performance of the LHP, especially at small heat load conditions, so the experimental results may not be applicable in space applications.

The objective of this study is to experimentally investigate the effect of NCG on the operating performance of a LHP. By injecting nitrogen into the LHP as NCG, the operating temperature variations at steady-state state with different NCG inventories, heat loads applied to the evaporator, heat load cycling and heat sink temperatures have been systematically studied, and some important conclusions have been drawn. Moreover, the temperature oscillation phenomena caused by NCG have been observed and analyzed. According to the temperature variations of the characteristic points along the loop at both steady-state operation and transient process, the physical mechanism of the effect of NCG on the operating performance of LHP is analyzed and discussed.

2. Experimental system

2.1. Experimental setup

Fig. 1 shows the schematic of the tested LHP in this paper, which is an ammonia–stainless steel type with nickel wick. Table 1 presents the basic parameters of the LHP where CC represents the compensation chamber and OD and ID represent the outer and inner diameters, respectively. Fig. 2(a) shows the detailed structure of the evaporator and CC. The vapor and liquid transport lines and condenser line were all stainless steel smooth-walled tubes.

Heat load was applied to the evaporator casing through thin-film electric resistance heaters attached to the outer surface of the evaporator, and adjusted by altering the output voltage of the DC power in the range of 0–200 W. The maximum uncertainty of the heat load is around ±5%. The condenser line was brazed with the copper heat expansion plate, and the heat expansion plate was adhered to the two sides of an aluminum cold plate with thermal grease. The cold plate was cooled by the circulating ethanol with a controllable temperature, as detailed in Fig. 2(b). The LHP was placed in a thermal-vacuum chamber, and all the components

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