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Theoretical analysis of steady-state performance of a loop heat pipe with a novel evaporator

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HIGHLIGHTS

- A loop heat pipe (LHP) with novel evaporator is proposed.
- The novel evaporator features very small heat leak from the evaporator to the CC.
- The LHP with novel evaporator has improved operating stability and reliability.
- Mathematical model of the LHP with novel evaporator is established.
- The operating characteristics and heat transfer limit are theoretically analyzed.

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ABSTRACT

A novel evaporator that features very small heat leak from the evaporator to the compensation chamber (CC) is proposed to improve the operating performance and reliability of loop heat pipes (LHPs). The mathematical model of the steady-state operation of the LHP is established, and its operating characteristics and heat transport limit are theoretically investigated. The modeling results show that the novel evaporator design can significantly reduce the heat leak from the evaporator to the CC. In this new evaporator design, the liquid flow pressure drop in the evaporator wick becomes the major component of the total pressure drop, and the LHP operation becomes insensitive to the adverse elevation. The heat transport limit of the LHP is found to be determined by the boiling limit under low adverse elevation, and by the capillary limit at relatively large adverse elevation.

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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]. Their long distance heat transport capacity and flexibility in design as well as strong antigravity capability could offer many advantages compared with traditional heat pipes, and they have been widely used in the spacecraft thermal control system [2,3]. Recently, their application fields have been extended to aircraft thermal management system [4,5] and terrestrial electronic cooling [6–10], and big progress has been made.

The current LHP evaporator design is typically of cylindrical shape, as shown in Fig. 1, where vapor grooves are manufactured at the outer surface of the evaporator wick. Liquid is supplied to the evaporator wick along the radial direction through the bayonet, and evaporation occurs at the outer surface of the wick. This type of design has many advantages, for instance, it can reduce effectively both the liquid flow pressure drop in the evaporator wick and the thermal resistance of the evaporator, which contributes considerably to the improvement of LHP performance.

However, for such a conventional design, the radial heat leak from the evaporator to the CC is comparatively large, which may cause several issues for the reliable operation of LHPs, notably (i) the LHP may not be able to startup below a certain heat load due to the failure of producing sufficient temperature/pressure difference between the evaporator and the CC [11,12]; (ii) the reverse flow phenomenon may occur in some situations during the startup process, increasing significantly the evaporator temperature [13,14]; (iii) the temperature oscillation phenomenon may occur at certain heat load range during the steady-state operation, making precise temperature control rather difficult [15–18]; and (iv) the temperature

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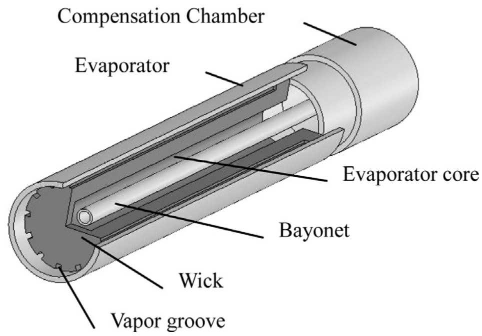

Fig. 1. Detailed structure of traditional LHP evaporator.

hysteresis becomes a common phenomenon during the power cycling process, i.e. the heat-load dependence of the operating temperature is not always deterministic [11,14,19], and accurate predictions of LHP operating temperature is hard to achieve.

The mechanisms responsible for the issues mentioned above have not all been clearly understood. However, it is accepted by most researchers that they are all closely related to the large heat leak from the evaporator to the CC. For current space applications of LHPs, some auxiliary measures such as the use of startup heater and thermal electric cooler (TEC) have to be employed to enhance the operating stability and reliability of LHPs. However, it destroys the unique nature of LHP as a completely passive heat transfer device, and requires necessary external power, which adds further difficulties for space applications.

A novel evaporator design is proposed in this work to enhance the operating stability and reliability of LHPs. The new design could reduce effectively the heat leak from the evaporator to the CC through active modulation of phase distribution and flow path of the working fluid in the evaporator. A detailed mathematical model of the steady-state operation of the LHP with the novel evaporator is established, and the operating characteristics and heat transport limit of the LHP are theoretically investigated, which contributes to a better understanding of the operating mechanism and can guide the design of the LHPs.

