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A numerical model for transient simulation of porous wicked heat pipes by lattice Boltzmann method

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ABSTRACT

A numerical model based on an analytical lumped vapor assumption was proposed for highly efficient simulation of transient performances of heat pipes. The wick is modeled as fully thawed porous medium in which both the Darcian and non-Darcian effects are considered. The evaporation and condensation rates of the working substance are calculated locally as a function of not only the liquid–vapor interface temperature but also the vapor state properties by the kinetic theory. The coupled equations for liquid flow and heat conduction in/between components of the heat pipe are solved by a thermal lattice Boltzmann algorithm. Validation of the model is conducted by reproducing representative cases from the literature and then comparing the present results with their experimental and theoretical data. It turns out that both the transient temperature variation and the steady-state temperature and pressure profiles are in accordance with the literature results. The vapor velocity profile inferred from the evaporation rates is also found to be sufficiently accurate, which even gives a more reasonable estimate than the reference in comparison. In order to further improve the simulation efficiency of the code, non-uniform lattice and parallel algorithm are incorporated, based upon which the lumped vapor model achieves a speed over 50 times faster than the plain model with complete vapor consideration. The present model could serve as an efficient tool for quick evaluation of transient heat pipe behaviors and for assisting parametric studies of heat pipes.

1. Introduction

Heat pipes transfer heat by using phase transition predominantly in addition to thermal conduction, which produces an equivalent conductivity of up to several orders of magnitude higher than that of pure metals. Theoretical modelings have been extensively implemented to study the operation performance of heat pipes due to the flexibility, convenience and low cost. Depending upon how the parts of heat pipe are modeled and solved, the modeling methods can be categorized as either analytical or numerical. Although these methods essentially solve the same heat transfer equations, the different perspectives taken in modeling the components result in different simulation efficiencies and different levels of understanding of the heat pipe mechanisms.

The analytical methods have been extensively studied for heat pipes. Despite the fact that the geometries of heat pipes are usually regular, the governing equations are almost impossible to be solved directly in an traditional analytical way due to the complexity. Faghri and Harley [1] proposed a transient model for conventional as well as gas-loaded heat pipes. The components were modeled as lumped capacitances which greatly simplified the solution. Zhu and Vafai [2] developed an analytical model to study the startup characteristics of asymmetrical flat-plate and disk-shaped heat pipes. The liquid-saturated wick was treated as solid using a conduction model, and this wick model is then thermally coupled to a pseudo-3D vapor model. Zuo and Faghri [3] analyzed the transient temperature variation by considering the heat pipe as a network of components with conduction and convection. Similarly, Yadavalli *et al.* [4] used a 1-D thermal resistance network model to analyze the thermal performance thresholds of ultrathin flat heat pipes. Nouri-Borujerdi and Layegi [5] proposed a 1-D analytical model for the liquid flow in wick and compared with 2-D numerical results, and found that the analytical result is closer to the one predicted by the Darcy's law than the 2-D numerical model. Mistry *et al.* [6] adopted the growing thermal layer concept to solve the conduction in the wall and in the wick, and evaluated the transient and steady-state performances of the heat pipe. Although being computationally efficient in calculating simplified profiles of velocity, pressure and temperature, many analytical methods use only a few variables to describe the heat pipe, while

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Nomenclature

c_p	heat capacity
c_s	speed of sound
$\mathrm{d}X$	lattice spacing in the X direction
$\mathrm{d}Y$	lattice spacing in the Y direction
$\mathbf{e}_i$	discrete velocity set
f_i	distribution function of flow field
g_i	distribution function of temperature field
h_{fg}	latent heat
k_{eff}	effective thermal conductivity of wick
k_{wall}	thermal conductivity of wall
M	molecular weight
$\dot{m}$	evaporation rate
m_{V}	mass of vapor
p	pressure
p_{V}	pressure in vapor core
p_{sat}	saturated vapor pressure
$\overline{R}$	universal gas constant
R_x	aspect ratio of the lattice
T	temperature
t	time
T_{LV}	liquid–vapor interface temperature
T_{V}	vapor temperature
T_{cool}	cooling water temperature
T_{∞}	ambient radiation temperature
$\mathbf{u}$	velocity
X_{a}	position of adiabatic end
X_{c}	position of condensation end
X_{e}	position of evaporation end
α_m	effective thermal diffusivity
ϵ	porosity
ν	viscosity
ν_e	effective viscosity
ρ	density
$\hat{\sigma}$	accomodation coefficient
σ	heat capacity ratio between solid and fluid

some rely on unrealistic assumptions like considering only thermal conduction in porous media. These factors restrict the applications of analytical methods in circumstances where thorough understanding of the flow and temperature fields is required.

