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Numerical simulation of flow patterns and the effect on heat flux during R32 condensation in microtube

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ABSTRACT

Based on the fluid volume approach, a transient numerical model for the condensation heat transfer and flow features in a microchannel is proposed. The flow condensation of R32 in a circular microtube with 0.1 mm diameter was studied. Four typical flow patterns, annular, injection flow, slug flow and bubbly flow are simulated along a two-dimension calculational domain successively. The numerical mode is verified by the experiments from the literature. The numerical results discern that the increase of mass flux, wall temperature and saturation temperature affect the detachment point of vapor slug further toward the outlet with higher occurrence frequency, which can be attributed to the higher Weber number and Capillary number of tail vapor core respectively. The local heat flux and wall shear stress will decrease along the flow direction overall, and tend to be constant in the single phase liquid area. However, there exit some rebounds and oscillations of the local heat flux and wall shear stress during injection and slug flow. The transient oscillations of wall shear stress can induce fluctuations and even waves in the annular flow upstream, which can be concluded as “surface tension force affecting upstream”, is proposed based on the minimum potential energy theory. This mechanism could be a supplement for the traditional theory of “flow pattern transition at high mass flux being induced by fluctuations which grow up while flowing downstream”.

1. Introduction

With the growing trend to the microscale of thermal control systems, condensation in microchannels has received a great deal of attention due to its important applications in micro reactors, micro heat exchangers, micro heat pipes, micro fuel cells, etc.

Many experimental researches have focused on the flow patterns and condensation heat transfer in microchannels. For vapor-liquid flow in microchannels, the dominant force is surface tension [1]. So it is reasonable to expect that the flow patterns, pressure drop and heat transfer characteristic for microchannel condensation may be different from what has been observed in macrochannels, where gravity is dominant. Coleman and Garimella [2,3] made visualization researches on the condensation of R134a in minichannels with different geometries, and recorded the flow patterns under various inlet steam qualities and mass fluxes. They categorized the flow regimes into four typical flow patterns: annular flow, wavy flow, intermittent flow and dispersed flow. It was observed that the intermittent and annular flow regimes become larger as the tube hydraulic diameter is decreased, and at the expense of the wavy flow regime. They also found that the tube shape had no obvious influence on the flow regime transition compared with the hydraulic diameter which had a substantial effect on flow patterns and the transitions. Médéric et al. [4] performed a visualization study on *n*-pentane condensation in single glass tube with inner diameters of 10, 1.1 and 0.56 mm. It was found that if the diameter was lower than the capillary length scale, the relative influence of gravity and capillary forces on the flow patterns will change significantly. They also attributed the interface instability to the velocity difference between the vapor and liquid phases. Wu and Cheng [5] conducted a visualization experiment to investigate the steam condensation flow patterns in trapezoidal silicon microchannels under different inlet pressures and various mass fluxes. The research indicated that the droplet flow, annular flow, injection flow and slug/bubble flow were the main flow patterns, and the injection flow induced fluctuations of wall temperatures and the other measurements. Wu et al. [6] and Quan et al. [7] indicated that increasing mass flux, decrease of cooling rate or microchannel diameter would lead to occurrence of injection flow moving toward the outlet with higher occurrence frequency. Zhang et al. [8,9] carried out a visualization experiment on steam condensation in rectangular microchannels with high aspect ratio. The results show that the shape, size and

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Nomenclature

Bo	Bond number, -
Ca	capillary number, -
Co	Courant number, -
C_p	specific heat capacity, J kg^{-1} K^{-1}
D	hydraulic diameter, m
E	energy per unit mass, J kg^{-1}
F_{vol}	interface-induced volume force, N m^{-3}
$\mathbf{g}$	gravitational acceleration, m s^{-2}
G	mass flux, kg m^{-2} s^{-1}
h_{fg}	latent heat, J kg^{-1}
L	tube length, m
$\mathbf{n}$	interface unit normal vector, -
P	pressure, Pa
q	local heat flux, W m^{-2}
r	radial coordinate, m
R	tube radius, m
R_v	radius of vapor inlet, m
Re	Reynolds number, -
S_E	energy source term, J m^{-3} s^{-1}
S_l	mass source term for liquid phase, kg m^{-3} s^{-1}
S_v	mass source term for gas phase, kg m^{-3} s^{-1}
T	Temperature, K
t	time, s
τ	wall shear stress, Pa
t_u	tunable coefficient, s^{-1}
$\mathbf{u}$	velocity vector, m s^{-1}
u	velocity, m s^{-1}
We	Weber number, -
x	vapor quality, -
X	axial coordinate, m
δt	calculational time step, s
δx	grid size, m
α	volume fraction, -
δ	thickness of liquid film, m
κ	interface curvature, m^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pas
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