2. Mathematical model

2.1. Operation of the LHP with a novel evaporator

The LHP with a novel evaporator proposed in this work consists of an evaporator, a condenser, a CC and vapor and liquid transport lines, as shown in Fig. 2. For the evaporator, there is no vapor grooves at the outer surface of the evaporator wick, instead the wick is composed of a thin layer of metal powder such as copper, nickel or stainless steel sintered directly onto the inner wall of the evaporator casing. Through such a novel design, the heat load applied to the evaporator is conducted through the thin layer of the wick, and evaporation occurs at the inner surface of the evaporator wick. The generated vapor flows into the vapor line through the evaporator core, then it enters the condenser where heat is rejected and fluid condenses. The condensed liquid flows into the CC through the liquid line, where liquid is supplied to the evaporator wick through the porous layer in the CC and forms a flow loop. The circulation of the working fluid is driven by the capillary pressure developed in the evaporator wick by the inverted meniscus, and no external power is needed.

Compared with the traditional evaporator design, as shown in Fig. 1, the radial heat leak from the evaporator to the CC can be

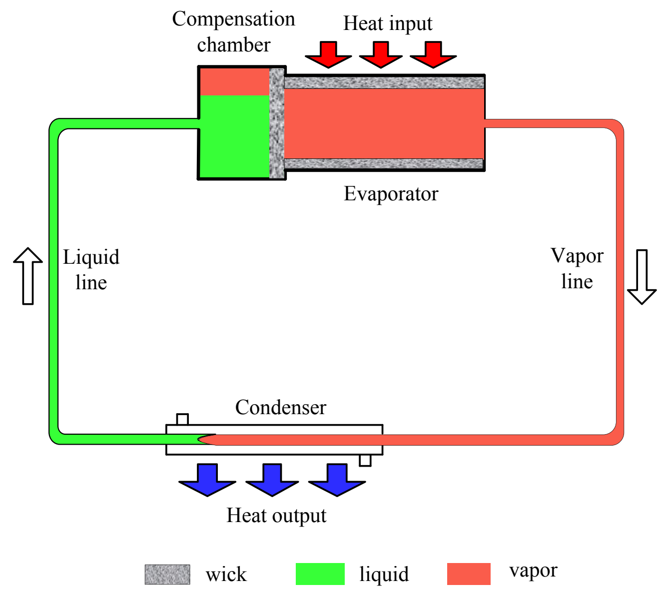

Fig. 2. Schematic of the loop heat pipe with a novel evaporator.

significantly reduced. The heat transfer from the evaporator to the CC is mainly by the thermal conduction through the evaporator and CC walls, and further evaporation could occur at the interface of the porous barrier between the CC and the evaporator. Consequently the heat leak from the evaporator to the CC can be reduced considerably, which would improve the operating stability and reliability of the LHPs, as analyzed below. In addition, the simple design makes the manufacturing process of the evaporator and the CC easier.

2.2. Heat transfer in the evaporator and CC

Fig. 3 shows the schematic of the evaporator and CC, and Fig. 4 shows the thermal network of the evaporator and CC. The heat load (Q_q) generated by the heat source is first transferred to the evaporator casing through the saddle, as expressed by Eq. (1):

$$Q_q = G_{q,w} \times (T_q - T_{w,e}) \tag{1}$$

It then transports along two paths: one part (Q_1) is transferred to the CC casing, i.e. the axial heat leak from the evaporator to the CC, as shown by Eq. (2):

$$Q_1 = G_{w,e-cc} \times (T_{w,e} - T_{w,cc}) \tag{2}$$

and the other part (Q_2) is transferred to the liquid/vapor interface at the inner surface of the evaporator wick through the evaporator wick, as shown by Eq. (3):

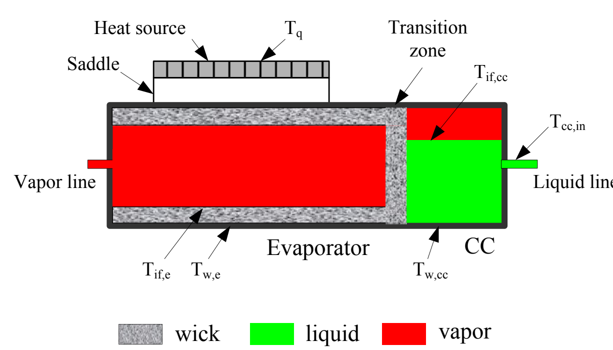

Fig. 3. Schematic of the evaporator and CC.

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