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Research Article

Analysis of Two-Phase Flow in the Capillary Wick Structure of Flat Heat Pipe with Different Orientation

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Abstract

This paper addresses simulation of phase change mechanism in the capillary wick of a flat heat pipe. The two-phase flow through porous media has wide application especially in heat pipes. It is a thermodynamic device that transports heat energy from one location to another with a negligible temperature drop. The present analysis concentrates only on the two-phase zone of the porous wick structure. The basic governing equations used for the formulation are continuity, mixture momentum, liquid conservation and energy. These equations are converted into ordinary differential equations using similarity transformation and two-phase similarity solutions are obtained for both boiling and condensing flows. The adjacent layer to the wall is considered to have two-phase region where the liquid and vapour can coexist. The liquid wall saturation, non-dimensional temperature and non-dimensional temperature gradient are predicted numerically during the phase change of water-steam system in the heat pipe for horizontal and vertical cases.

Keywords: *Flat heat pipe, Similarity transformation, Two-phase flow, Saturation, Gear stiff method*

1. Introduction

Two phase flow is usually a complex transport process and its complexity increases when the heat transfer in porous media is also involved simultaneously. One such situation is encountered in the capillary structure of heat pipe. The purpose of the present work is to analyse the two-phase flow inside the heat pipe. Heat pipes find widespread application in thermal systems due to their ability to provide effective heat transport with minimum heat losses. Even though the vapour flow and the liquid flow in the heat pipe have been studied by various researchers in the past, not much emphasis is given to the liquid flow in the wick structure due to its complexity. Hence simplified models have been used to study the liquid flow in the heat pipe wick. The present study mainly focuses on boiling and condensing in the porous medium of a heat pipe.

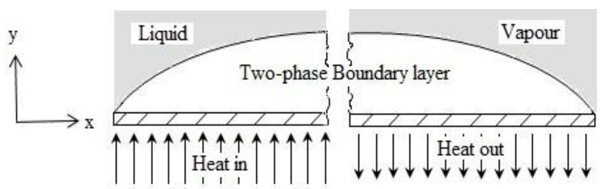

Fig.1 Schematic model of porous region of flat heat pipe

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The physical model of horizontal heat pipe used for carrying out the numerical analysis is shown in Fig.1. The coordinate system chosen for the analysis is in such a way that the axial direction is taken as the X coordinate and along the boundary layer, the Y coordinate, as taken in the boundary layer problem.

Usually vertical model, which is gravity assisted in which liquid flow from the condenser section is aided by gravity along with capillary force is preferred over the horizontal due to better performance. But in practical application due to space constraint and design complexity, horizontal heat pipes in which flow occurs due to capillary effect are considered. Hence in this paper more investigations are carried out for the heat pipe with horizontal orientation and the results are compared with that of the vertical.

A review of the published literature on heat pipes reveals that numerical studies on heat pipes have been carried out by various researchers. Due to the inherent nonlinearity of two-phase problems, exact solutions are limited to a small class of problems, and many simplifying assumptions are employed. A model for two-phase transport in capillary porous media is presented in which the two phases are treated as constituents of binary mixture (Wang and Beckermann, 1993). Classical separate flow model were used to derive the conservative equations. It presents formulation of conservation of mass, liquid mass, momentum and that of energy. This formulation is used in many problems such as boundary layer two-phase flows, conjugate two and single-phase flows in multiple regions and transient flows. The two-phase mixture model developed by Wang and Beckermann in Part-I is applied to investigate a pressure-driven two-phase boiling flow along a heated surface embedded in a porous medium. The general governing equations simplified using approximations analogous to classical boundary layer theory, are derived by similarity transformation for a two phase flow (Wang and Beckermann, 1993). The resultant ordinary differential equations are numerically solved using Gears Stiff method and shooting procedure. Wang and Beckermann (1995) presented a boundary layer analysis in porous media considering boiling and condensation. A set of boundary layer equations which has been derived from two-phase mixture motion was transformed into differential equations by means of similarity transformation and solved to obtain saturation and velocity profiles. Similarity transformations are employed to solve the effect of slip in the boundary layer flow (Bhattacharyya, *et al*, 2013). The steady laminar boundary layer flow over a stretching sheet with partial slip under a convective surface boundary condition was studied (Bakar, *et al*, 2012) using the similarity transformations.

