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CPL : a dynamic phase field model of the evaporator

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Abstract :
In this paper, we propose a numerical study of the unsteady behavior of a capillary pumped loop evaporator. A two dimensional mathematical model of flat evaporator is developed to simulate heat and mass transfer in unsaturated porous media with phase change. The governing equations are solved using the Finite Element Method. The simulations results are presented then for a sintered nickel wick and methanol as a working fluid. Dynamic and thermodynamic behavior of the working fluid in the capillary structure are discussed in this paper.

Key words : CPL evaporator, phase change, two phase flow, porous media, dynamic model

1. Introduction

Capillary Pumped Loop (CPL) and Loop Heat Pipe (LHP) are developed to transport heat flux from a hot source to a cold source without need of any mechanical pump. It answers to many industrial needs (space and terrestrial applications especially for electronic cooling). All existing global models of CPL or LHP assume that the porous wick of evaporator is saturated with liquid. In this work, we focus our study on the evaporator which is the important component of CPL. Z.M. Wan [1] developed a two-dimensional numerical model for the global evaporator of miniature flat plate capillary pumped loop (porous wick, compensation cavity, the vapor grooves and metallic wall). He supposed that the porous media is rigid, homogeneous, isotropic, and fully saturated with fluid. The working fluid, which is the ammonia, is considered as incompressible and has constant proprieties. Kaya [2] investigated the boiling limit of the porous structure of cylindrical evaporator of LHP. The formulation of the problem is based on the work of Demidov and Yatsenko [3]. One of the main results of this work is that the evaporation could take place within the porous wick, so he putted in question the assumption made in the works mentioned above : wick saturated with liquid. Figus and all [4] presented two steady approaches to study the heat transfer in the porous wick : continuum model (Darcy model) and pore scale model. He demonstrated that both approaches lead to the same result when the network used to describe the porous structure is uniform. Both of two models demonstrated also the existence of vapor zone under the fins. Prat [5] developed a pore network model to study the vaporization phenomena within a porous wick of LHP. The result of the model is interesting and gives a better understanding of physics phenomena within the porous wick but it is too difficult to couple it with other LHP components in order to obtain the dynamic behavior of LHP. Z.C.Liu [6] presented also an unsteady model of CPL evaporator ; he studied separately the liquid and the vapor flows. The porous wick is divided only in two regions : vapor-saturated region and liquid-saturated region and the interface thickness is supposed zero. The goal of this study is to analyze the influence of the geometries on flow and heat transfer of the evaporator. Huang [7] developed a three region model : single phase regions (vapor or liquid) and two-phase region to study heat and mass transfer with phase change in the porous wick of evaporator of capillary pumped loop. The numerical results demonstrated the existence of liquid-vapor interface within the porous wick, which is in accordance with the results given by Figus and Prat.

Some experimental investigations about porous structure have been conducted. Liao [8] made a visual study on the phase-change heat transfer in a vertical two-dimensional porous structure by using a high-speed video imaging system. Coquard [9] made a visualization experiment on two-dimensional porous wick. The experimental results are in agreement also with the numerical results : a stable vapor film is formed underneath the heated surface.

The purpose of the present study is to gain a better understanding of heat and mass transfer in porous wick of a flat evaporator, the growth of a vapor zone under the fins. For this purpose, an unsteady model for two dimensional mixture flow is developed in which the conservation equations of mass, momentum and enthalpy are formulated for the two-phase mixture. Since this model is valid in all regions of the porous wick, there is no need to add internal boundary conditions at the phase interface [10, 11].

2. Mathematical Model

2.1. Governing equations

The mathematical model is developed and applied to study coupled heat and mass transfers in the porous structure for CPL or LHP (figure 1). It is based on the following assumptions :

- The working fluid is compressible and has variant proprieties with temperature and pressure.
- The capillary structure is homogeneous and isotropic.
- The vapor is considered as an ideal gas.
- Porous wick, vapor and liquid are in a local thermal equilibrium.

