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Dynamic model of capillary pumped loop with unsaturated porous wick for terrestrial application

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ABSTRACT

This paper presents a dynamic model of a Capillary Pumped Loop designed for gravitational applications. The CPL model is divided into subsystems, for which transient mass, energy, and momentum balances have been developed. The heat and mass transfer inside the evaporator structure is precisely described by a 2D mathematical model, which takes into account the existence of a vapor pocket inside the porous wick. The liquid lines are discretized into small elements. The comparison of the numerical results and data experiment validates the proposed model in a transient regime. The model is then used to analyze the thermohydraulic behavior of a capillary pumped loop by modifying external conditions such as the cold source temperature and the operating conditions such as the reservoir temperature.

1. Introduction

In the recent years, the thermal management of high-power electronic systems has become a major challenge. The Capillary Pumped Loop (CPL) and the Loop Heat Pipe (LHP) are two-phase devices capable of transporting large heat loads over long distances without need of any mechanical pump [1–3]. CPLs have been successfully tested in many spatial applications [4]. The capillary pumped loop studied in this paper has been designed for the world's first use aboard a train, where it is employed for cooling electronic devices in a railroad traction chain [5].

Just a few studies have been done describing the thermal and hydraulic coupling of a complete capillary pumped loop during steady states and transient regimes. Dickey [6] developed a mathematical model to investigate the operational characteristics of a Capillary pumped loop. An experimental investigation was conducted to validate the CPL model. Shelestynsky [7] studied an enhanced two-phase thermal transport loop by adding an Electrohydrodynamic (EHD) pump. A relationship between the pressure generation through the EHD pump and the EHD number (conductive electric Rayleigh number) was determined. Komeili [8] et al. conducted an experimental study to investigate the effect of electrohydrodynamic forces in the CPL performance. The experimental results showed that adding EHD forces to the evaporator can enhance the efficiency of heat transport in CPLs. Pouzet [9] developed a complete transient model to study the dynamic response of a capillary pumped loop subjected to various heat load transients. The proposed model takes into account the dynamic behavior of the liquid/vapor interface in the condenser and the reservoir. However, in the evaporator, the liquid/vapor interface is fixed at the top of porous wick. Launay [10] developed an analytical solution to predict the thermal and hydrodynamic behavior of a standard loop heat pipe. The transient modeling of the overall loop is divided into four subsystems (compensation chamber, evaporator, condenser, liquid and vapor transport lines). Zhang [11] studied the effect of disturbance in the evaporator on the performance of capillary pumped loop. Kaya [12] presented a dynamic model to simulate the overall dynamic behavior of a loop heat pipe exposed to transient thermal loads. The mathematical model is based on the one-dimensional and time-dependent conservation equations for heat and fluid flow. Recently, Lachassagne [13] developed a steady state model of a capillary pumped loop in gravitational field. The nodal method is used to determine temperature, pressure and fluid phase distribution in the whole loop. The model is based on the nodal method with electrical analogy. However, this model is insufficient to describe the transient operation of a CPL. Delalandre [14] then proposed a transient

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Nomenclature

a	accommodation number, ambient
R	universal gas constant, $J\,mol^{-1}\,K^{-1}$
M	molar mass of fluid, $kg\,mol^{-1}$
C_p	specific heat, $Jkg^{-1}K^{-1}$
h	convective heat transfer coefficient, $Wm^{-2}K^{-1}$
h	specific enthalpy, Jkg^{-1}
A	surface, m^2
A	cross section, m^2
D	diameter, m
L	length, m
G	thermal conductance, WK^{-1}
Q	power input, W
L_v	latent heat, $J\,kg^{-1}$
p	pressure, Pa
t	time, s
T	temperature, K
V	darcian velocity, ms^{-1}
v	velocity, ms^{-1}
g	gravitational acceleration, ms^{-2}

