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Film condensation on a vertical microchannel☆

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ABSTRACT

In this paper, a two dimensional laminar liquid film which condenses on a vertical microchannel is investigated analytically. A liquid film thickness, condensation mass flux flow and the variation of the velocity through the liquid thickness were determined by modified Navier–Stockes and energy equations. The effect of some parameters on the liquid film thickness, condensation mass flow rate and velocity are investigated. These parameters include slipping in temperature, β, and velocity, α, due to microscale interaction. It was found that, the liquid film thickness, δ, decreases as the slipping factors increases, and diminishes as a value of slipping factors (α and β) become more than or equal to 0.1. Increasing the slip in temperature due to microscale interaction causes the condensation mass flow rate to increase as the value of slip in velocity increases. Additionally, the slip value in the channel was found to increase as the slip value in velocity, α, increases.

1. Introduction

The art of the utilization of microchannels for achieving high heat transfer rates in fact much further ahead than the science of obtaining a comprehensive understanding of phase change in theses channels. The large heat transfer coefficients in microchannels and the large surface-to-volume ratios they offer has led to their use in compact condensers for air-conditioning systems in automobiles for many years [1]. The flow of liquids in microchannel is different from that of gas in the same microchannel [2]. Where is a standard results usually apply with liquid flow, this is not the case with gases: the most noticeable difference between micro and macro domains with gases is the presence of the slip at the solid interface [3]. The operation of MEMS-based ducts, nozzle, valve bearings, turbo-machines, etc., cannot always be predicted from conventional flow models such as the Navier–Stokes equations with no-slip boundary conditions at gas–solid interfaces, as routinely and successfully applied for larger flow devices. Most previous investigations of the pressure gradient and electrosmotic liquid flow in microchannel were performed using no-slip condition [4–10]. The analysis of laminar heat transfer in slip flow were first taken for tubes with uniform heat flux and parallel plate channels for a circular tube with uniform wall temperature using continuum theory subjected to slip-velocity and temperature jump boundary conditions [11]. Tuckmann [12] was the first to investigate systems using microchannel heat exchangers and forced single-phase liquid cooling through microchannels for cooling electronic devices. A model was proposed by Weisberg et al. [13], which could predict the temperature distribution in a microchannel evaporator for water used as working fluid and laminar flow. Due and Zhao [14] show that the average heat transfer coefficient of steam condensate inside a triangular channel is higher than that inside round tube for the same hydraulic diameter. Flow heat transfer coefficients were presented by Riehl et al. [15], who reviewed the available analytical models and experimental data obtained for microchannels.

Few previous experimental and analytical investigations have been performed regarding microchannels condensation. Quan et al. [16] show that decrease of microchannel diameter tends to enhance stability of the condensation film on the wall. However, noncircular channels perform better than circular channel near the inlet which leads to increase condensate loading along the channel [17]. Smirnov et al. [18] have presented an approach for condensation in small channels. This model was able to predict condensation in channels where the gravitational forces do not influence the flow. In addition, the model could predict the liquid film thickness along the channel, which is important for analysis of the condensation capability. The basic understanding of the transfer mechanisms of heat, momentum, and mass in microchannels during phase change is still under development. The problem of film condensation in microchannels has attracted the attention of investigators because of its significance in numerous engineering applications including evaporative, condensers, geothermal energy utilization, thermal enhancement of oil recovery and heat pipes distillation facilities.

2. Mathematical formulation

Consider the two dimensional laminar liquid film which condenses on a vertical microchannel as shown in Fig. 1. The following assumptions were made for the mathematical formulation:

1. Laminar flow and constant properties are assumed for the liquid film.

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Nomenclature

b	Liquid film width (m)
g	Gravitational acceleration (m s^{-2})
h	Convection heat transfer coefficient (W m s^{-2} K^{-1})
h_{fg}	Latent heat of condensation (J kg^{-1})
h'_{fg}	Augmented latent heat of condensation (J kg^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	Condensation mass flow rate (kg s^{-1})
p	Pressure (Pa)
q_s	Surface heat flux (W m^{-2})
T	Temperature (K)
T_w	Wall temperature (K)
T_{sat}	Saturation temperature (K)
u	Axial velocity (m s^{-1})
x	Axial coordinate (m)
y	Transverse coordinate (m)

Greek symbols

δ	Liquid film thickness (m)
μ	Viscosity (kg m^{-1} s^{-1})
Γ	Condensation mass flow rate per unit length (kg m^{-1} s^{-1})
ρ	Density (kg m^{-3})
β	Slip in temperature due to microscale interaction (K)
α	Slip in velocity due to microscale interaction (m s^{-1})

Subscript

l	Liquid
w	Wall
sat	Saturated properties
v	Vapor

2. The gas is assumed to vaporize at a uniform temperature equal to T_{sat}, with no temperature gradient in the vapor and heat transfer to the liquid–vapor interface occurring only by condensation at the interface.
3. The stress levels at the liquid–vapor interface is assumed to be negligible, in which case, we have $\partial u(\delta)/\partial y=0$. This assumption is combined with a uniform vaporization temperature, in which case the vapor velocity or thermal boundary layers are no longer considered.