The forced convection in a channel partially filled with porous material and subjected to constant wall heat flux was examined analytically (Karimi, *et al*, 2014). Incorporating the porous material thickness exact solution for the solid and fluid temperature was developed. Panda, *et.al* (2013) discussed the effect of various fluid flow parameters and heat transfer in a channel partially filled with porous material bounded by parallel heated oscillating plates. Studies in porous medium were carried out (Jha, *et al*, 2014). They extended the work (Cheng, *et al*, 2006) and presented analytical solutions for fully developed natural convection heat and mass transfer in a vertical annular non Darcy porous medium. Boundary layer flow and heat transfer in a porous media with variable surface heat flux were carried out by using similarity solutions (Mandal and Mukhopadhyay, 2013). The momentum and heat transfer in a laminar boundary layer flow over a flat plate with slip boundary condition were considered (Martin and Boyd, 2006). A two-phase analysis is carried out for the heat pipe to study the vapour dynamics of the working fluid. Using finite volume method, the compressible flow equations for vapour-phase interaction with water particle phase were solved (Mehta and Jayachandran, 1996). A three dimensional simulation of cylindrical heat pipe which incorporates the phase change mechanisms at the liquid and vapour interface was presented (Brahim and Jemni, 2012). The model predicted the behaviour under critical conditions where a high heat input is exposed to its evaporator region. The temperature, pressure and velocity profiles within the wick structure and vapour phase were analyzed.

The objective of this paper is to perform the boundary layer analysis for two phase flow in porous media in a heat pipe using mixture model for both boiling and condensing phenomena. The present model is validated (Wang and Beckermann, 1995) and is extended to solve the energy equation also. It is envisaged to quantitatively examine the variation of different parameters - saturation, temperature and velocity vector fields - in the porous structure of both vertical and horizontal heat pipe.

2. Governing equations

The conventional forms of two phase mixture model equations governing with the assumption of two-phases are immiscible, incompressible flow through porous medium are used here.

The basic equations are:

Continuity: $$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \quad (1)$$

Darcy's equation (mixture momentum):

$$\rho u=-\frac{K}{v}\left(\frac{\partial p}{\partial x}\pm\rho_k g\right) \quad (2)$$

Liquid mass conservation:

$$\rho\frac{d\lambda}{ds}\left(u\frac{\partial(s)}{\partial x}+v\frac{\partial(s)}{\partial y}\right)=\frac{\partial}{\partial y}\left(D\frac{\partial s}{\partial y}\right)\pm\frac{K\Delta\rho}{v_v}g\frac{df}{ds}\frac{\partial s}{\partial x} \quad (3)$$

Energy equation: $$\rho u\frac{\partial T}{\partial x}+\rho v\frac{\partial T}{\partial y}=\frac{\mathrm{k_{eff}}}{\mathrm{c_k}}\left(\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

Thermo physical properties and isothermal two-phase zone are assumed to be constant in the present work. Similarly as the heat transfer is gradually enhanced at the wall, it takes its limiting value of zero for boiling and unity for condensation.

3. Similarity transformation

The above governing equations need to be solved to get the numerical solution. For simplification, the above partial differential equations may be converted to ordinary differential equations. Applying similarity transformation along with assumptions this non-linear set of equations are transformed into ordinary differential equations. The boundary conditions are also transformed accordingly. The similarity variables used are defined below:

$$\eta = (y/x)\,Ra_x^{1/2};\ \Psi = D_c Ra_x^{1/2} F(\eta);\ s=s(\eta) \quad (5)$$

$\theta(\eta)=\frac{T-T_l}{T_w-T_l}$ for boiling ; $\theta(\eta)=\frac{T-T_v}{T_w-T_v}$ for condensing .