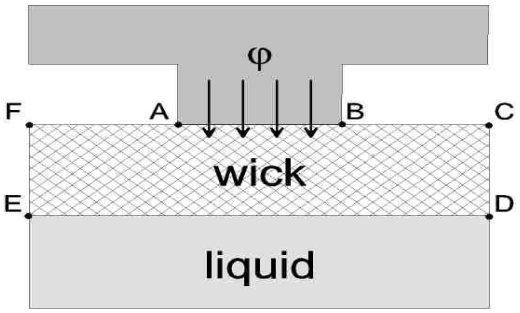


Figure 1 : CPL evaporator

To establish the equations of the model, we apply heat, momentum and mass balances to a Representative elementary volume (REV) of the porous wick [12]. In this volume, we make a spatial average on the characteristics of fluid (vapor and liquid phase) and the solid. The mixture equations largely resemble those for a single-phase flow but are represented in terms of the mixture variables and proprieties. This approach is used to hide brutal fluctuations at pore scale.

- Continuum equation

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{v}) = 0 \qquad (1)$$

- Momentum equation

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\,\vec{v}\right) = -\vec{\nabla}\,p + \mu\Delta\vec{v} - \varepsilon\frac{\mu}{\kappa}\vec{v} - \vec{\nabla}\,p_{cap} \qquad (2)$$

- Energy equation

$$\overline{\rho C_p}\frac{\partial T}{\partial t} + \varepsilon\rho C_p \vec{v}.\vec{\nabla}T = \lambda_{eff}\Delta T - \dot{\Gamma}L_v \qquad (3)$$

The mixture variables and proprieties are defined as :

Density : $\rho = (1-\alpha_v)\rho_l + \alpha_v\rho_v$

Velocity : $\rho\vec{v} = (1-\alpha_v)\rho_l\vec{v}_l + \alpha_v\rho_v\vec{v}_v$

Viscosity : $\mu = (1-\alpha_v)\mu_l + \alpha_v\mu_v$

Heat capacity : $\overline{\rho C_p} = (1-\varepsilon)\rho_s C_{ps} + \varepsilon\rho C_p = (1-\varepsilon)\rho_s C_{ps} + \varepsilon\left((1-\alpha_v)\rho_l C_{pl} + \alpha_v\rho_v C_{pv}\right)$

Effective thermal conductivity : $\lambda_{eff} = (1-\varepsilon)\lambda_s + \varepsilon\left((1-\alpha_v)\lambda_l + \alpha_v\lambda_v\right)$

The mass flux produced in the liquid-vapor interface is obtained as the difference between the actual vapor phase concentration and the equilibrium one [11] :

$$\dot{\Gamma} = \varepsilon\rho_v(\alpha_{v,eq} - \alpha_v) \qquad (4)$$

The Capillary pressure is given by Leverett's equation [7] :

$$p_{cap} = \sigma\sqrt{\frac{\varepsilon}{\kappa}}(1.417\alpha_v + 2.120\alpha_v^{\,2} + 1.263\alpha_v^{\,3}) \qquad (5)$$

2.2. Boundary conditions (see figure 1)

At bottom boundary ED $T = T_0 \quad p = p_0$

At upside boundary AB $\lambda\dfrac{\partial T}{\partial y} = \varphi\,,\, v_x = 0\,,\, v_y = 0$

At upside boundary AF and BC $p = p_0$

At symmetric boundary EF and DC $v_x = 0\,,\ \dfrac{\partial T}{\partial x} = 0$

3. Results and discussion

The above equations are solved using Finite Element Method assuming that vaporization starts when the temperature is higher than the temperature of vaporization [13]. Numerical results are determined for the following geometric parameters : L_x = 1mm, L_y = 1mm. The working fluid used is methanol. Its proprieties depend on temperature and pressure. A sintered nickel is chosen as the material of metallic wall, its proprieties are : $\varepsilon = 0.73$, $\rho_s = 2405 kg\,m^{-3}$, $\lambda_s = 5 W m^{-1} K^{-1}$, $C_{ps} = 10^3\, J\, K^{-1} kg^{-1}$. The inlet temperature is $T_0 = 300K$, and the heat flux imposed varies between $20 W\,cm^{-2}$ and $40 W\,cm^{-2}$. Initially, the wick structure is saturated by liquid, pressure and temperature are respectively $10^5\, Pa$ and $300K$ in fully porous media.

