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Numerical Simulation on Two-Phase Flow Patterns for Water Boiling in Horizontal Heated Tubes

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ABSTRACT

The study of flow pattern in the flow boiling process holds great significance for the safety and automation production in nuclear, aerospace and other industries. A numerical simulation study on flow patterns for water boiling in horizontal heated tubes was conducted by volume of fluid (VOF) multiphase flow model and LEE evaporation-condensation model. And the effect of heat flux on the flow pattern evolution was analyzed. Four boiling flow patterns was obtained in the tubes, namely bubble, slug, annular, and stratified flows. The increment of heat flux pushes the starting point of each flow pattern toward the inlet of the tube, which gradually compresses the range of bubble and slug flow and expands the region of stratified flow. Due to the formation of stratified flow, the tube metal in the upper part is at high temperature, resulting in tube failure.

Keywords: horizontal heated tube, boiling two-phase flow, VOF, flow pattern

1. INTRODUCTION

Two-phase flow boiling is extensively used in petrochemical, nuclear, cryogenic refrigeration, aerospace and other industries because of its higher heat flux capacity compared to single-phase flow [1,2]. So far, a lot of experimental research has been done on two-phase flow and heat transfer characteristics in horizontal tubes [3,4]. However, the observation range of the visualization measurement methods in the experiment is limited, making the variation of bubbles in the two-phase flow and the flow pattern evolution process difficult to record. More and more researchers pay attention to the flow boiling process based on computational fluid dynamics (CFD) to reveal the intrinsic mechanism in the flow and heat transfer.

In general, the refrigerants are mainly utilized as the working mass for flow boiling studies in horizontal tubes. Wu et al. [5,6] simulated numerically the boiling heat transfer process of near-azeotropic refrigerant mixture R1234ze(E)/R152a in a 6 mm horizontal tube using the VOF multiphase model. The results showed that the evolution process of bubbles can be completely displayed when the phase change coefficient γ is 0.1. Yang et al. [7] studied the flow boiling characteristics of R141B by experimental measurement and numerical simulation. The simulation results showed the flow pattern evolution process comprehensively and coincided with the experimental dates. Wang [8] conducted the numerical simulation using the Mixture multiphase flow model on boiling heat transfer performance of the refrigerant R417A in horizontal tubes and investigated the distribution and variation law of the temperature and velocity field. Wang [9,10] simulated the flow boiling characteristics of R245fa by Mixture multiphase flow model and discovered that simulation results matched the experimental dates at larger vapor quality. Shao et al. [11] investigated the heat transfer characteristics of R410A during flow boiling at low vapor quality in a horizontal tube by the Eulerian multiphase flow model. The results showed the best agreement with a mean absolute deviation mostly less than ±15% for heat transfer.

Most of the studies on the flow boiling are concerned with the pressure drop and the average heat transfer coefficient of the flow. But the simulation of the flow pattern for two-phase flow is less reported. In the present paper, the two-phase flow patterns for water boiling in horizontal heated tubes are investigated numerically. The influence of the heat flux on the evolution and transition of flow patterns is discussed based on the numerical simulation results.

2. NUMERICAL APPROACH

2.1 Geometrical model

The inner diameter and length of the horizontal heating tube used in the present simulation are 6 mm and 100 mm, as shown in Fig.1. The geometry is meshed using the O-block structure by ICEM-CFD to optimize the mesh quality. To balance computing time and accuracy

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of result, the 3,424,941 cells are chosen in the present simulation since the grid aspect ratio is better to below 5 in the fluent software [12].

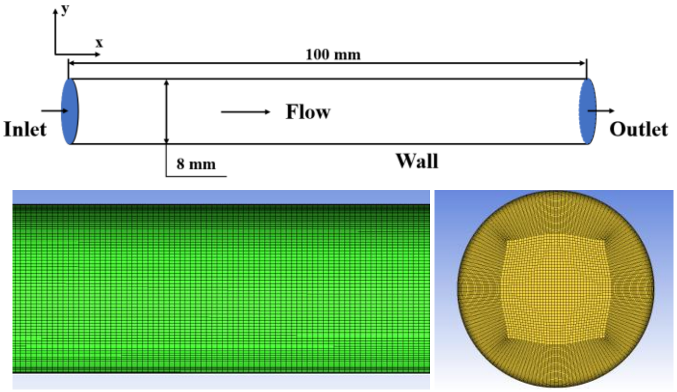


Fig.1 Schematic diagram of horizontal heating tube

2.2 Multiphase flow model

The two-phase flow patterns for water boiling in horizontal heated tubes under different heating conditions are simulated using the commercial CFD package FLUENT version 2021 R1. The basic equations can be described as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla(\rho \vec{u})=0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \vec{u})+\nabla(\rho \vec{u}\vec{u})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla \vec{u}+\nabla \vec{u}^{T}\right)\right]+\rho g+F \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E)+\nabla[\vec{u}(\rho E+\rho)]=\nabla(k\nabla T)+Q \tag{3}$$