Greek symbols

α	volumetric fraction
κ	permeability, m^2
κ_r	relative permeability
λ	thermal conductivity, $Wm^{-1}\,K^{-1}$
μ	dynamic viscosity, $kg\,m^{-1}s^{-1}$
η	two-phase zone length, m
ρ	density, $kg\,m^{-3}$
ϕ	heat flux W
$\dot{\Gamma}$	volumetric mass rate of phase change, $kg\,m^{-3}s^{-1}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
Ω	volume, m^3

Subscripts

ℓ	liquid
v	vapor
s	solid
eff	effective
cap	capillary
sat	saturation
gr	groove
R	reservoir
E	evaporator
C	condenser, casing
V	vapor line
L	liquid line
b	bottom part
h	high part
CS	cold source
in	inlet
o	outlet
W	wall
w	wick
int	internal
ext	external
p	parasitic

thermohydraulic model of a capillary pumped loop for terrestrial application. The proposed model provides a good description of the CPL behavior in a gravitational field.

In all existing global models of Loop Heat Pipes or Capillary Pumped Loops found in the literature, the heat and mass transfer inside the evaporator structure is not precisely described. The porous wick is assumed to be fully saturated with liquid and the evaporation takes place only at the wick/groove interface. This last assumption greatly simplifies the evaporator model, however the growth of a vapor pocket inside the porous wick can have a significant influence on the heat transfer inside the evaporator. Many numerical models can be found in the literature which focus on the modeling of the heat and mass transfer inside the porous wick of the evaporator, in the case where the evaporator is not connected to the rest of the loop. Cao and Faghri [15] presented an analytical solution for heat and mass transfer processes during evaporation in the wick of a CPL evaporator. The liquid-vapor phase is fixed at the top of the wick structure. Wan [16] presented a two-dimensional mathematical model of the miniature flat plate capillary pumped loop (CPL) evaporator to simulate heat and mass transfer in the capillary porous structure and heat transfer in the vapor grooves and metallic wall. Mariya [17] developed a three-dimensional mathematical model to simulate only heat transfer processes in the flat evaporator of a copper-water LHP with a porous wick. In this study, it is assumed that the porous wick is completely saturated with fluid. Kaya [18] investigated the heat and mass transfer in the capillary porous structure of a loop heat pipe (LHP). The formulation of the problem is based on the work of Demidov et al. [19]. The results of the simulation demonstrate the existence of a vapor pocket inside the porous wick. Ren [20] developed an axisymmetric two-dimensional mathematical model of the wick of the cylindrical evaporator with azimuthal vapor grooves of a LHP to simulate transient/steady heat transfer with capillary-driven convection and evaporation in the capillary porous structure. Figus [21] presented two steady approaches to study the heat transfer in the porous wick: a continuum model (Darcy model) and a pore scale model. Both approaches demonstrated the existence of a vapor pocket under the fins. Xuan [22] proposed a two-dimensional transient model based on the lattice Boltzmann method to simulate the heat and mass transfer with evaporation in the global evaporator of a capillary pumped loop. Different working fluids are tested and numerical results showed that heat and mass transfer processes inside the porous wick are very sensitive to the working fluid. Liu [23] presented a numerical method to describe the fluid flow and heat transfer inside the porous wick. The mathematical model is then used to optimize the structure of a CPL evaporator. Boubaker [24] presented a numerical study of a Capillary Pumped Loop evaporator. A two-dimensional unsteady mathematical model of a flat evaporator is developed to simulate heat and mass transfer in an unsaturated porous wick with phase change. The dynamic growth of the vapor pocket inside the porous wick is studied in this paper.

The present paper focuses on the thermohydraulic modeling of a Capillary Pumped Loop with an unsaturated porous wick. The CPL model is divided into subsystems, for which transient mass, energy, and momentum balances have been developed. Unlike in the work of Pouzet [9], the originality of this work consists in combining a precise description of the complex phase change phenomena inside the porous wick with a dynamic model of a capillary pumped loop. The CPL evaporator model gives a better understanding of the