3.1. Vapor region

In this paragraph, we study the growth of the vapor region in the wick. The figure 2 shows that the wick structure contains vapor zone separated from liquid phase by the vapor-liquid interface. The vapor zone takes place under the fins. It grows as an exponential law and stabilizes after a few seconds.

The simulations are in agreement with the results presented by Prat [5] and Liao [8]. Prat used a dynamic pore network model to describe the transfers in the porous wick of loop heat pipes. While Liao made a visual study on the phase-change heat transfer in a vertical two-dimensional porous structure by using a high-speed video imaging system, and he confirmed the existence of vapor zone within the wick.

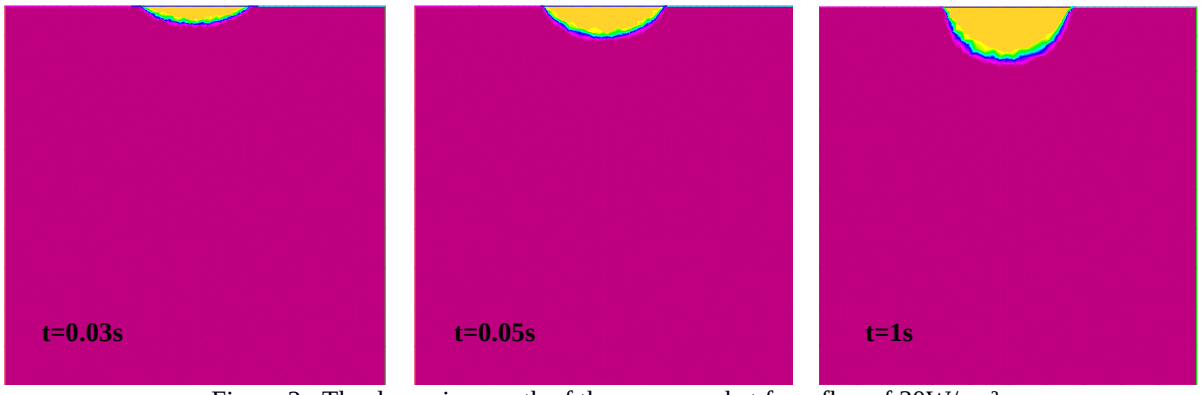
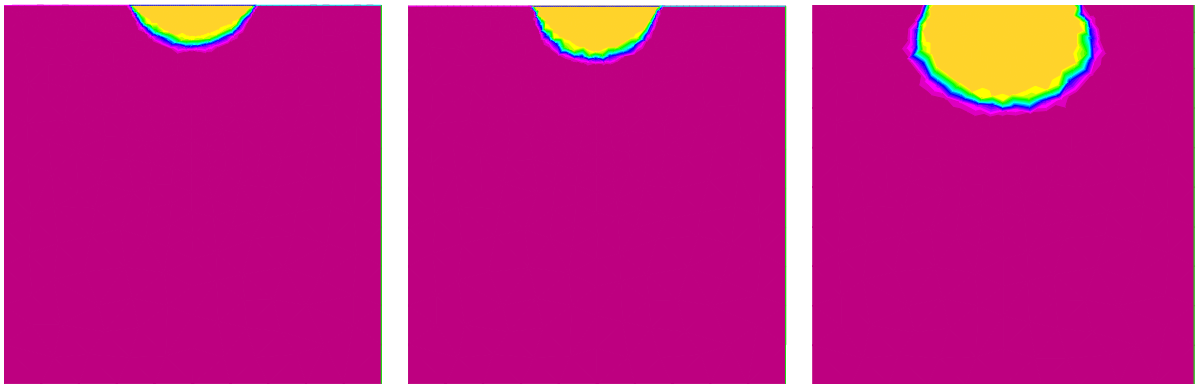


Figure 2 : The dynamic growth of the vapor pocket for a flux of 30W/cm².

The following figure shows the growth of the vapor zone for different heat flux density in steady state. It is deeper when the heat flux increases.



a) Heat flux of $20W\,cm^{-2}$ b) Heat flux of $30W\,cm^{-2}$ c) Heat flux of $50W\,cm^{-2}$

Figure 3 : The vapor pocket for different applied thermal loads.

