Two dimensional simulation of nucleation pool boiling and investigation of phase change mechanism at low heat fluxes

Maryam Hassani[1], Ramin Kouhikamali[2*]

[1]PhD student, Faculty of Mechanical Engineering, Guilan University, Rasht, Iran
[2]Associate Professor, Faculty of Mechanical Engineering, Guilan University, Rasht, Iran

ABSTRACT

At the present study, nucleation pool boiling of the saturated refrigerant R-245fa on the horizontal tube at pressure of 123.8 kPa and temperature of 20°C under different heat fluxes (18-27 kW/m^2) has been simulated numerically and the details of the flow are investigated. Numerical simulation is carried out based on the volume of fluid model with piecewise linear interface construction method, without pre-determined bubbles by Lee phase change model and surface tension model of continuum surface force. The importance of this study and the numerical model, in addition to its industrial applications at nuclear reactors and flooded evaporators, is the model validation at predicting boiling portion of forced falling or climbing flows on horizontal tubes or bundle of tubes. The heat transfer coefficient of the present model, in comparison with the experimental data at two heat fluxes of 18 and 24 kW/m^2 and the results of pool boiling Cooper correlation at heat fluxes of 18-27 kW/m^2 has the maximum error of 6.67% and 8.64%, respectively. In addition, at this study, bubble nucleation and its departure from the tube wall and superheated liquid beside the wall, liquid and bubble temperature and modality of fluid movement due to the generated bubbles around the tube have been studied.

KEYWORDS

Pool boiling, nucleation, heat transfer coefficient, numerical simulation, volume of fluid model

* Corresponding Author: Email: kouhikamali@guilan.ac.ir

1. Introduction

Boiling is one of the efficient ways of heat transfer and can be a proper solution for the present modern industry to develop efficient equipment. In spite of significant progress in realization of boiling, accurate prediction of boiling curve has not been possible fundamentally.

There are lots of experimental and analytical studies to understand boiling phenomena. For example, Moreno et al. [1] studied heat transfer coefficient and critical heat flux of R-245fa at low saturation temperatures at hydrogen precooling applications.

Among numerical modeling, Liu et al. [2] simulated nucleate, transient and film boiling of liquid nitrogen on a flat surface. Tian et al. [3] simulated pool boiling over a vertical tube bundle by using volume of fluid method and Lee phase change model. Hosseini and Kouhikamali [4] studied Lee and Tanasawa phase change models to investigate the effects of surface type on bubble dynamics. They found out that Lee phase change model predicts boiling more accurately.

This article has simulated pool boiling of R-245fa over a horizontal tube at low heat fluxes and studies the details of the flow. Alongside the validation of the present numerical model in simulation of boiling, this model can be used in design of some industrial applications such as flooded evaporators.

2. Numerical Modeling

According to the experiment of Chien and Tsai [5], the present numerical modeling of pool boiling is carried out around a single tube with 19 mm diameter in the middle of a 59×38 mm^2 reservoir which is filled with saturated R-245fa at saturation pressure of 123.8 kPa. Different heat fluxes (18, 21, 24 and 27 kW/m^2) are applied to the tube wall to start the natural convection and boiling around the tube.

Liquid and vapor are considered as Newtonian flows, described by continuity, momentum and energy equations as follows:

$$\frac{\partial\left(\alpha_g \rho_g\right)}{\partial t}+\nabla.\left(\alpha_g \rho_g \vec{v}_g\right)=s_g \quad (1)$$

$$\frac{\partial\left(\rho\vec{v}\right)}{\partial t}+\nabla.\left(\rho\vec{v}\vec{v}\right)=-\nabla P+\nabla.\left(\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right)+\rho\vec{g}+\vec{F} \quad (2)$$

$$\frac{\partial\left(\rho E\right)}{\partial t}+\nabla.\left(\vec{v}\left(\rho E+P\right)\right)=\nabla.\left(k\nabla T\right)+s_e \quad (3)$$

where α is the vapor volume fraction, $\vec{v}$ is the velocity, P is the pressure, $\vec{g}$ is the gravitational acceleration, E is the energy per unit mass and T is the temperature. In order to track the phases' interface, the volume of fluid model is used by which the continuity equation is solved for vapor (subscript g) and $\alpha_g+\alpha_f=1$ specifies liquid (subscript f) volume fraction. In addition, one single momentum and energy equation is solved for phases in which density ρ, dynamic viscosity μ, and conductivity k, is calculated based on the phases' properties and volume fractions. s_g is the mass source term of continuity equation and is modeled based on Lee phase change model [6]. s_e, the energy source term, supplements the energy equation by resulting latent heat of phase change. The volumetric force $\vec{F}$ is due to surface tension which is modeled by Continuum Surface Force (CSF) model.

For pressure-velocity coupling, the Pressure Implicit with Splitting Operators (PISO) is implemented. For discretization of pressure and momentum/energy equations, PRESTO! and 2nd-order upwind is used. The interface is tracked by Geo-reconstruct method. The variable time step size with the average value of 10^{-6} s is used for the problem with the highest heat flux.

The boundary layer mesh is used near the tube wall and farther parts are meshed with pave ones. Four grids are generated for mesh independency procedure. The result of heat transfer coefficient of the grid with 133319 cells differs maximally 3% with the grid with smallest cells for all studied cases and is chosen as the final grid.

3. Results and Discussion

In order to validate the numerical model, the simulated heat transfer coefficient of heat fluxes of 18 and 24 kW/m^2 is compared with the experimental data of Chien and Tsai [5] in "Table 1". The errors are 6.67% and 0.83%, respectively.

