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Modeling and analysis of startup of a loop heat pipe

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ABSTRACT

The startup behavior of a loop heat pipe (LHP) is one of the key aspects in evaluating its working performance. A mathematical model of the startup process of a LHP is established based on the node network method in this work. A parametric analysis on the startup characteristics of the LHP is conducted, where the effects of startup heat load, thermal capacity of the evaporator and compensation chamber, heat sink temperature, ambient temperature, heat leak from the evaporator to the compensation chamber and cooling on the compensation chamber on the startup characteristics of the LHP are evaluated, which contributes to the improvement of the LHP startup performance.

1. Introduction

Loop heat pipes (LHP) 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 fluid [1]. Their high pumping capability and good heat transfer performance have been traditionally utilized to address the thermal-management problems of spacecraft, and been successfully applied in many space tasks [2,3]. Their long distance heat transport capability and flexibility in design could offer many advantages compared with traditional heat pipes. More recently, its application has extended to terrestrial surroundings such as in high power density electronics cooling and low grade heat utilization [4–7].

The startup performance is one of the key aspects in evaluating the working performance of a LHP. Starting a LHP rapidly and smoothly is the first problem to be solved for any practical applications. The startup of LHP is a complex dynamic process that includes the redistribution and circulation of working fluid in the loop while accompanying many phase-change phenomena such as nucleate boiling, evaporation and condensation before every component in the system reaches a steady state. So far, the investigation of the startup characteristics of LHP is mainly through experimental method [8–15]. For instance, Ref. [8] firstly identified four startup situations depending on the initial liquid/vapor composition in the evaporator. The startup was found to be the most difficult when the vapor grooves were flooded with liquid while there was vapor trapped in the evaporator core. Similar conclusions were reached in Refs. [9,10]. The influence of various parameters including liquid/vapor distribution in the evaporator, adverse elevation, startup heat load and heat sink temperature on the startup behaviors was investigated in Ref. [11], where a saturated temperature rise of the compensation chamber (CC) due to a "pressure transfer" phenomenon was discussed. The startup performance test of an ammonia LHP was conducted in Ref. [12], which showed that a successful startup could be reached when the startup heat load was higher than 50 W, whereas a temperature overshoot exceeding the maximum allowable value would occur for smaller heat loads, i.e., <25 W. The incidence rate of unsuccessful startup increased as the decrease of startup heat loads. To address such a problem, Ref. [13] investigated the effects of two active auxiliary measures, i.e., local heating on the evaporator and local cooling on the CC using a thermoelectric cooler, and a passive auxiliary measure based on phase-change materials (PCM), aiming to maintain the CC temperature at its melting point during the startup. Experimental results indicated that all these three auxiliary measures were useful to establish the temperature difference between the evaporator and CC, and reduce the startup temperature overshoot and the startup time. However, at very low startup heat loads, the PCM could only delay the rise of the evaporator temperature. In order to aid the startup process, the concept of dual compensation chambers was proposed and investigated in Refs. [14,15], which showed that lower startup heat load and larger heat leak from the evaporator to the CC were adverse to the startup performance.

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Compared with experimental studies, only a few theoretical studies on the startup characteristics of LHP have been conducted. Among these, the effects of the thermal mass of the device to be cooled, the superheat, the startup heat load, non-condensable gas (NCG) and adverse elevation on the startup performance of a LHP were first analyzed in Refs. [16,17], and recently reviewed in Refs. [18,19]. A dynamic mathematical model of a LHP was established in Refs. [20,21], which could simulate the startup process of the LHP, but the startup characteristics was not studied in detail.

This work aims to establish a mathematical model for the startup process of a LHP based on the node network method. A parametric study of the effects of startup heat load, thermal capacity of the evaporator and compensation chamber, heat sink temperature and ambient temperature on the startup performance of the LHP will be investigated, which will contribute to the understanding and improvement of the LHP startup performance.

2. Mathematical model

A typical LHP consists of an evaporator, a condenser, a compensation chamber (CC), and vapor and liquid transport lines, and Fig. 1 shows the detailed structure of the evaporator, CC and condenser. The vapor transport line connects the vapor grooves and the condenser inlet, and the liquid transport line connects the bayonet and the condenser outlet. The basic working principles and operating characteristics of LHP were introduced in Ref. [1]. When LHP start to work, liquid is vaporized in the vapor grooves, and the menisci formed in the evaporator wick develop a capillary pressure to push the vapor through the vapor transport line to the condenser where heat is rejected. The condensed liquid is pushed back through the liquid transport line to the evaporator.