The present work uses the multiphase flow approaches with volume of fluid (VOF) model where liquid and gas are treated as two distinct phases. The VOF model is a method used to track and capture the volume fraction of gas and liquid phase throughout the domain by solving a single set of momentum equations, but independent continuous equations [13]. For the flow boiling process of water, the phase volume fraction can be expressed by equation (4). The RNG *k-ε* model is used to treat turbulence phenomena in the fluids. In the paper, the volume fraction formulation is set to be implicit.

$$\alpha_{\mathrm{l}}+\alpha_{\mathrm{v}}=1 \tag{4}$$

α_l=1: The cell is fully occupied by liquid;

α_l=0: The cell is fully occupied by vapor;

0<α_l<1: The cell is at the interface between liquid and vapor.

where α_l and α_v are the volume fractions of the liquid phase and the vapor phase, respectively.

2.3 Evaporation-Condensation mechanism

Flow boiling is a complex physical process of gas-liquid two-phase flow including mass and heat transfer. The evaporation-condensation mechanism model proposed by Lee [14] is adopted to calculate the mass transfer source term in the process of phase changing. Based on the following temperature regimes, the mass transfer can be described as follows:

$$\begin{aligned} S&=-\gamma\alpha_{\mathrm{l}}\rho_{\mathrm{l}}\frac{T-T_{\mathrm{sat}}}{T_{\mathrm{sat}}}, T\geq T_{\mathrm{sat}} \\ S&=\gamma\alpha_{\mathrm{v}}\rho_{\mathrm{v}}\frac{T_{\mathrm{sat}}-T}{T_{\mathrm{sat}}}, T< T_{\mathrm{sat}} \end{aligned} \tag{5}$$

where phase change coefficient *γ* can be interpreted as a relaxation time, *T* is the current unit temperature and T_{sat} is the saturation temperature at the current pressure. In the paper, *γ* is set to be 0.1.

The source term for the energy equation can be obtained by multiplying the rate of mass transfer by the latent heat, as shown in equation (6).

$$Q=hS \tag{6}$$

where *h* is the vaporization latent heat.

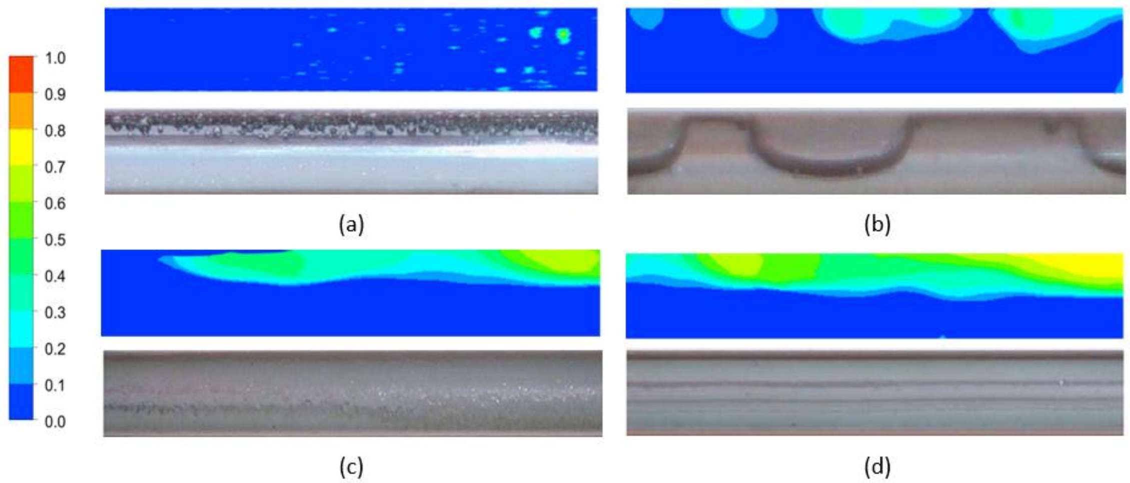
3. RESULTS AND DISCUSSIONS

3.1 Phase distribution

The simulated flow patterns are compared with typical experimental photos by Yin S [4], as shown in Fig.2. Four boiling flow patterns are observed in horizontal heated tubes, namely bubble, slug, annular, and stratified flows. The lighter (vapor) phase tends to accumulate at the top of the tube because of differences in density. For bubble flow, the vapor is dispersed in the form of small bubbles into the liquid phase, and moves upward across the entire cross section, as shown in Fig.2(a). As vapor fraction increases, the small vapor bubbles merge into vapor slugs and tend to flow toward the top of the tube, as shown in Fig.2(b). When the vapor fraction gets even larger, the slug bubbles will aggregate to become a vapor core and a liquid film forms at the pipe wall, as shown in Fig.2(c). Stratified flow occurs at lower mass velocities and has a clear gas–liquid interface to separate vapor from water, as shown in Fig.2(d).

