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Parametric effects on heat transfer in loop heat pipe's wick

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ABSTRACT

The capillary-driven flow with conductive, convective and evaporative heat transfer occurs in the capillary wick of a loop heat pipe, so-called the inverted meniscus evaporator. An axisymmetric two-dimensional mathematical model is developed to investigate the effects of heat flux and porous structure parameters on wick's working states and performances. The full effects of the interaction between the flowfield and the liquid–vapor interface are adequately considered in this model, as well as the capillary effect of evaporation and the combined effect of conductive, convective and evaporative heat transfer. Wick's performances are introduced and discussed while parametric effects are discussed in detail. Wick's working states are classified into three operating modes while all operating modes are discussed in detail. Furthermore, the phase-diagrams on the q–$k_{t,l}$ plane and the q–K plane are also obtained and discussed.

1. Introduction

In the past decades, two self-driving and two-phase heat transfer devices have been developed and tested, so-called the capillary pumped loop (CPL) and the loop heat pipe (LHP) which depend on evaporation to absorb heat load and the capillary force developed on menisci to drive a working fluid to flow and transfer heat over large distance in a direction. Except that the large CPL, which attempted the full thermal management of the large space station, failed to engineering application because of its inherent complexity, the "simplified" CPL has the same system structure as the LHP, so that the study to both small/miniature CPLs and LHPs is actually interacting and indistinguishable. The LHP/mini-CPL has many excellences such as: (1) high heat transfer efficiency, small temperature difference among the components and compact volume which are all related to the latent heat of evaporation; (2) the self-driving cycle and the capability of anti-gravity operation due to the capillary force; (3) the capability of transferring heat over large distance in a direction, the auto-controlling capability on its operating temperature, higher operating limits and flexible connection among the components due to its structure and thermodynamics; (4) high reliability due to no moving/rotating parts. So it is actively responded and increasingly applied in thermal management of advanced satellites and spacecrafts, cooling of electrical and electronic devices, as well as anti-gravity operation in aerocrafts and ground tests. Not only the LHP/mini-CPL is the baseline design for next generation spaceborne thermal management system [1], but also it has the developing application in thermal management of electronic devices, such as heat removal from separated components to the remote heat sink and cooling of the array of chips with high heat fluxes, and it also acts as the most important link in the thermal bus [2].

Generally, a LHP consists of the evaporator–compensation chamber, the condenser, the vapor line and the liquid line. In a LHP, the evaporator with the capillary porous structure, i.e. the capillary/primary wick, is the key functional component which accepts heat fluxes, organizes evaporation and produces the driving force of cycling the working fluid in the whole device. Heat transfer with capillary-driven convection and evaporation occurs just in the capillary/primary wick. In some literatures, the combination of the capillary wick with liquid on a side and the grooved heated wall on the opposite side was also called the inverted meniscus evaporator [3,4]. Different from the meniscus evaporator (ME) in a heat pipe (HP), the inverted meniscus evaporator (IME) in a LHP has higher operating limit due to its action as the "hydraulic lock" and "thermal lock" [1]. So the physical phenomenon in the capillary/primary wick, i.e. the inverted meniscus evaporator, is complicated and of great interest for both researchers and engineers.

Cao and Faghri [5] developed a two-dimensional mathematical model for heat transfer in the capillary wick and the cover plate with three-dimensional vapor flow in the groove, and they [6] obtained the two-dimensional analytical solutions of flow and heat transfer in the capillary wick based on the Laplace-type equation for pressure and the perturbation method for temperature. By using the Green's function method, LaClair and Mudawar [7] developed a one-dimensional approximate solution without convection for the coupled liquid core, capillary wick and metal shell to investigate the startup behavior of a CPL evaporator. But these papers considered the capillary wick as a fully liquid-saturated wick with

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Nomenclature

A_{in}	the inlet area of the wick (m^2)
A_s	the area of a close-contacted heated fin (m^2)
A_{wick}	the area of any radial section of the wick (m^2)
c	special thermal capacity (J/kg K)
h	enthalpy (J/kg); convective heat transfer coefficient (W/m^2 K)
h_e	local evaporative heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	permeability (m^2)
L	characteristic length (m)
$\dot{m}$	mass flow rate of the working fluid (kg/s)
$\mathbf{n}$	normal vector on the liquid–vapor interface
p	pressure (Pa)
p_c	capillary force (Pa)
q	heat flux (W/m^2)
q_e	evaporative heat flux (W/m^2)
Q_{leak}	heat leak (W)
$\mathbf{r}$	position vector of meniscus (m)
r_p	effective pore radius (m)
$\mathbf{s}$	displacement vector of interface (m)
t	time (s)
T	temperature (K)
U	wick's total heat transfer coefficient (W/m^2 K)
U^*	characteristic speed (m/s)
$\mathbf{V}$	velocity vector of infiltration (m/s)
V	velocity of infiltration (m/s)