Table 1. Comparison of experimental data [5] and numerical simulated heat transfer coefficient

Heat flux (kW/m^2)	Heat transfer coefficient (W/m^{2}K)		Error (%)
	Experimental data	Numerical simulation	
18	1800	1920	6.67
24	2400	2420	0.83

As an example, "Figure 1" shows the bubble growth procedure of heat flux of 18 kW/m^2 at three time of 0.08, 0.1 and 0.13 s by green, blue and black colors, respectively, alongside the superheated temperature of liquid near the tube wall at 0.13 s. The thermal boundary layer around the tube has caused the nucleation. The nucleus has grown and the shape of the superheated liquid layer changes. The grown bubble starts to detach from the wall at times less than 0.13 s. Meanwhile, a nucleus in the thermal micro-layer is growing.

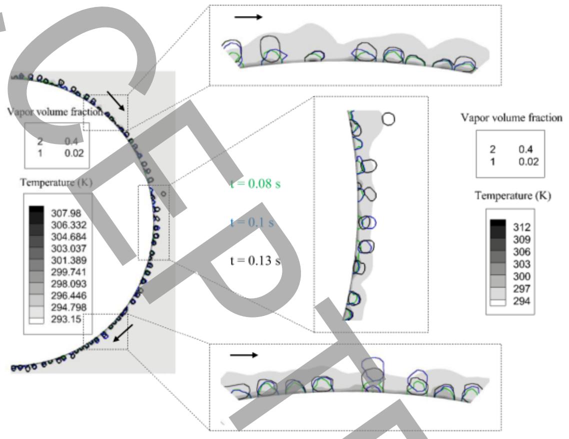

Figure 1. Bubble growth with temperature contour for the heat flux of 18 kW/m^2

"Figure 2" shows the influence of bubble presence, growth and detachment on the flow around the tube. The bubbles which are departing from the wall move faster upward. Meanwhile, a vortex has been forming. This case is not seen much at the lower part of the tube.

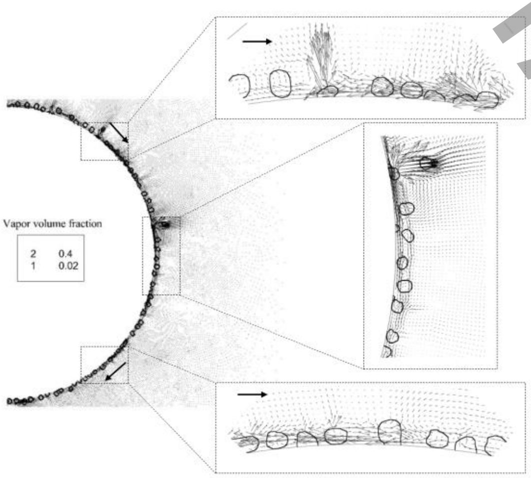

Figure 2. The influence of bubbles on the velocity vectors for the heat flux of 18 kW/m^2 at 0.13 s

According to "Figure 3" Cooper correlation [7] predicts heat transfer coefficient with maximum error of 16.56% in comparison with the experimental data for the heat flux of 18 kW/m^2. The present numerical is maximally 8.64% different from the correlation result for the heat flux of 21 kW/m^2.

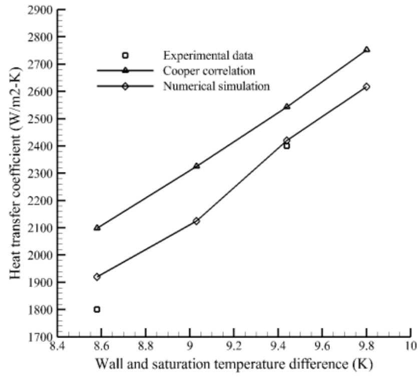

Figure 3. Heat transfer coefficient of experimental data [5], Cooper correlation [7] and numerical simulation

4. Conclusions

This article has numerically studied pool boiling of R-245fa over a horizontal tube at different heat fluxes (18-27 kW/m^2). The volume of fluid multiphase model and Lee phase change model are used and the details of the flow are studied alongside the validation of the numerical model in simulation of boiling. The effects of wall heat flux are investigated on the nucleation, bubble detachment, liquid superheating and flow movement.

5. References

[1] G. Moreno, B. Kekelia, H. Sitaraman, S. Narumanchi, K. Bennion, Nucleate pool boiling of R-245fa at low saturation temperatures for hydrogen precooling applications, International Journal of Heat and Mass Transfer, 132 (2019) 172-183.

[2] Y. Liu, T. Olewski, L.N. Vechot, Modeling of a cryogenic liquid pool boiling by CFD simulation, J. Loss Prev. Process. Ind. , 35 (2015) 125–134.

[3] Y. Tian, K. Zhang, N. Wang, Z. Cui, L. Cheng, Numerical study of pool boiling heat transfer in a large-scale confined space, Applied Thermal Engineering 118 (2017) 188–198.

[4] S.A. Hosseini, R. Kouhikamali, The effect of surface types on bubble dynamic formation during nucleate pool boiling by use of Lee and Tanasawa phase change models, Amirkabir Journal of Mechanical Engineering, (2019).

[5] L.-H. Chien, Y.-L. Tsai, An experimental study of pool boiling and falling film vaporization on horizontal tubes in R-245fa, Appl Therm Eng, 31 (2011) 4044-4054.

[6] W. Lee, A pressure iteration scheme for two-phase flow modeling, Hemisphere Publishing, Washington, DC, 1980.

[7] M.G. Cooper, Saturation nucleate pool boiling - a simple correlation, International Chemical Engineering Symposium, 86 (1984) 785-792.