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Numerical study on the operating characteristics of cryogenic loop heat pipes based on a one-dimensional heat leak model

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ABSTRACT

The cryogenic loop heat pipe is an effective and reliable heat transfer system in the space technology. A global model of cryogenic loop heat pipe is developed by full consideration of the subcooled effect and the mass flow rate variation of the working fluid along the evaporator core. The heat leak is calculated on the basis of one-dimensional temperature distributions in the evaporator core. The calculation of the proposed model improves the prediction accuracy relative to traditional zero-dimensional models. The effects of filling pressure, parasitic heat load, auxiliary heat load, and use of bayonet on the CLHP performance are investigated. A normal "U-shape" of the evaporating temperature curve appears at a low filling pressure (1.45 MPa). At moderate and high filling pressures (1.465 MPa and 1.5 MPa, respectively), two new evaporating temperature curves with "flat bottom U-shape" and "L-shape", which shows the unique operating characteristics of cryogenic loop heat pipes, are found. The two new profiles are attributed to the coupling of mass and energy between gas reservoir and primary compensation chamber. The determinant factor for the minimum working heat load is the void fraction of the primary compensation chamber. By contrast, the maximum working heat load is determined by the void fraction at a low filling pressure (below 1.4 MPa) and the maximum capillary pressure at a high filling pressure (above 1.4 MPa). The use of a bayonet can decrease the maximum vapor quality in the evaporator core and effectively avoid burnout.

1. Introduction

Loop heat pipes (LHPs) utilize the latent heat of working fluids to transport heat [1]. LHPs are widely used to deal with thermal control problems with the temperature range from 270 K to 350 K due to their highly efficient heat transfer capability and long heat transport distance [2]. The cryogenic loop heat pipe (CLHP) is developed from the LHP to specifically address heat transfer problems in the cryogenic applications (under 100 K), such as the thermal control of optical devices in deep space probes [3].

A CLHP consists of primary and secondary loops as well as a gas reservoir. Each loop consists of a compensation chamber (CC), a condenser, liquid line, vapor line, and an evaporator. The CLHPs also use latent heat to transport heat. Owing to the superior heat transfer performance of CLHPs in the cryogenic applications, many scholars have investigated their operating characteristics and improved their performance. Most investigations on CLHPs are experimental because of their complex operating mechanisms including multiphase flow and phase changes. In these experiments, the operating characteristics of CLHPs are studied by measuring the temperature of each component at variable heat loads. For example, Hoang et al. [4,5] fabricated and measured the temperature of all the components of a CLHP. Hydrogen was selected as the working fluid. The experiments confirmed that the CLHP can start at a supercritical state and work reliably in the temperature range of 20–30 K. However, the physical explanation for the operation of CLHPs is insufficient. Gully et al. [6] tested a nitrogen CLHP and investigated the thermal behavior experimentally to explain the performance characteristics in the start-up and the steady-state. The authors revealed the physical processes of the operation and proved that the secondary loop is helpful in realizing a supercritical startup. They also found that the filling pressure greatly affects the maximum heat transfer capability of CLHPs. However, the approach of improving the maximum heat transfer capability is not determined. Zhao et al. [7,8] aimed to improve the heat transfer performance of CLHPs and designed a novel condenser for CLHPs. The condenser could effectively reduce the flow resistance because it replaced the single pipe with parallel pipes. With this new condenser, the authors achieved a large maximum heat transfer capacity up to 41 W. The startup performance is another

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Nomenclature

A	area, m^2
C_p	specific heat, $J\cdot kg^{-1}\,K^{-1}$
h_{fg}	latent heat, $J\cdot kg^{-1}$
k	thermal conductivity, $W\cdot m^{-1}\,K^{-1}$
L	length, m
M	mass, kg
$\dot{m}$	mass flow rate, $kg\cdot s^{-1}$
P	pressure, Pa
P_{fill}	filling pressure, Pa
P_{cap}	capillary pressure, Pa
q	heat flux, $W\cdot m^{-2}$
Q	heat load, W
R_{tc}	thermal contact resistance, $m^2\cdot K\cdot W^{-1}$
T	temperature, K
T_{ev}	evaporating temperature, K
(UA/L)	per unit length thermal conductance, $W\cdot K^{-1}\cdot m^{-1}$
V	volume, m^3
x	vapor quality