Greek symbols

ϕ	porosity
β_T	expansion coefficient with constant pressure (1/K)
β_p	expansion coefficient with constant temperature (1/Pa)
λ	latent heat of evaporation (J/kg)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

e	reference
eva	evaporation
f	fluid
g	vapor
in	inlet
l	liquid
n	normal direction
out	outlet
r	in radial direction
s	saturated
t	total
$wall$	on the heated wall
z	in longitudinal direction

the liquid–vapor interface fixed on the surface of the wick. Demidov and Yatsenko [4] developed a two-dimensional mathematical model considering both convection and the free liquid–vapor interface in the wick, and investigated numerically steady capillary-driven flow and heat transfer in rectangular porous media. Khrustalev and Faghri [8] developed a one-dimensional mathematical model on the basis of heat transfer with thin-film evaporation theory in a pore and heat transfer in the dry porous media and close-touched heated fins (or flat), and the analytical steady solution was derived. Figus et al. [9] developed two two-dimensional mathematical models based on the Darcy model and the pore network model respectively, both of which considered the moving liquid–vapor interface in the wick and no convection in the energy equations, to study steady heat transfer in the wick with a single or varying pore-size distribution. Zhao and Liao [10–13] investigated experimentally heat transfer in glass-bead packed cubic porous media with a groovy heated wall on the top at different heated fluxes, and the one-dimensional approximate solutions derived from [12] agreed with these experimental results. Huang et al. [14] developed a nonsaturated evaporation model with six field variables, including temperature, pressure, liquid velocity, vapor velocity, liquid content and phase-change rate, to investigate heat and mass transfer with phase change in CPL's porous wick. Kaya and Goldak [15] used the mathematical model and boundary conditions similar to Demidov and Yatsenko's [4] to investigate heat and mass transfer in the capillary structure of a LHP as well as the relation between the boiling limit and the capillary limit on the basis of the cluster nucleation theory [16,17]. Because of their assumptions, all of these above papers neglected more or less some important information that is parts of the complicated physical phenomenon.

In this paper, an axisymmetric two-dimensional mathematical model of the cylindrical evaporator's wick with azimuthal vapor grooves of a LHP is developed to simulate transient/steady heat transfer with capillary-driven convection and evaporation in the capillary porous structure, so-called the inverted meniscus evaporator. The full effects of the interaction between the flowfield and the liquid–vapor interface on the flowfield, the position of the interface and the curvature of menisci, i.e. the capillary force, are adequately considered in this model, as well as the combined effect of conductive, convective and evaporative heat transfer. Due to the capillary effect, the superheating liquid–vapor interface is also considered in this model, and the capillary force is matched to superheat and heat load. Wick's performances, including the driving performance, the heat transfer performance and the capillary effect of evaporation, are introduced while parametric effects of heat flux and porous structure parameters are discussed in detail. As results of the investigation, wick's working states are classified into three operating modes in this paper: the mode of complete heat conduction, the mode of incomplete heat conduction and the mode of convection. All operating modes are discussed in detail. Furthermore, the phase-diagrams on the q–$k_{t,l}$ plane and the q–K plane are also obtained and discussed.

2. Mathematical model and numerical simulation

The evaporator of 16 mm in diameter, investigated in this paper, has the primary wick, the secondary wick, eight deeper longitudinal grooves and plenty of shallower azimuthal grooves in its shell wall. The configuration is illustrated in Fig. 1. The primary wick is 5 mm thick in the radial direction and it is made of sintered nickel powders with the effective pore radius of 0.001 mm and porosity of 0.5. The width of an azimuthal groove is 1 mm, and so the width of a heated fin is. In our simulation, a cell shown in Fig. 2 is used to represent the entire primary wick because of the periodic heated boundary on the top and the geometrical and physical symmetry. It is 5 mm thick in the radial direction and 1 mm wide in the longitudinal direction.

Some assumptions are introduced: (1) there is homogeneous, isotropic and rigid capillary porous medium while the fluids are slightly compressible. (2) The properties for solid, liquid and vapor are constant. (3) Gravity, heat radiation and viscous dissipation are neglected; there is no inner heat source. (4) There is axisymmetric