The governing equations in terms of similarity variable get transformed into following equations:

$$F' = \overline{v}K_{rv} \quad (6)$$

$$(\hat{D}s')' + \frac{1}{2}\frac{d\lambda}{ds} F\, s' = \pm\frac{1}{2}\,\overline{\upsilon}\frac{df}{ds}\eta s' \qquad (7)$$

The plus and minus in Eq. (7) correspond to boiling and condensation flows, respectively.

$$\theta'' + \frac{1}{2}R(\lambda + c(1-\lambda))F\,\theta' = 0 \qquad (8)$$

where $R = \frac{c_{pl}D_c}{k_{eff}}$ and c is the ratio of specific heat of vapour to liquid defined as $c = \frac{c_{pv}}{c_{pl}}$.

In condensing case when a pure liquid film appears adjacent to porous structure of the wall, the wall saturation is taken as unity. In boiling case when heat flux value is increased, it reaches a maximum point where pure vapour form at the wall. It corresponds to dry out condition and wall saturation takes value of zero. For the horizontal orientation, gravity assisted term in the above governing equation vanishes.

Another significant advantage is that the formulation does not affect inherent characteristics of the individual phases, although the differential governing equations deal solely with the bulk behaviour of the mixture. This is because the formulation expresses simple relations between the motions of the multiphase mixture and separable phases. While analysing horizontal orientation, the gravity assisted term in the above equations is neglected. As far as the thermo physical properties in the analysis are concerned, once the similarity transformation is applied then the wall saturation and the viscosity ratio become the only parameters. In the present analysis of water-steam system the value of viscosity ratio is taken as 0.01466.

3.1. Boundary conditions

Boundary conditions for differential equations in terms of similarity variable become,

when $\eta = 0$ $\quad F = 0 \quad s = s_w \quad \theta = 1$

when $\eta \to \infty$ $\quad F' = 0 \quad s = \begin{cases} 1 & boiling \\ 0 & condensing \end{cases} \quad \theta = 0$

3.2. Methodology

Using classical boundary layer assumptions the simplified governing equations are numerically solved using the similarity variables. Three differential equations along with corresponding boundary conditions are solved for both boiling and condensing flows using software Matlab 7.10. The equations are solved numerically by Gear stiff method combined with a shooting procedure for which Matlab uses built-in function ode15s. The governing equations are solved for liquid saturation, saturation gradient, non-dimensional mixture temperature, temperature gradient and for velocity vector plot.

4. Results and Discussion

The present numerical work is compared with available numerical results of Wang and Beckermann (1995). For boiling flow, the comparison of liquid saturation against similarity variable for two saturation values is shown in Fig. 2. Similarly, in condensing flow the liquid saturation is compared as in Fig. 3 for a saturation value. The results for both boiling and condensing flows are found to be in good agreement with that of Wang and Beckermann.

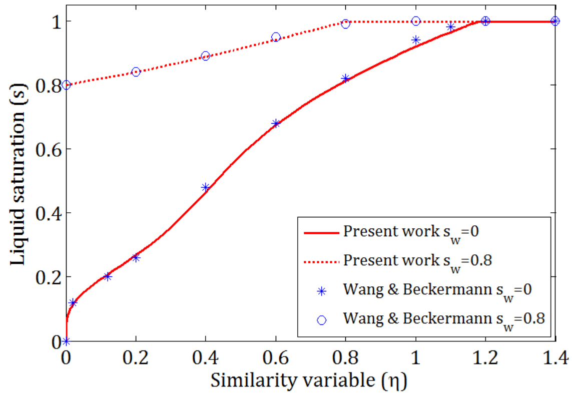

Fig.2 Comparison of the present numerical results with Wang and Beckermann for variation of liquid saturation (Boiling)

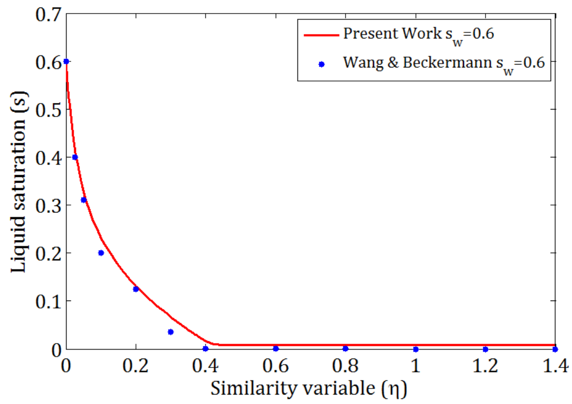

Fig. 3 Comparison of the present numerical results with Wang and Beckermann for variation of liquid saturation (Condensation)