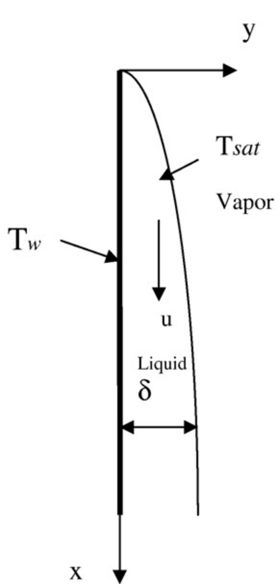

Fig. 1. Schematic diagram of the problem under consideration.

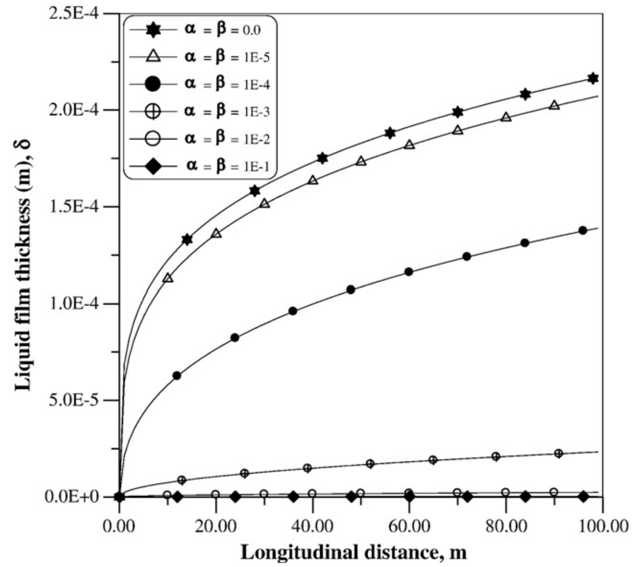

Fig. 2. Liquid film thickness vs longitudinal distance.

4. Momentum and energy transfer by advection in the condensate film are assumed to be negligible. This is reasonable for the low velocities associated with the film. It follows that the heat transfer across the film occurs only by conduction, in which case the liquid's temperature distribution is linear.
5. Slip boundary conditions were assumed
6. The slip coefficient was constant and the same at each microchannel wall, and
7. The liquid was assumed to be incompressible.

The governing equation of the momentum equation in x-direction can be given as:

$$\frac{\partial^2 u}{\partial y^2}=\frac{1}{\mu_l}\frac{dp}{dx}-\frac{X}{\mu_l} \tag{1}$$

Where the body force, X, within the film is equal to $\rho_l g$, and the axial pressure gradient in the liquid film is approximated in terms of the conditions outside the film. When invoking the boundary layer approximation, $\partial p/\partial y=0$, it follows that $\partial p/\partial x=\rho_v g$. The momentum equation is therefore expressed as:

$$\mu_l\frac{\partial^2 u}{\partial y^2}=-g\left(\rho_l-\rho_g\right) \tag{2}$$

Different from non-slip flow, the flow velocity is no longer zero at the microchannel walls under slip flow. A molecular flow with nonzero velocity at the microchannel boundaries occurs. So the following boundary condition for Eq. (2) is taken:

$$u(0)=\alpha\frac{\partial u}{\partial y}|_{y=0}$$

where α represents the interaction of the molecules with the microchannel wall, resulting in a velocity slip at the wall. Taking in consideration the third assumption leads to the second boundary condition as:

$$\partial u(\delta)/\partial y=0$$

Integrating Eq. (2) twice and applying the above boundary conditions, the velocity profile in the film becomes

$$u(x,y)=M\delta^2\left[-\frac{y}{\delta^2}+\frac{y}{\delta}+\frac{\alpha}{\delta}\right] \tag{3}$$

where $M=\left(\rho_l-\rho_g\right)\frac{g}{\mu_l}$.