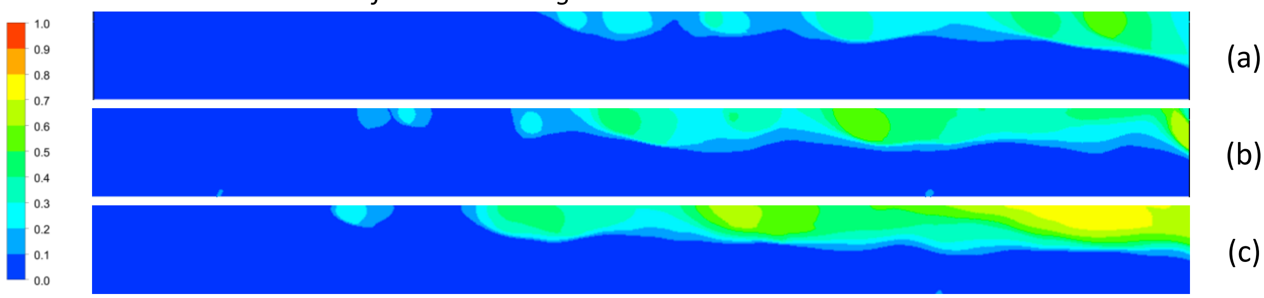
3.2 Influence of heat flux to the flow patterns

Fig.3 shows the influences of heat flux on boiling flow patterns under a mass velocity of 150 kg·m^{-2}·s^{-1} and inlet temperature of 372 K with subcooling degree of 1 K. When heat flux is 20 kW·m^{-2}, mainly bubble flow occurs in horizontal heated tubes. With the increase of



(a) Bubble flow; (b) Slug flow; (c) Annular flow; (d) Stratified flow

Fig. 2 Comparison between the simulations results (top) and the experimental observations [4] (bottom) of flow patterns for water boiling in horizontal heated tubes



(a) 20 kW·m^{-2}; (b)34.5 kW·m^{-2}; (c) 58.5 kW·m^{-2}

Fig. 3 The evolution and transition of flow patterns with the increment of heat flux

Table 1 The vapor volume fraction at the outlet and maximum wall temperature at a mass velocity of 150 kg·m^{-2}·s^{-1} and inlet temperature of 372 K.

Heat flux (kW·m^{-2})	*Vapor volume faction at the outlet*	*Location of the highest wall temperature (mm)*	*Maximum wall temperature (K)*
20.0	*0.18*	*92*	*388*
34.5	*0.26*	*90*	*404*
58.5	*0.40*	*85*	*441*

heat flux, stratified flows appear along the tube length. The results show that the starting point of each flow pattern tends to relocate toward the inlet of the tube with the increase of heat flux. The stratified flow is formed earlier and the region of bubble and slug flow becomes smaller when vapor volume fraction is high. That' s because higher heat flux contributes to producing more bubbles, leading to an increase of merging and growth among bubbles. Table 1 displays the vapor volume fraction at the outlet and maximum wall temperature at different heat flux. The vapor volume fraction at the outlet increases substantially from 0.18 to 0.40 with increasing heat flux. The maximum wall temperature is 441 K at 85 mm with the heat flux of 58.5 kW·m^{-2}. Due to the formation of stratified flow, the tube metal in the upper part is at high temperature. This work condition should be avoided by all means.

4. CONCLUSION

In this paper, numerical simulations on flow patterns for water boiling in 8 mm horizontal heated tubes are conducted by VOF multiphase flow model and LEE evaporation-condensation model. And the influences of heat flux on the evolution and transition of flow patterns are analyzed. The results show four boiling flow patterns, namely bubble, slug, annular, and stratified flows. As the increase of heat flux, the starting points of each flow pattern are pushed toward the inlet of the tube, which gradually compresses the range of bubble and slug flow and expands the region of stratified flow. Furthermore, the tube metal in the upper part is at high temperature at stratified flow, resulting in tube failure due to thermal fatigue or overheating. This work condition should be avoided by all means.

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