Node network method is used in this work to simulate the startup process of LHP. In this method, the LHP is divided into several nodes, each one represents a certain control volume, and the LHP is represented by a network of nodes. Governing equations including mass, momentum and energy equations are established for every node to achieve the modeling of the startup of the LHP. There are two types of nodes in the node network of the LHP, namely the wall node and fluid node, representing the wall and fluid of each component, respectively. Energy exchange between wall nodes and fluid nodes is permitted. Note that, only energy equation is needed for the wall nodes as the wall is stationary, while all mass, momentum and energy equations are required for the fluid nodes. The mathematical description of each node is presented below.

2.1. The transport lines

The transport lines include the vapor transport line and liquid transport line, which are usually smooth small pipes with long

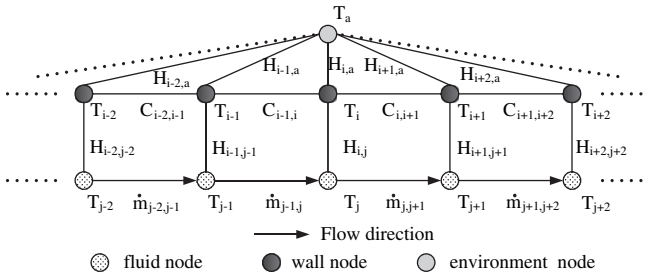

Fig. 2. The node network of the transport lines.

transport length. In the model, the transport lines are evenly divided into a number of nodes where each node represents a certain control volume with governing equations. The model accuracy can be improved by the increase of the node number, but the computational requirement would be increased accordingly. The node number should be determined appropriately. Fig. 2 shows the node network of the transport lines.

According to Fig. 2, the energy equation of the wall node i of the transport lines is:

$$m_i C_{pi}\frac{dT_i}{dt} = C_{i-1,i}(T_{i-1}-T_i) + C_{i,i+1}(T_{i+1}-T_i) + H_{i,j}(T_j-T_i) + H_{i,a}(T_a-T_i) \quad (1)$$

In equation (1), the thermal conductance between wall nodes $i-1$ and i ($C_{i-1,i}$) and between wall nodes i and $i+1$ ($C_{i,i+1}$) can be simply determined by the Fourier law of thermal conduction. The calculations of the thermal conductance between wall node i and fluid node j ($H_{i,j}$) by forced convection and between wall node i and ambient ($H_{i,a}$) by natural convection were detailed in our previous paper (Ref. [22]), which are not repeated here.

The mass equation of the fluid node j of the transport lines is:

$$\frac{dm_j}{dt} = \dot{m}_{j-1,j} - \dot{m}_{j,j+1} \quad (2)$$

The momentum equation between the nodes j and $j+1$ of the transport lines is:

$$\left(\frac{L_{j,j+1}}{A_{j,j+1}}\right)\frac{d\dot{m}_{j,j+1}}{dt} = P_j - P_{j+1} - \left(\Delta P_f\right)_{j,j+1} - \rho_{j,j+1} g \Delta z_{j,j+1} \quad (3)$$

The energy equation of the fluid node j of the transport lines is:

$$\frac{d(m_j h_j)}{dt} = H_{i,j}(T_i - T_j) + \dot{m}_{j-1,j}h_{j-1} - \dot{m}_{j,j+1}h_j \quad (4)$$

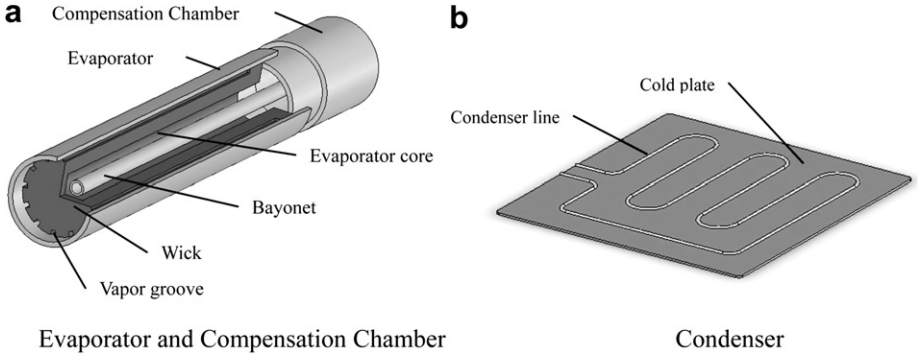

Fig. 1. Construction of the evaporator, CC and condenser.