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Numerical analysis on heat transfer of a complete anti-gravity loop-shaped heat pipe

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ABSTRACT

Anti-gravity loop shaped heat pipe (AGLSHP) with continuous step-graded sintered wick is useful for enhancing the effective heat transfer in the anti-gravity direction. In this work, a complete steady state model has been presented to investigate in the thermal performance and hydraulic behavior of the AGLSHP. The governing equations for the heat and mass transfer are developed for the loop operation, with specific attention given to the evaporator region. By comparing the numerical simulation with the experimental data, the heat transfer mechanism is revealed. The liquid/vapor velocity and pressure distribution in the evaporator are discussed, and the temperature distribution along the transport line is also analyzed. The numerical results indicate that with the increase of the heat load, the maximum velocity and pressure value of the liquid and vapor increase as expected. The highest temperature position occurs at the outlet of evaporator surface. Providing the capillary pressure for the circulation of working fluid, the wick in the liquid line is paid more attention. Moreover, the longer condensation length is more effective in decreasing the temperature at the outlet of condenser and improving the heat transfer capacity of the AGSLHP.

1. Introduction

Loop heat pipes (LHP) are highly efficient heat transfer devices based on the phase change phenomenon [1–3]. Through operating on a closed evaporation-condensation cycle under capillary pumping mechanism, LHP can provide passive and controllable heat transfer from the heat source to the heat sink. In comparison with the conventional heat pipes, these devices offer several unique advantages, such as transferring heat in a long distance [4], addressing the thermal management problem for spacecraft [5] and ground environment [6]. Additionally, since the evaporator and condenser of LHP are linked together by separate lines for liquid and vapor, it is more flexible to configure the LHP particularly in potential demands [2]. The details of the operational mechanism were presented by Maydanik et al. [7] and Dickey and Peterson [8].

There have been numerous numerical simulations and theoretical research studies concerning on the completed LHP modeling in the literatures historically [9–12]. As the LHP operation behavior depends on the device design features, the thermochemical characteristics of the materials used and environmental conditions, it is always complicated to improve the upstream pre-design [13]. The main theoretical models can be divided into two categories. The first group of papers presents transient operation process and characteristics of LHP in order to control thermal systems accurately. Kaya et al. [14] developed a transient mathematical model to study the transient response of the LHP, and they also researched on the temperature distribution for the model. The numerical results showed no time lag in comparison with the experimental results through updating the heat load ratios. Bai et al. [15] established a mathematical model of the LHP based on the node network method and predicted the transient start-up performance in various operating conditions reliably. Blet et al. [16] showed a new design for the LHP and presented the transient thermohydraulic modeling based on the nodal method. A multi-evaporator loop model was also introduced and compared with the experimental results. The second modeling subgroup found in the literature focuses precisely on the steady-state operation condition. Ku [17] first presented an analytical model to investigate the operating principles and performance characteristics of LHP. Through studying the thermal and hydraulic interactions between compensation chamber and other elements, the LHP

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Nomenclature

A	cross-sectional area, m^2
C_p	specific heat, J/kg K
d	diameter, m
h	heat transfer coefficient, W/m^2 K
h_{fg}	latent heat, J/kg
I	interface
k	thermal conductivity, W/m K
K	permeability, m^2
L	length, m
$\dot{m}$	mass flux, kg/s
n	unit normal vector
P	pressure, Pa
q	heat flux, W/m^2
Q	heat load, W
r	radius, m
R	radial direction of cylindrical coordinate, m
R_g	gas constant, J/kg K
t	thickness, m
T	temperature, K
U	velocity, m/s
X	axial direction of cylindrical coordinate, m

Greek symbols

α	property of the parallel fins
μ	dynamic viscosity
σ	surface tension
τ	shear stress
ε	porosity
ρ	density, kg/m^3
φ	vapor length in condenser, m

Subscripts

amb	ambient
anti	anti-gravity
c	condenser
cap	capillary
e	evaporator
eff	effective
f	friction
g	gravity
in	inner surface
l	liquid
max	maximum value
min	minimum value
out	outlet
s	solid
sat	saturation
t	total
v	vapor
w	wick

operation limitations was evaluated with various physical and operational parameters. To predict the steady-state behavior of loop heat pipe, Launay et al. [18] developed a closed-form analytical model based on the momentum and energy balance equations and thermodynamic relations. In particular, they compared the two operation models, variable conductance model and fixed conductance model with various fluids, wick characteristics and geometries. Singh et al. [19] developed a mathematical model on the basis of the operating temperature and thermal resistance of the LHP. Under the experimental verification with copper and nickel wicks, the predicted results could be easily used to analysis the operating thermal performance.

As the key component of the LHP, evaporator provided the driving force to circulate the working fluid for the loop. Plenty of experimental investigations were carried out to investigate in the operation behaviors of evaporator previously [20–23]. Based on the wick with porous media, the evaporator was designed and manufactured into different types to enhance capillary. The heat transfer performance of evaporator depends on the types of working fluids, shapes and structures. It should be mentioned that the choice of appropriate evaporator is related with the locations and dimensions of heat source. In addition, the working fluid with a high vapor pressure, for instance, ammonia, may be more efficient than water when the evaporator wall thickness is increased [2].

However, when the LHP operates in the anti-gravitational regime, the heat transfer performance is greatly influenced by the higher hydrostatic resistance [1]. It is necessary to investigate the capillary fed action and compensate the pressure drop by the fine-pored wick. By transferring the working liquid through the porous media in anti-gravity orientation, Weibel et al. [24,25] developed a facility which feeds the wick by capillary action, which can measure the overall performance of wick, such as wick thickness and particle size. They also improved the wick performance and enhanced the boiling heat transfer via the implementation of controlled CNT growth techniques in microwave plasma-enhanced chemical vapor deposition. There are also some experimental researches on operating characteristics of LHP in the 1-g condition [26–28].

Based upon the analysis above, the present work develops a complete model of the anti-gravity loop shaped heat pipe (AGLSHP) with continuous step-graded sintered wick. The heat and mass transfer processes in evaporator are analyzed together with the flow characteristics. The governing equations are solved together to predict the heat flux distribution for the pipe wall, wick and vapor regions. The thermal and hydraulic states of evaporator are also coupled with all the working parts in the loop to improve the understanding of the physical mechanisms during AGLSHP operation. Additionally, the influence of anti-gravity length on heat and mass transfer performance is evaluated, and the condensation length is also characterized.

2. AGLSHP global model formulation

2.1. AGLSHP description

As shown in Fig. 1, the AGLSHP consists of four sections, an evaporator, a condenser, vapor line and liquid line. In the present work, the AGLSHP operated in the anti-gravity direction. The working fluid stored in the evaporator was evaporated into vapor. The vapor was delivered to the condenser. Then wick in the liquid line developed the capillary force to pump the working fluid back to evaporator from the condenser. In particular, the AGLSHP did not include the compensation chamber. The continuous step-graded sintered wick [29] was filled in the liquid line and the evaporator to supply operation of the working fluid. Two different types of irregular copper powder were used for the liquid line and evaporator regions, respectively. The detailed fabrication process of AGLSHP was described in Ref. [27].

The steady-state model presented below is based on the continuity, momentum and conservation energy equations similar with previous studies [30–33]. The major assumptions of mathematical model are: