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Effect of evaporator tilt on a loop heat pipe with non-condensable gas

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ABSTRACT

The coupling effect of non-condensable gas (NCG) and evaporator tilts on the steady state operation of a loop heat pipe (LHP) was investigated both experimentally and theoretically in this work. Nitrogen was injected quantitatively into an ammonia-stainless steel LHP to simulate NCG, and the steady state characteristics of the LHP were studied under three typical evaporator tilts. According to the experimental results, the main conclusions below can be drawn. (1) The temperature is the highest under adverse tilt and the lowest under favorable tilt no matter whether there is NCG in LHP. (2) The existence of NCG could cause the increase of temperature under all three typical evaporator tilts, but the temperature increment caused by NCG seems to be relatively small under adverse tilt. (3) The increments of the temperature caused by NCG display different patterns under different tilts. Theoretical analysis was conducted to explain the results: the temperature under the coupling effect of NCG and evaporator tilt was determined by the energy balance between the heat leak from evaporator to compensation chamber and the cooling capacity of returning subcooled liquid. With the increase of heat load, the augmentation of heat leak caused by NCG and the enhancement of subcooled liquid cooling effect were incongruent. The coupling effect of NCG and evaporator tilts should be considered in the terrestrial application of LHP.

1. Introduction

Loop heat pipe (LHP) is an efficient and reliable two-phase heat-transfer device that utilizes the phase change of working fluid between heat source and heat sink to transfer heat. The capillary force developed in the efficient porous structure is the driving force that circulates the working fluid in the loop [1,2]. Compared with traditional heat pipe, LHP possesses many unique advantages such as high heat transfer capacity and flexible application [3–5], and has been applied to aerospace field for many years [6–8].

However, degradation of LHP performance has been found in practical spacecraft application [9–11]. The non-condensable gas (NCG) produced during the operation of LHP was believed to be responsible for the performance degradation and lifespan issues of LHP [12]. NCG is the gas that cannot condense into liquid phase within the operating temperature range of the two-phase systems. In recent years, a few studies about the NCG effect on the performance of LHP have been conducted, and corresponding solutions have been studied as well. Ref. [13] and Ref. [14] studied the impacts of NCG on the steady state characteristics of LHP by injecting NCG into LHP quantificationally. Experiments showed that the operation of LHP was insensitive to the presence of NCG compared with conventional heat pipes, but NCG would increase the startup time and operating temperature. Ref. [15] investigated the heat transport characteristics of reservoir embedded loop heat pipe with different NCG inventories by experiment and calculation. It was found that NCG increased the operating temperature due to the partial pressure of NCG in compensation chamber (CC) and the effect was more significant when the heat load was small. Ref. [16] investigated the effects of NCG on the operating characteristics of LHP systemically, including temperature hysteresis phenomenon. Besides, in the operating of LHP with NCG, distinct temperature oscillation phenomenon was observed. Ref. [17] designed a LHP that can operate at 125 °C, and tested the operating performance in the case with NCG. Ref. [18] investigated the control effect of thermoelectric cooler on the operating of LHP and found that the application of thermoelectric cooler could significantly reduce the temperature rise caused by NCG.

Recently, LHP technology has been developed for aircraft applications and the gas/liquid distribution in LHP would be affected significantly by gravity, which is quite different from the case in space [19,20]. It seems that the relative position between evaporator and CC has much great impacts on the performance of LHP because the tilt of evaporator could change the heat and mass

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Nomenclature

C_p	specific heat at constant pressure (J/(kg·K))
G	thermal conductance (W/K)
I	current (A)
m	mass (kg)
P	pressure (Pa)
Q	heat (W)
R	electric resistance (Ω), thermal resistance (°C/W)
T	temperature (°C)

Subscripts

eva	evaporator
heater	kapton heater
leak	heat leak
loss	pressure loss of the flow
return	return subcooled liquid
sink	heat sink

transfer process in evaporator and CC significantly. So far, there has been some literature that reported the effect of evaporator tilt on LHP performance. Ref. [20] investigated the operating temperature of a LHP without secondary wick under terrestrial surroundings experimentally. The evaporator tilt was found to have a significant effect on the operating temperature of LHP. The operating temperature was much higher when the evaporator was above the CC, and the weak cooling effect of returning liquid on the vapor in CC or evaporator core was considered as the main reason. Ref. [21] investigated the tilt effects on the operation of LHP at small heat load, and the test results showed that the tilt of evaporator affected the operating of LHP by changing the void fraction inside evaporator core. Ref. [22] investigated the behaviors of a flat-oval evaporator LHP under different orientations in two perpendicular planes. Ref. [23] studied the operating performance of a LHP with liquid guiding holes. The research found that, when the tilt angle between evaporator and CC increased, the change of operating temperature was disparate within different heat load range. Ref. [24] tested a miniature loop heat pipe under horizontal and four vertical orientations. The operating temperature under the orientation "evaporator above CC" was quite special. Ref. [25] studied the effect of tilts on the operation of a miniature LHP with two evaporators and two condensers. The heat transport capability decreased with an increasing adverse tilt angle.

