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Numerical analysis of a screen mesh wick heat pipe with Cu/water nanofluid

A. Brusly Solomon, K. Ramachandran [*], L. Godson Asirvatham, B.C. Pillai

Centre for Research in Material Science and Thermal Management, School of Mechanical Sciences, Karunya University, Coimbatore 641114, India

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ABSTRACT

A two-dimensional transient numerical model is developed to predict the vapor core, wall temperatures, vapor pressure, vapor velocity and liquid velocity in the screen mesh wick heat pipe. The mass, momentum and energy equations are solved numerically for liquid and vapor regions. The effect of Cu–water nanofluid on the heat transfer performance of heat pipe is studied using the developed model and the same is compared with that of the DI water. The transient profiles of vapor and liquid velocities in the wick region and the location of dry-out in the evaporator section of the heat pipe are also obtained using the developed model. It is found that the addition of nanoparticles leads to the reduction in wall temperature, operating pressure, vapor temperature and total resistance of the heat pipe; thereby, increasing the heat transfer of the heat pipe at the same heat load. Interestingly, the liquid and vapor velocities of the heat pipe charged with 0.1 wt% of Cu-water nanofluid is found to be 20% higher when compared with that of the heat pipe with DI water at the same operating conditions. It is also observed that the decreased pore size of the wick due to the addition of nanoparticles increases the effective thermal conductivity of the wick structure which acts as a coating layer and enhances the heat transfer capability of the heat pipe.

1. Introduction

Heat pipes are hollow metal enclosures partly filled with a liquid coolant that moves heat from one end to another continuously by evaporation and condensation of the liquid due to capillary pressure. After the invention of heat pipe much advancement have been taken place during the past few decades with respect to the design construction and operating fluid etc. specific to the application. Recently, Faghri [1] reviewed the advances in heat pipe technology including various types of heat pipes, heat pipe analysis and simulations. Heat pipes have been used in several applications such as electronic cooling [2], heat recovery in renewable energy [3], and heat exchangers [4], etc. Modern developments in coolant fluid such as a nanofluid led to further advancement in heat pipe technology in the field of electronic cooling applications. Kakac and Pramuanjaroenkij [5] reviewed the flow and heat transfer characteristics of nanofluids under free and forced convection modes. This study showed that the nanofluids significantly improved the heat transfer capability of conventional fluids such as oil and water. It is also reported that the reason for enhancement is due to the higher thermal conductivity of the suspended nanoparticles in the base fluids. Following that many experimental studies [6–10] have been carried out to study the effect of nanofluids on the heat transfer performance of heat pipes. In a study [11] various types of nanofluids (silver, copper, Al_2O_3, gold, diamond) used in heat pipes and the mechanism for the heat transfer enhancement are presented. It is observed that the enhancement in heat transfer is not only by the thermo physical properties of nanofluids but also by the nature of the surface formed during boiling process in the evaporator section. Similarly, many numerical studies have also been performed to predict the heat transfer enhancement of nanofluid by conventional numerical methods and new Lattice Boltzmann Method (LBM) [12]. Though the mechanism for heat transfer enhancement is understood to an extent, still there are lots of issues taking place in the micro level are unclear. Hence more numerical studies are necessary to get more insights on the heat transfer enhancement mechanism.

Tien and Rohani [13] analyzed the effects of vapor pressure variation on the vapor temperature distribution, evaporation and condensation rates, and the overall performance of the heat pipe. Chen and Faghri [14] analyzed the heat conduction between the wall and liquid-wick interface and the compressibility effects. Huckaby et al. [15] performed a one dimensional analysis using a

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[*] Corresponding author. Address: Department of Physics, Bharathiar University, Coimbatore, India. Tel.: +91 422 2614439; fax: +91 422 2615615.

E-mail address: ramspsg@yahoo.com (K. Ramachandran).

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Nomenclature

u	x directional velocity (m/s)
v	y directional velocity(m/s)
P	pressure (Pa)
K	permeability (m^2)
C_E	Ergun coefficient
C	specific heat (J/kg K)
k	thermal conductivity (W/m-K)
T	temperature (K)
N	number of layers
d	diameter (m)
q	heat flux (W/m^2)
L	length (m)
h	heat transfer coefficient (W/m^2-K)
x	axial distance (m)
A	area (m^2)
$\dot{m}$	mass flow rate (kg/s)
m_i''	mass flux (kg/m^2s)
$\overline{M}$	molecular weight (g/mol)
M	mass (kg)
R	gas constant (J/kg-K)
R	Resistance (°C/W)
h_{fg}	heat of vaporization (J/kg)
$\overline{V}$	velocity vector (m/s)
V_{cell}	volume of the cell (m^3)
t	time (s)
r	wire radius (m)

