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Research paper

Steady-state modeling and analysis of a loop heat pipe under gravity-assisted operation

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HIGHLIGHTS

- Steady-state model of a LHP under gravity-assisted operation has been established.
- Two driving modes have been identified and theoretically analyzed.
- Operating temperature curve of LHP exhibits unique trend under gravity-driven mode.
- Positive elevation has great effect on LHP performance under gravity-driven mode.
- Enhanced cooling and reduced heat leak to the CC lead to better LHP performance.

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ABSTRACT

Loop heat pipes (LHPs) are efficient two-phase heat transfer devices that have found many space and terrestrial applications. This work addresses our insufficient understanding of LHP operation under gravity-assisted attitude, i.e. the condenser is located higher than the evaporator. A steady-state mathematical model of a LHP under gravity-assisted operation was established based on two driving modes: gravity driven mode and capillarity-gravity co-driven mode, determined by a defined transition heat load. The model was validated by the experimental results, and was employed to predict the operating characteristics of a LHP under the gravity-assisted attitude. Comparing to LHPs operating under horizontal or antigravity attitudes, some distinctive features have been identified, which include: i) the total mass flowrate in the loop shows a unique V-shape with the increase of applied heat load; ii) the steady-state operating temperature is much lower under the gravity driven mode, and is in similar values under capillarity-gravity co-driven mode and iii) the thermal conductance of the LHP increases with increasing positive elevation especially in the variable conductance zone. Such results contribute greatly to the understanding of the complicated operating principle and characteristics of LHPs especially for terrestrial applications.

1. Introduction

Loop heat pipes (LHPs) are effective and efficient 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]. Their high pumping capability and superior heat transport performance have been traditionally utilized to address the thermal-management problems of spacecraft, and they were successfully applied in many space tasks [3–7]. More recently, its application has been extended to terrestrial surroundings such as in electronics cooling [8–11] and thermal-management systems for aircraft and submarines [12–15]. Their long distance heat transport capability and flexibility in design could offer many advantages compared with traditional heat pipes and other heat transfer devices.

So far, quite a few studies on the mathematical modeling of LHPs have been conducted, which revealed some working principles and operating characteristics of LHPs [16–23], as briefly reviewed below. Kaya et al. [16] established a one-dimensional steady-state

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mathematical model of a LHP, which could reflect the variable conductance characteristics of the LHP, but the oversimplification in calculating the radial conductance of the wick and two-phase pressure drop in the condenser brought large difference between the modeling and experimental results. Improved treatment on the two-phase pressure drop in the condenser was conducted by Hoang et al. [17], where five different two-phase pressure drop correlations were assessed and better predictions were achieved. The modeling of the radial conductance of the evaporator wick was improved by Parker [18] through solving a radial one-dimensional energy equation, in which the effect of the fluid convection was considered. Chuang et al. [19] developed a comprehensive steady-state model, which showed good predictions when the evaporator was horizontal with or higher than the condenser, but large deviation from the experimental results was observed under the gravity-assisted attitude. Further improvement was attempted by Vlassov et al. [20] where the liquid/vapor interface in the condenser and the void fraction in the compensation chamber (CC) could be determined. Bai et al. [21] developed a steady-state mathematical model of a LHP by considering the evaporator wick as either single-layer or two-layer composite structures, and the condenser having the annular flow pattern. The effects of surface tension of liquid and the interaction between the liquid and vapor phases in the condenser including both frictional and momentum-transfer shear stresses were considered. The model revealed the observed thermal conductance reduction phenomena when LHPs operated in the constant conductance zone, which cannot be reflected by traditional models. Fang et al. [22] conducted a numerical analysis based on a two-dimensional dynamic mesh model to investigate the influence of non-uniform heat load on the performance of a flat-plate evaporator LHP. The variations of evaporation heat transfer coefficient, outflow working fluid temperature, vapor and liquid interface position and surface temperature at different heat loads were analyzed. A mathematical model of the startup process of a LHP was established by Bai et al. [23] based on the node network method, and a parametric analysis including the effects of startup heat load, thermal capacity of the evaporator and CC, heat sink temperature and ambient temperature on the startup characteristics of the LHP were conducted.