As briefly reviewed above, NCG and the tilt of evaporator both had great effects on the performance of LHP under terrestrial conditions. On one hand, the existence of NCG would usually affect the steady state operation of LHP adversely, such as the degradation of heat transfer performance. On the other hand, the evaporator tilts could have favorable or adverse effect on the performance depending on the specific tilt. The effects of the two factors would usually coexist in the practical terrestrial applications of LHP, and the research on their coupling effect was necessary consequently. However, although the effect of NCG and that of evaporator tilt have been studied in depth respectively, few studies have investigated the coupling effect of them, and their coupling effect and corresponding mechanism were still vague. The main objective of this paper is to experimentally investigate the effects of NCG on the performance of LHP under different tilts and the corresponding physical mechanism was analyzed theoretically based on the results of the experiments.

2. Experimental setup

2.1. Experimental apparatus

The schematic of the experimental apparatus is shown in Fig. 1. The experimental apparatus included the tested LHP, DC power supply, coolant circulation device, data acquisition system and air conditioning system. As shown in Fig. 2, the tested LHP in this paper is an ammonia-stainless steel loop heat pipe, consisting of an evaporator, a compensation chamber, a condenser, liquid and vapor lines. The basic parameters of the tested LHP were illustrated in Table 1, where OD/ID represent the outer/inner diameters respectively. The vapor line, liquid line and condenser line were all smooth stainless steel tubes. Fig. 3 showed the photo of evaporator and CC, and Fig. 4 showed the internal structure of the evaporator and the CC. The evaporator and CC were not coaxial, and the evaporator casing was tangent to the CC casing. The primary wick was sintered with nickel powder and the evaporator core was filled with stainless steel wire mesh (not displayed by Fig. 4) as the secondary wick.

The heat load was applied to the evaporator by the kapton heater glued closely on the surface of the evaporator and the different heat loads were simulated by changing the output current of the DC power supply. Because of the contact thermal resistance between the evaporator casing and the kapton heater, the temperature difference between them would rise with the increase of heat load. Limited by the maximum allowable temperature of the kapton heater (about 120 °C), the maximum heat load was 135 W. As shown in Fig. 5, the condenser line was brazed on the groove of copper plate and the copper plate was glued to the two surfaces of an aluminum cold plate with thermal grease. The cold plate was cooled by a temperature-controlled coolant circulation machine. The pipes connecting cold plate and coolant circulation machine were covered with rubber foam insulation material. The thermal conductivity of the insulation material was 0.034 W/(m·K) and the thickness was about 1 cm. Since the specific heat capacity of coolant (water) was huge and the connecting pipes were insulated, the heat sink temperature was considered equal to the temperature of coolant in coolant circulation machine. The temperature control precision of heat sink was ± 0.5 °C.

Eighteen type T thermocouples were attached on the outer surface of the tested LHP to monitor the temperature along the loop and the measure point locations were displayed in Fig. 6. The Data acquisition system consisted of a computer (with Benchlink Data Logger 3 software) and an Agilent 34970A data acquisition module. The measured temperature data was recorded and stored every 5 s. The tilt angle of evaporator was adjusted by raising the end of evaporator or CC. The geometric centers of evaporator and condenser were placed at the same level of height in all experiments of this paper and the height difference was less than 2 cm. In order to reduce the heat transfer between the tested LHP and ambient, all components of the tested LHP were covered by rubber foam insulation material. The ambient temperature was controlled through the air conditioning system of which the temperature control accuracy was ±2 °C.

2.2. Experimental conditions

As shown in Fig. 7, the symbol β refers to the angle between the evaporator axis and the horizontal plane, and β is defined as positive when the evaporator is higher than CC. The condition $\beta > 0°$ was called adverse tilt and $\beta < 0°$ was favorable tilt. In order to