The variation of temperature and temperature gradient against similarity variable for both boiling and condensing flows for vertical orientation of heat pipe is depicted in the following figures. Temperature at different wall saturations, plotted against similarity variable is shown in Fig. 4. For high liquid wall saturation the graph is a straight line, but as wall saturation decreases the shape becomes parabolic. This is due to the fact that when wall liquid saturation is zero, the heat transfer rate is high thus high temperature gradient within boundary layer. Towards boundary layer, temperature is varying slowly compared to very near to wall. Temperature gradient plotted against similarity variable for different wall saturations is shown in Fig. 5. It is found that for boiling, temperature gradient has high variation for saturation values of zero and it decreases towards the boundary layer. The reason is that for low liquid saturation, high heat flux rate is induced on the wall. For high values of wall liquid saturation, temperature gradient variation remains almost constant along the wick in the evaporator region.

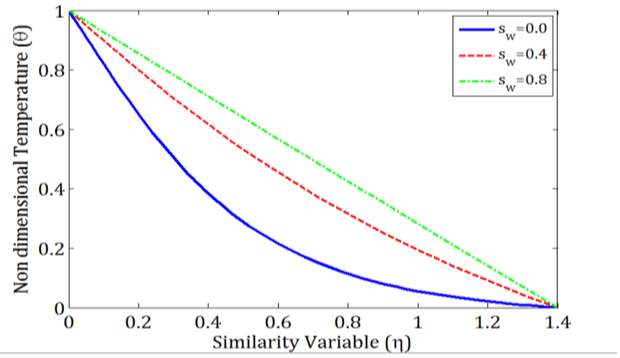

Fig.4 Variation of Non dimensional temperature against similarity variable (Boiling) for vertical case

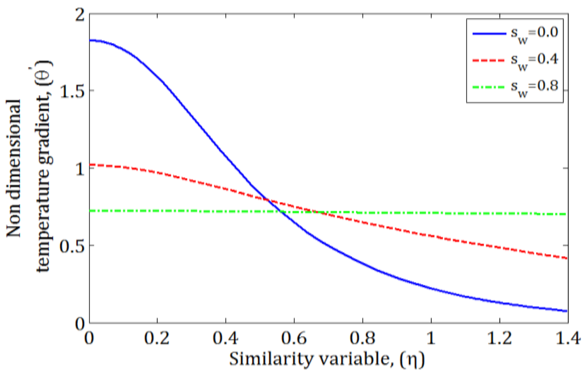

Fig.5 Variation of Non dimensional temperature gradient against similarity variable (Boiling) for vertical case

Non-dimensional temperature plotted against similarity variable for different wall saturations for condensing flow is shown in Fig. 6. The temperature profile shows a similar variation to that exhibited in boiling flow. Here the variation of wall saturation at unity is more than that at wall saturation at zero in the case of boiling.

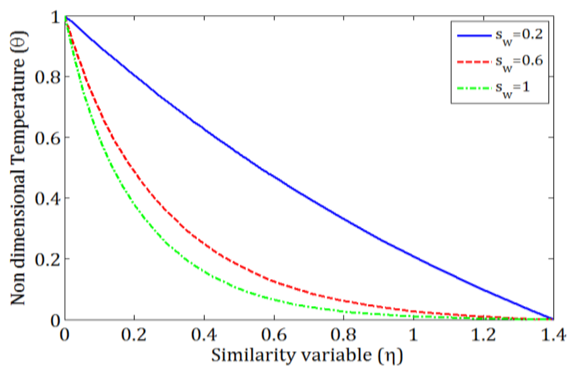

Fig. 6 Variation of Non dimensional temperature against similarity variable (Condensing) for vertical case

Temperature gradient plotted against similarity variable for different wall saturations is shown in Fig. 7. Unlike the temperature gradient in boiling flow for wall saturation equal to zero, temperature gradient in condensation has high value at unity, and it decreases towards the boundary layer. The value of temperature gradient in boiling flow reaches zero after the boundary layer region. For low values of wall liquid saturation, temperature variation becomes constant anywhere inside wick.