Greek symbols

α	void fraction
ρ	density, $kg\cdot m^3$
δ	criterion of energy balance

Superscripts

(1)	primary loop
(2)	secondary loop

Subscripts

2ϕ	two-phase zone
b	bayonet
c	evaporator core
$casing$	evaporator casing
cc	compensation chamber
$cc\text{-}amb$	compensation chamber and ambient
$c\text{-}b$	evaporator core and bayonet
ch	charged
$comp$	component
ev	evaporation
gr	gas reservoir
hla	axial heat leak
hlr	radial heat leak
i	inner surface
l	liquid
ll	liquid line
sat	saturation
v	vapor
w	wick

important indicator of CLHPs performance. Guo et al. [9,10] measured the supercritical startup behavior of a neon-CLHP to investigate its startup performance. The authors found a minimum secondary heat load to achieve the supercritical startup process. For the test neon CLHP, the minimum secondary heat load was 1.5 W. Experimental works can reflect the thermal behaviors and heat transfer capabilities of CLHPs. However, it is difficult to provide physical explanations for the operating characteristics of CHLPs and describe the mass distribution inside the tubes through experiments.

Theoretical studies can describe the mass and temperature distribution inside the tubes of CLHPs conveniently, which are usually used to guide the system design and the parameter optimization. Many theoretical studies focused on the common LHPs, whereas theoretical studies specific to CLHPs are insufficient. Fortunately, the current progress for LHP research can provide references for modeling CLHPs. In the existing theoretical studies on LHPs, global models are used to investigate the heat leak and performance characteristics of the whole system. The heat leak refers to the heat load which is not transferred by the latent heat of working fluids. The first completed global model was developed by Chuang [11]. This model comprised the mass and energy conservations of each component. Many empirical formulas were used to describe the temperature and pressure distributions in each component under a specific working condition. The variable and fixed conductance zones were predicted successfully with this model by showing a good agreement with the author's experimental data. The evaporator core and the compensation chamber (CC) are considered as one node (zero-dimensional heat leak model) in the model of Chuang [11]. However, this model cannot derive a detailed description of the temperature and mass flow rate variations in the evaporator core which may generate inaccurate heat leak results. Chuang's model are widely used and further improved by many scholars because of its simple implementation. Adoni et al. [12–14] improved Chuang's global model by introducing another node at the boundary between the evaporator core and the CC. They focused on the effect of the bayonet and "hard filling" phenomenon which indicates that the CC is filled with liquid. They found the superheat liquid in the CC of the LHP with a bayonet when the hard filling occurred. In this condition, the LHP might fail to work. Adoni's model [12–14] set two nodes in the evaporator core and considers the temperature difference between the core and the CC. The detailed variations of temperature and the mass flow rate in the core are also ignored. A concise and clear global model was proposed by Bai et al. [15], and it was carried out with the help of the nodal network method. In this improved global model, an annular flow is applied to replace the empirical formulas, and the condensation in a condenser is simulated. Bai et al. [16,17] extended the previous model to simulate the CLHP performance for the steady state and startup conditions. These two studies are among the few published modeling researches related to CLHPs. Both studies considered the flow in the secondary loop and investigated the effects of parasitic and secondary heat loads, as well as those of heat sink temperature, to show the operation characteristics of CLHPs. However, the authors did not detail the heat and mass transfer in the core.

The global models offer a simple method to predict the temperature in each component under a specific working condition. However, the global models usually consider the evaporator core as a node and lack a detailed description of the temperature and mass flow rate variations in the core. The radial heat leak is in direct proportion to the temperature difference between the outer surface of the wick and the core. Therefore, ignoring temperature variations in the core results in an inaccurate radial heat leak. Moreover, the mass distribution in the CLHPs is different from that in the LHPs because the former comprises a unique gas reservoir. Thus, a heat leak model that can consider the distributions of the temperature and mass flow rate along the evaporator core is necessary to obtain accurate heat leak results for the CLHPs.

To overcome the shortcomings of zero-dimensional heat leak models, the present work establishes a one-dimensional heat leak model which is coupled with a global model. The mass transfer between the gas reservoir and the loop is fully considered. The temperature and mass flow rate variations along the evaporator core are obtained. The operation characteristics and the determinants for the minimum and working heat load are also identified.