Symbols

ε	porosity
ρ	density (kg/m^3)
μ	viscosity (Nm-s)
ω	wire
σ	accommodation coefficient

Subscripts

eff	effective
s	solid
l	liquid
m	mean
i	interface
e	evaporator
a	adiabatic
c	condenser, capillary
w	wick, wall
v	vapor
o	stagnation
op	operating
sat	saturation
P	center of the computational cell

collocation-spectral method to compute the dynamic behavior of the vapor flow in a heat pipe. Two-dimensional, heat pipe transient analysis model (HPTAM) is developed and benchmarked by Tournier et al. [16] using transient experimental data for cumulative operations of fully-thawed heat pipes. Tournier and El-Genk [17] developed free-molecular, transition and continuum vapor flow model, based on the dusty gas model, incorporated in HPTAM, to analyze the startup of a radiatively-cooled sodium heat pipe from a frozen state. Legierski et al. [18] conducted a study on the modeling and measurements of heat and mass transfer in heat pipes using the FLUENT commercial code. Alizadehdakhel et al. [19] studied a gas/liquid two-phase flow and the simultaneous evaporation and condensation phenomena by using the volume of the fluid model (VOF) technique in a thermosyphon using FLUENT code.

Vadakkan et al. [20] developed a numerical model to analyze the transient performance of flat heat pipes for high heat fluxes and high wick conductivity. In another study, Vadakkan et al. [21] developed a three-dimensional model to analyze the transient and steady-state performance of the flat heat pipe with multiple heating sources. Ranjan et al. [22] developed a micro scale evaporation model for thin-film evaporation in capillary wick structures. This micro scale evaporation model is coupled with the general (macro) model to include the microstructure effects in the liquid/vapor interface [23]. The meniscus curvature at every location along the wick is calculated as a result of this coupling. This coupled model is used to predict the thermal transport in heat pipes and vapor chambers. Carbajal et al. [24] developed a quasi-3D numerical model to analyze the flat heat pipe. Rice and Faghri [25] performed a complete numerical analysis of heat pipes including flow in the wick. Wang et al. [26] simulated the two-phase flow in vapor chamber and compared the simulation results with experimental test data. Xiao and Faghri [27] developed a three-dimensional model to analyze the thermal hydrodynamic behaviors of flat heat pipes without empirical correlations. Chen et al. [28] performed a mathematical analysis for a whole set of thermal module which consists of a plate-fin heat sink embedded with a vapor chamber. Aghvami et al. [29] developed a simplified analytical thermal-fluid model including the wall, and both liquid and vapor flows for flat heat pipes and vapor chambers with different heating and cooling configurations.

Shafahi et al. [30] developed an analytical model to investigate the thermal performance of rectangular and disk-shaped heat pipes with nanofluids as working fluid. The pressure and velocity profile of liquid, temperature distribution of the heat pipe wall, temperature gradient along the heat pipe are obtained. Also, thermal resistance at various heat loads is obtained for the flat-shaped heat pipes. Do et al. [31] studied the effect of water-based Al_2O_3 nanofluids on the thermal performance of a flat micro-heat pipe with a rectangular grooved wick. One dimensional conduction equation for the wall and Young–Laplace equation for the phase change process were solved to predict the axial variations of the wall temperature, the evaporation and condensation rates. The thermo physical properties of nanofluids, the surface characteristics formed by nanoparticles such as a thin porous coating are also considered in this model. Shafahi et al. [32] performed a two-dimensional analysis to study the thermal performance of a cylindrical heat pipe utilizing nanofluids. Three of the most common nanoparticles, namely Al_2O_3, CuO, and TiO_2 are considered as the working fluid. Based on the review of literatures mentioned above, most of the numerical analysis on heat pipe have been carried out only with conventional working fluids. Also it is clearly observed that most of the investigations (numerical analysis & model development) have been reported in the open literature that uses the metallic oxides nanoparticles for predicting the liquid and vapor velocities in the evaporator and condenser sections. However no numerical analysis and model development has been made to predict the liquid and vapor velocities in the evaporator and condenser sections by using low weight concentrations of pure metallic nanoparticles. Hence in the present study, an attempt is made to numerically analyze the effect of Cu–water nanofluids in the heat pipe for predicting the liquid and vapor velocities in the evaporator and condenser sections. Also the effect of heat input on the axial