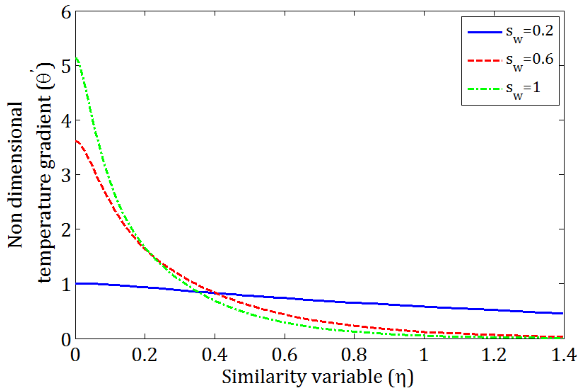

Fig. 7 Variation of Non dimensional temperature gradient against similarity variable (Condensing) for vertical case

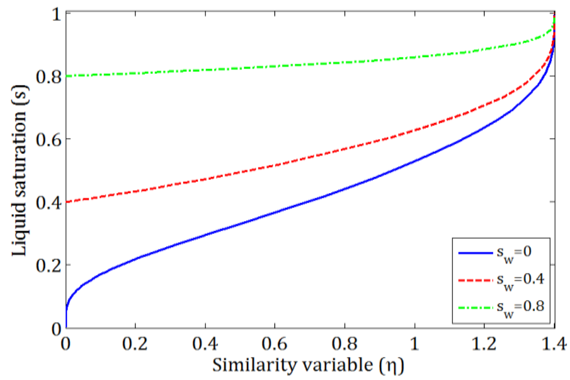

Fig. 8 Variation of Liquid saturation against similarity variable in boiling (Horizontal case)

The variation of liquid saturation for different wall saturation plotted against similarity variable for boiling flow in horizontal orientation is shown in Fig. 8. The saturation profile shows sharp edge of two-phase boundary layer for all wall liquid saturation, since the capillary diffusion coefficient becomes extremely small. The saturation gradient plotted against the similarity variable is shown in Fig. 9. It has high values when the wall saturation is small. The variation is found to decrease as the saturation value increases. The profiles obtained are found to be contrasting with the simple concentration profile in single-phase mass transfer problem due to the fact that mean transport properties of a two phase-mixture are highly nonlinear.

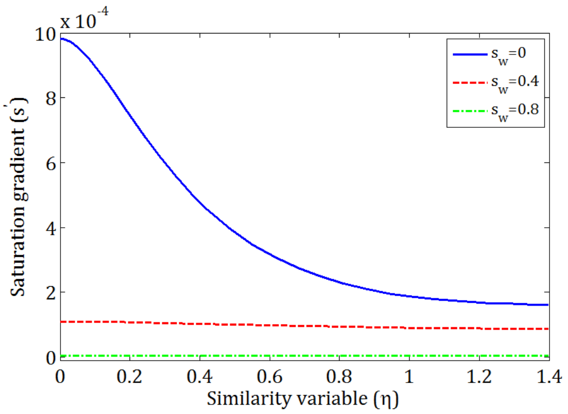

Fig. 9 Variation of Liquid saturation gradient against similarity variable in boiling (Horizontal case)

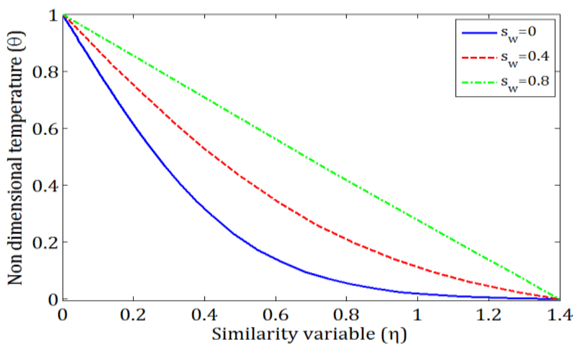

Fig. 10 Variation of Non dimensional temperature against similarity variable in boiling (Horizontal case)

The non-dimensional temperature at different wall saturations is plotted in Fig. 10 against similarity variable. The graph is a straight line for high liquid wall saturation, but it takes parabolic shape as the wall saturation decreases, due to the fact that when the wall liquid saturation is zero, the heat transfer rate is high thus occurring high temperature gradient within boundary layer. The temperature is varying slowly towards the boundary layer compared to very near the wall for higher value of saturation.