3.2. Temperature field

The heat flux imposed on the upper surface of the wick is transferred by conduction, convection and phase change on the liquid-vapor interface. Figure 4 shows the temperature distributions inside the porous wick. As expected the temperature gradient increases along the boundary (ED) where the heat flux is applied and it varies very slightly at bottom zone.

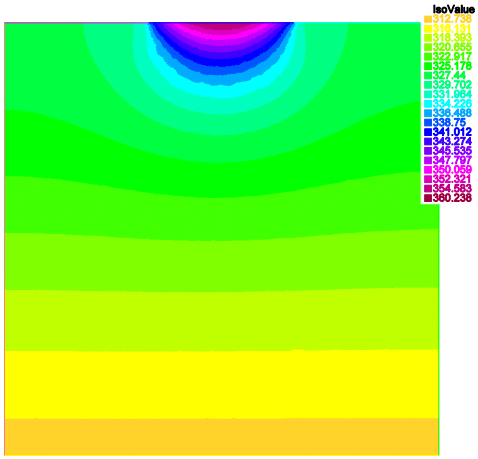


Figure 4 :Temperature field in porous wick for $\varphi = 30W\,cm^{-2}$.

3.3. Parasite flux

The parasite flux is the heat flux loss by conduction across the liquid input porous wick. It plays an important role for the CPL and the LHP. It can cause dangerous situations of percolation for the global loops. In the case of LHP, it can rise the temperature in the reservoir. It is calculated by the following equation :

$$Q_p = \int_E^D \lambda_{eff} \frac{\partial T}{\partial y} dx$$

Figure 5 shows the evolution of the parasitic flux with time for $\lambda_s = 5 Wm^{-1}K^{-1}$ for different heat load densities.

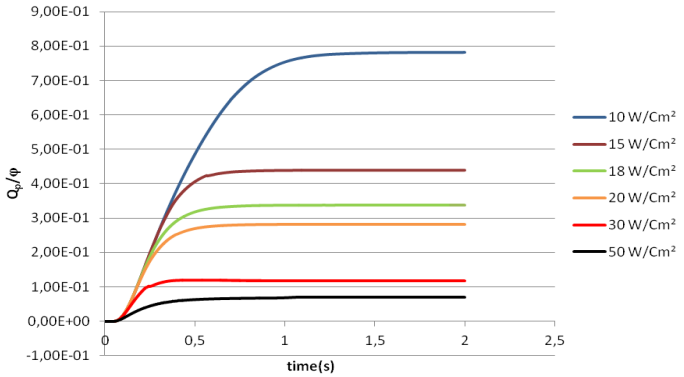


Figure 5 **:** Evolution of parasitic flux with time for different heat loads.

We observe that the ratio Q_p / φ decreases with the applied heat flux : when the imposed flux is too small, it is not able to vaporize the liquid, then the majority of flux is lost by conduction, and when the imposed flux increases, the largest share of this flux serves to vaporize the liquid (growth of the vapor pocket), thus reducing the parasite flux.

Conclusion

A two dimensional mixture model has been developed to describe heat and mass transfer with phase change in porous wick of a CPL evaporator. We have demonstrated that a vapor zone is formed in the wick structure under the fins separated from the liquid region by the vapor-liquid interface. It can be observed clearly that the vapor region grows if the heat loads are increased. The obtained results have shown that ratio of parasitic flux by the applied heat load decreases increasing heat loads.

The unsteady evaporator model will be coupled with other CPL components in order to obtain a global CPL model with an unsaturated porous wick.

Nomenclature

Cp	specific heat, J $kg^{-1}K^{-1}$	ε	porosity
S	surface, m^2	κ	permeability, m^2
L_x	total length in x direction, m	μ	dynamic viscosity , kg $m^{-1}s^{-1}$
L_y	total length in y direction, m	ρ	density, kg m^{-3}
L_v	Latent heat, J kg^{-1}	σ	interfacial surface, N m^{-1}
p	pressure, Pa	α_v	volumetric vapor fraction
t	time, s	Index	
T	temperature , K	l	liquid
v	velocity, m s^{-1}	v	vapor
Greek symbols		s	solid
φ	heat flux, W cm^{-2}	eff	effective
$\dot{\Gamma}$	mass rate of phase change, Kg $m^{-3}s^{-1}$	p	parasitic

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