t-av	time-averaged
l	liquid phase
s	saturated value
v	vapor phase
w	wall

generation frequency of the released bubbles could be controlled by cooling rate, and the breakup of vapor-liquid interface took place at the tip of the elongated bubble. The processes of vapor thread formation and breakup in the side channels of parallel channels were affected by the Marangoni effect. Chen et al. [10] and Wu et al. [11] experimentally investigated the steam flow condensation focused on the effect of mass flux, hydraulic diameters and microchannel shape on the injection frequency and dimensionless location in the triangular and wide rectangular microchannels respectively. They observed droplet-annular compound flow in the wide rectangular channel, which would not appear in other cross-sectional shape microchannels, and discovered the injection frequency in the wide rectangular microchannels is lower than that in triangular microchannels with the same hydraulic diameter. Ma et al. [12] investigated the vapor-liquid flow patterns and the transition characteristics for steam condensation in silicon microchannels. They determined the local heat transfer rate and the steam quality by testing the temperature profile of a copper cooler and established the flow regime maps in terms of steam mass flux and quality. The research results revealed that the effect of surface tension and vapor inertia dominates gravity and viscous force at the injection flow pattern.

Some theoretical models for microchannel condensation are proposed with necessary simplifications and empirical correlations. Zhao and Liao [13] presented an analytical model for predicting film condensation of vapor flowing inside a vertical mini triangular channel, taking into consideration the influences of surface tension, interfacial shear stress, gravity, axial pressure gradient, etc. The research found that the cross-sectional average heat transfer coefficient is higher than that of the circular channel with the same hydraulic diameter. This enhancement is attributed to the extremely thin liquid film on the sidewall resulted from the liquid flow toward the triangular channel corners due to the effect of surface tension. Wang et al. [14], Wang and Rose [15,16] presented a theoretical model for film condensation heat transfer in noncircular microchannels. Basing on the laminar condensate flow assumption and taking surface tension, interfacial shear stress, and gravity into account, the mode also revealed the significant heat transfer enhancement due to surface tension. Nebuloni and Thome [17] proposed a theoretical model to predict film condensation heat transfer in mini and microchannels of different internal shapes based on the finite volume method. This mode included the contributions of the unsteady terms, surface tension, axial shear stress, gravity, wall conduction and near-wall effect.

At the aspect of numerical models, Da Riva et al. [18,19] conducted a steady simulation for the condensation of R134a inside a 1 mm circular tube by the volume of fluid approach. The film thickness remained almost constant in the upper half of the tube while the film in the bottom half became thicker with condensation due to gravity. The turbulence in the condensate film was taken into account for the simulation to predict the experimental heat transfer coefficient at high mass flux. Bortolin et al. [20] compared the condensation of square and circular minichannels and found that a small heat transfer enhancement can be acquired for square channels at lower mass flux because surface tension has an important influence on liquid film thickness at lower mass flux. Ganapathy et al. [21] simulated the condensation heat transfer and flow characteristics of R134a in a microchannel with 100 μm hydrodynamic diameter. The flow pattern, pressure drop and heat transfer coefficients agreed well with the experimental results. Chen et al. [22] numerically simulated the condensation flow of FC72 inside a rectangular channel with 1 mm hydrodynamic diameter. The slug flows were observed to be generated periodically.

Up to now, few researches have presented the details of the flow field, heat transfer and interface motion. In this paper, a theoretical transient model for the direct simulation of microchannel condensation is proposed to capture the transient flow field and interface motion which in turn influences the condensation mass flux and heat transfer. This model aims to simulate the laminar vapor-liquid flow patterns including annular flow, injection flow, slug flow and bubbly flow. An explanation for the occurrence of injection flow is proposed by analyzing the dominant forces acting on the vapor phase at different conditions. The parameters affect-