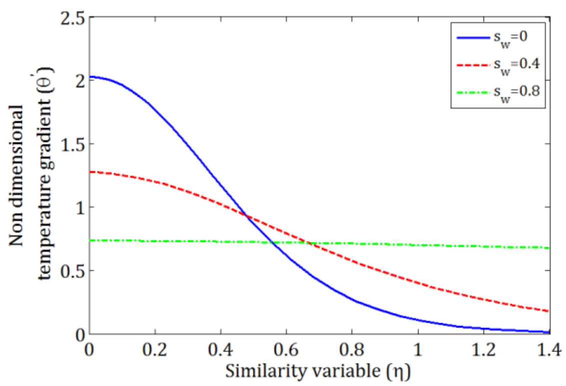

Fig. 11 Variation of Non dimensional temperature gradient against similarity variable in boiling (Horizontal case)

The temperature gradient plotted against similarity variable for different wall saturation is depicted in Fig. 11. The temperature gradient decreases towards the boundary layer, the reason being for low liquid saturation, high heat flux rate is induced in the wall. The variation is found to decrease for the increased value of wall saturation.

The vector plots of the simulations for liquid flow in case of boiling is been presented in Fig. 12. The vector plot clearly indicates that as heat is supplied, more and more vapour formation takes place. The vapour formed is transported in transverse direction, making the liquid flow towards the wall. The liquid coming from the condenser section moves towards the wall, where it absorbs heat from the evaporator region and gets converted into vapour. The slight decrease in the velocity magnitude near the wall is due to the heat input given to the wall.

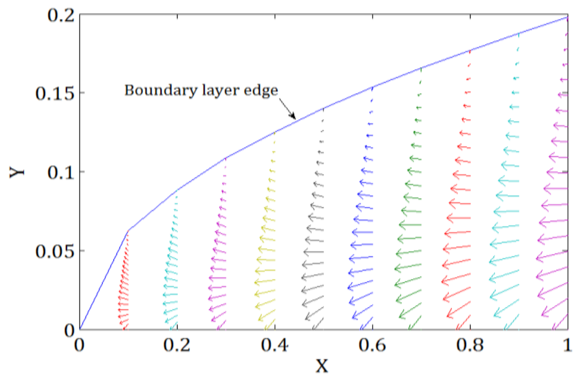

Fig. 12 Liquid velocity vector plot in boiling

The vapour flow field in boiling flow is shown in Fig. 13. When the bottom wall is heated, the wick which is initially saturated with liquid absorbs the heat and gets converted in to vapour. Thereafter it moves primarily upwards so as to move in the transverse direction to the vapour core.

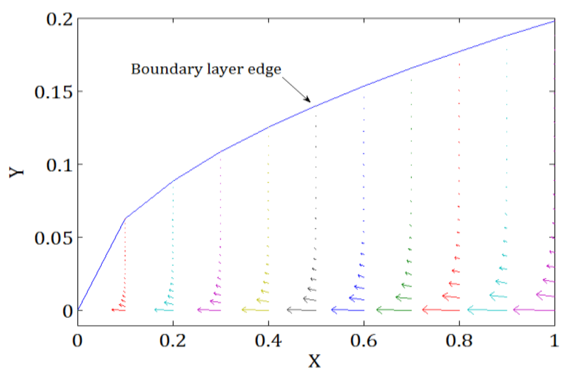

Fig. 13 Vapour velocity vector plot in boiling

Liquid saturation profile for different wall saturation plotted against similarity variable for condensing flow in horizontal case is shown in Fig. 14. It is noted that there is a sudden variation of liquid saturation towards the wall. The variation is found to increase as the saturation value is increased and has the maximum value for saturation equal to one.