To the best of our knowledge, the mathematical models presented above are only applicable to the situation when the LHP is under horizontal or antigravity attitudes. When the LHP is operating under the gravity-assisted attitude, i.e. the condenser is located higher than the evaporator, large deviation will exist between the modeling and experimental results. Chuang et al. [24] conducted an experimental and analytical study of a loop heat pipe at a positive elevation using neutron radiography. The change of the liquid/vapor distribution and flow pattern in the vapor transport line under the gravity-assisted attitude was captured by the employment of the non-destructive visualization technique. Experimental results showed that when the LHP was operating under the gravity-assisted attitude, the operating temperature exhibited unique variation trend, and the authors proposed a gravity-assisted operating theory, which categorized the steady-state operation into capillary-controlled and gravity-controlled modes to better explain the observed experimental phenomena.

However, theoretical investigation on the LHP operation under the gravity-assisted attitude is quite limited and obviously inadequate so far, i.e. in the experimental and analytical study of Ref [24], the positive elevation range is quite small (0–127 mm), and the heat sink temperature is set as a fixed value of 5 °C, which cannot reflect the unique characteristics at a relatively large positive elevation and lower heat sink temperature; in addition, how the transition heat load separating the LHP operation into the capillary-controlled and gravity-controlled modes changes with operating parameters such as the positive elevation and heat sink temperature is still not well understood. With the rapid development of LHP application in terrestrial surroundings, it is of great interest to establish an accurate mathematical model of LHPs operating under the gravity-assisted attitude to better understand its operating principle and characteristics and guide the engineering design, which forms the objective of this study.

2. Mathematical modeling

2.1. Two driving modes

When the LHP is operating under horizontal or antigravity attitudes, the capillary force generated by the evaporator wick is the driving source for the circulation of the working fluid in the loop. However, when the LHP is operating under the gravity-assisted attitude, the situation becomes much different and very complicated.

As reviewed above, two driving modes have been identified under the gravity-assisted attitude [24,25]: gravity-driven mode and capillarity-gravity co-driven mode, depending on the applied heat load. At a small heat load, the LHP tends to operate in the gravity-driven mode where the gravity is the only driving source for the circulation of the working fluid. Under such a condition, the working fluid in the vapor line is in the two-phase state due to the existence of additional liquid mass flow, and no clear liquid/vapor interface exists at the outer surface of the evaporator wick, as shown in Fig. 1(a). At a relatively large heat load, the LHP operates in the capillarity-gravity co-driven mode, where the capillary force and gravity are both driving sources for the circulation of the working fluid. Under this condition, the working fluid in the vapor line is pure vapor, and there is a clear liquid/vapor interface at the outer surface of the evaporator wick, as shown in Fig. 1(b).

2.2. Determination of the transition heat load

To realize the steady-state modeling of a LHP under gravity-assisted operation, the first and most important step is to determine the transition heat load (Q_{tr}), i.e. the heat load responsible for the transition from the gravity driven mode to capillarity-gravity co-driven model. With the transition heat load applied to the evaporator, the working fluid in the vapor line is pure vapor, and the gravitational pressure head generated in the liquid line just satisfies the requirement to drive the circulation of the working fluid in the loop, so the pressure balance equation can be expressed as:

$$\int_{ll} \rho_l g \mathrm{d}H = \Delta P_{vg} + \Delta P_{vl} + \Delta P_c + \Delta P_{ll} + \Delta P_{wi} \tag{1}$$

Because the gravitational pressure head in the liquid line and the frictional pressure drop in each component of the LHP are both strong functions of the operating temperature, however, the steady-state operating temperature is initially unknown, it is impossible to directly calculate the transition heat load based on Equation (1). At the same time, it reminds us that the transition heat load and the steady-state operating temperature should be obtained simultaneously.

In order to obtain the transition heat load and the operating temperature simultaneously, a detailed solution flowchart is presented in Fig. 2. Below are some introductions to the solution flowchart:

1) Calculation of the heat transfer and pressure drop in each component of the LHP in Fig. 2 is the same as that in our previous mathematical model [21], and is not repeated here.