Numerical methods, on the other hand, generally present a detailed view of each part of the heat pipe. The coupled conduction and convection equations are solved iteratively by discreting the solid wall, wick, and vapor with control volumes or finite elements. The well-known general heat pipe solvers “HPTAM” [7] and “THROHPUT” [8] are both based on this method. A major advantage of the numerical methods is the capability of calculating detailed temperature and flow fields, enabling much more flexible explorations on the performances of heat pipes. For instance, one can modify the numerical model by including more sophisticated governing equations to study the non-Darcian effects [9], or by conducting parametric investigations to learn the dry-out characteristics [10,11], effect of heating and cooling configurations [12], etc. The disadvantage of the numerical methods is its relatively higher expenses in computational cost and time consumption compared to the analytical methods, since usually a sufficiently large mesh is required to ensure reliable and accurate results. Although the numerical methods are useful for in-depth studies of heat pipes, it’s less efficient for a large number of comparative cases, particularly for the transient simulations.

Transient performance is an important factor for evaluation of heat pipes. A number of transient studies on heat pipes focus on the startup process such as the low-temperature heat pipe starting from supercritical state or the high-temperature heat pipe starting from frozen state [13]. In those cases, the initiation of the phase change of the working fluid and thereafter the formation of the fluid circulation is the dominant phenomenon. In another scenario, the transient response to a heat load being suddenly applied or changed without a phase change from frozen or supercritical state is also of interest. For example, an abrupt increase of a CPU load could lead to a temperature rise of over 50 °C in a few seconds, and it is of great significance to see how quickly the heat pipe in the electric cooling device responds, and how long it takes to reach the steady working state.

This paper intends to present a numerical model for fast simulation of the transient behavior of heat pipes. The temperature and the pressure of the vapor region are treated as lumped parameters. Conduction in the wall and the wick, liquid flow in the wick, and phase change are numerically solved by the lattice Boltzmann method (LBM). Our transient heat pipe model is fully capable of performing the above mentioned numerical methods for further analysis of the temperature and flow profiles. The inclusion of the lumped vapor consideration greatly lowers the total computational cost, which enables it to be an efficient tool for fast simulation of the transient processes of heat pipes.

2. Transient heat pipe model and numerical implementation

2.1. Physical and mathematical description of heat pipes

Conventionally, a heat pipe is divided into three thermally coupled parts: the solid wall (container), the wick filled with working fluid, and the vapor core. The working fluid undergoes continuous phase change between liquid and vapor, driven by the input heat and the capillary effect of the wick. The working mechanism of porous wicked heat pipes is schematically shown in Fig. 1.

Heat transfer in the wick includes conduction, convection and phase transition in saturated or unsaturated porous media. The wick is assumed to be fully thawed, in which the momentum equation for the working fluid follows the Brinkman–Forchheimer-extended Darcy model, including the linear (Darcy) term, the viscous (Brinkman) term and the non-linear (Forchheimer) term:

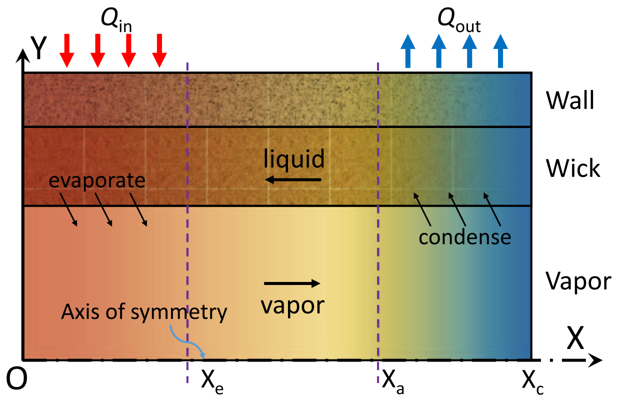

Fig. 1. Schematic of the working mechanism and boundary conditions of porous wicked heat pipes.