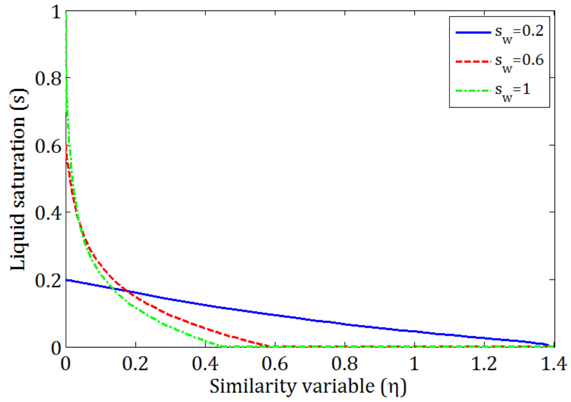

Fig. 14 Variation of Liquid saturation against similarity variable in condensing (Horizontal case)

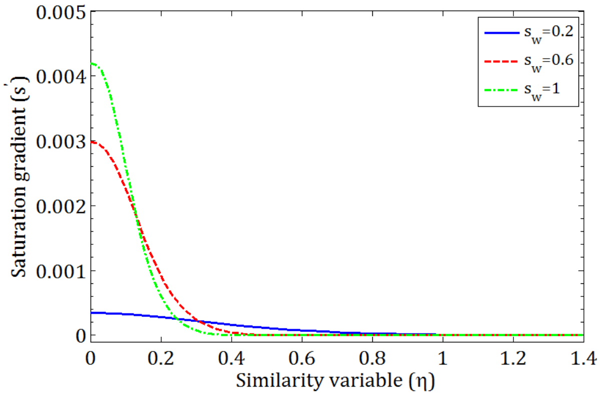

Fig. 15 Variation of Liquid saturation gradient against similarity variable in condensing (Horizontal case)

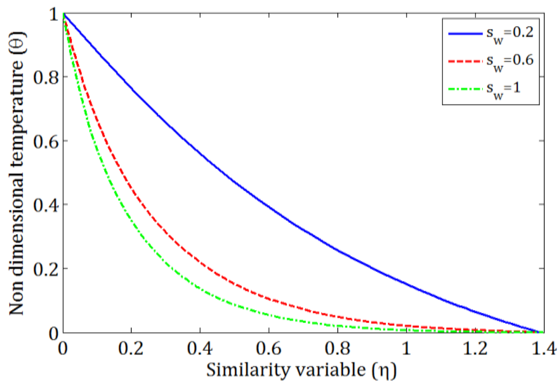

Fig. 16 Variation of Non dimensional temperature against similarity variable in condensing (Horizontal case)

Saturation gradient is plotted against similarity variable for different wall saturations as shown in Fig. 15. For higher value of wall saturation, its value is high at the wall and decreases towards the boundary layer and reaches zero at the edge of the boundary layer. For lower values of wall saturation, saturation gradient becomes smaller. Similarly, non-dimensional temperature at different wall saturations is plotted against similarity variable in Fig. 16. It is observed that for low liquid wall saturation, for the condensing flow, the graph is almost approaching to a straight line. But as wall saturation increases the shape becomes parabolic, when the wall liquid saturation approaches unity, the heat transfer rate is low and the temperature gradient will be less within boundary layer. Even though density difference has influence in two phase flow, it does not enter in the present similarity solution because of mixture stream function.

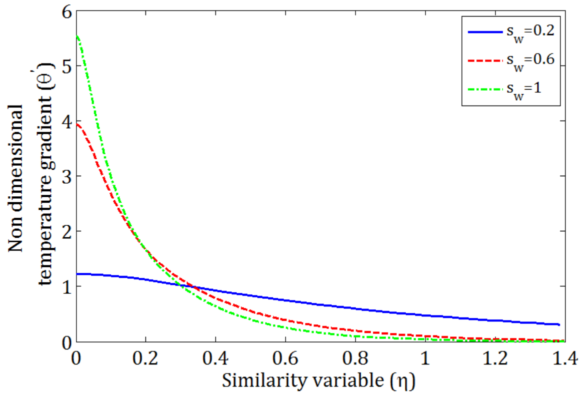

Fig. 17 Variation of Non dimensional temperature gradient against similarity variable in condensing (Horizontal case)

The temperature gradient against similarity variable for different wall saturation is shown in Fig. 17. The temperature gradient decreases towards the boundary layer. The liquid vector plot for the condensing flow shown in Fig. 18 which clearly depicts that as heat is rejected from the bottom wall, the wick section which is initially saturated with vapour liberates heat and liquid is formed very near the wall. The condensed liquid then flows towards the boiling section due to the capillary effect.

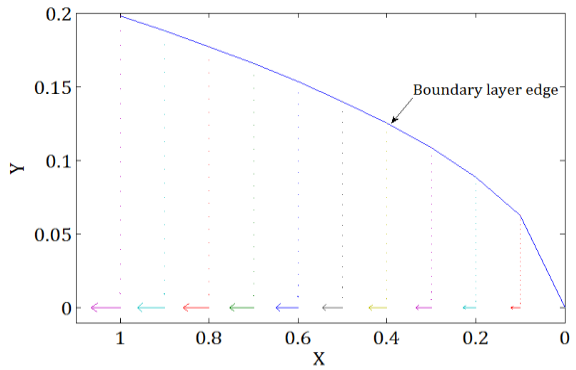

Fig. 18 Liquid velocity vector plot in condensing

Similarly from the vapour velocity vector shown in Fig. 19, it can be seen that as the heat is rejected in the condenser section, more and more liquid gets displaced towards the boiling side. This makes the vapour above the liquid region to move towards the wall and to occupy the space due to the mass conservation principle. Adjacent to the wall, the vapour velocity reduces since the heat is being taken out through the wall.

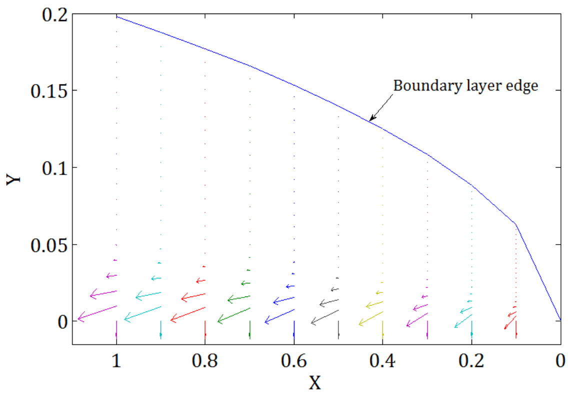

Fig. 19 Vapour velocity vector plot in condensing

Conclusions

In the present work, the analysis of phase change mechanisms that occur in the porous wick structure of a flat heat pipe using two-phase mixture formulation was carried out. The governing equations are numerically solved for liquid saturation and non-dimensional mixture temperature using similarity variables. Numerical results obtained were validated with the available results. The saturation, saturation gradient, temperature and temperature gradient for both boiling and condensing flows were found out. Velocity vector plots obtained convey the physical mechanism for both flows. Out of the two models presented, the vertical heat pipe is capable of carrying more heat load compared to the heat pipe with horizontal orientation since the effect of gravity will assist the flow along with capillary force from the condenser to the evaporator region.

Nomenclature

c	Ratio of specific heats of vapour to liquid
c_{pl}	Specific heat of liquid
D_c	Constant part of capillary diffusion coefficient
F	Dimensionless stream function
K	Relative permeability
k	Thermal conductivity
s	Saturation
x	Cartesian coordinate (along the axis of heat pipe)
y	Cartesian coordinate (perpendicular to the axis)
Ra	Rayleigh number
$\overline{\nu}$	Ratio of kinematic viscosities of the liquid to vapour
η	Similarity variable
θ	Non dimensional temperature
ψ	Stream function
λ	Liquid relative mobility

Subscript

eff	Effective
l	Liquid
r	Relative
v	Vapour
w	Wall

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