MODELLING OF SUBCOOLED FLOW BOILING HEAT TRANSFER OF WATER THROUGH A VERTICAL HEATED PIPE

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Abstract- the sub cooled flow boiling of water in a vertical heated pipe is numerically investigated. For this purpose, the Eulerian-Eulerian (E-E) two-phase CFD model is used in this study. A sensitivity test is carried out to present the effects of the nucleate boiling parameters (i.e. nucleate site density, bubble frequency, and bubble departure diameter) on the heat transfer prediction of water subcooled flow boiling.

Index Terms- nucleate boiling parameters, Eulerian-Eulerian model, and boiling heat transfer

I. INTRODUCTION

Among different heat transfer mechanisms, boiling shows a significant enhancement of heat transfer coefficient because of bubble motions [1]. In some applications the fluid bulk temperature is lower than the saturation temperature. Subcooled flow boiling is a phenomenon that could be used in such an application. Subcooled flow boiling is also known to be of considerable importance in the design, operation and thermal–hydraulic safety analysis of a nuclear reactor [2-4].

In case of numerical studies, many numerical investigations [2, 5-8] have been focused on conventional fluids like water. Almost all these studies investigate the accurate prediction of bubble dynamics. For example, Tu et al. [5] carried out numerical modelling of low-pressure subcooled boiling flows. They found that the closure relationships (i.e. partition of the wall heat flux, bubble size distribution, interfacial area concentration, bubble departure diameter and frequency) play crucial role in an accurate prediction of void fraction distributions. Sensitivity tests were made using different closure models. Predictions of the proposed model agreed closely with the experimental results from literature. Cheung et al. [2] numerically investigated the distribution of vapor void fraction during subcooled flow boiling of water in vertical channels at low pressure. They carried out sensitivity tests on different combinations of the empirical boiling models (e.g. active nucleation site density models, bubble departure diameter models and bubble departure frequency models) covering a wide range of subcooled flow conditions and imposed wall heat fluxes. Some of the model combinations were proposed to be able to predict the distribution of the vapor void fraction comparing with the experimental data from literature. According to the literature, a sensitivity test is needed to assess the effect of bubble dynamics on accurate prediction of the boiling heat transfer.

The subcooled flow boiling of water in a vertical heated pipe is numerically investigated. For this purpose, the Eulerian-Eulerian (E-E) two-phase CFD model is used in this study. A sensitivity test is carried out to present the effects of the nucleate boiling parameters (i.e. nucleate site density, bubble frequency, and bubble departure diameter) on the heat transfer prediction of water subcooled flow boiling.

II. METHODOLOGY

A. Geometry structure

A cylindrical tube in a vertical position and with dimensions of 0.0154 m diameter, 5mm thickness and 2m length is considered in the current study. A constant heat flux is applied to the tube wall. The two-dimensional (2D) axisymmetric geometry has been considered and as a result, a rectangular domain with dimensions of 0.0077m × 2 m is created.

B. Governing Equations

The Eulerian-Eulerian (E-E) two-phase CFD model is used in this study. Ensemble-averaged of mass, momentum and energy transport equations are considered for each phase in the Eulerian–Eulerian modelling framework. The liquid phase (α_l) is the continuum and the vapor phase (bubbles) is the disperse phase (α_g). These equations can be written as [2]:

Continuity equation of liquid phase

$$\frac{\partial \rho_l \alpha_l}{\partial t} + \nabla.\left(\rho_l \alpha_l \overrightarrow{u_l}\right) = \Gamma_{lg} \quad (1)$$

Continuity equation of vapour phase

$$\frac{\partial \rho_g \alpha_g}{\partial t} + \nabla.\left(\rho_g \alpha_g \overrightarrow{u_g}\right) = \Gamma_{gl} \quad (2)$$

Momentum equation of liquid phase

$$\frac{\partial \rho_l \alpha_l \overrightarrow{u_l}}{\partial t} + \nabla.\left(\rho_l \alpha_l \overrightarrow{u_l}\overrightarrow{u_l}\right) = -\alpha_l \nabla p + \rho_l \alpha_l \overrightarrow{g} + \nabla\left[\alpha_l \mu_l^e \left(\nabla \overrightarrow{u_l} + \left(\nabla \overrightarrow{u_l}\right)^T\right)\right] + \left(\Gamma_{lg}\overrightarrow{u_g} - \Gamma_{gl}\overrightarrow{u_l}\right) + F_{lg}^d \quad (3)$$

Momentum equation of vapor phase

$$\frac{\partial \rho_g \alpha_g \vec{u_g}}{\partial t} + \nabla.\left(\rho_g \alpha_g \vec{u_g}\vec{u_g}\right) = -\alpha_g \nabla p + \rho_g \alpha_g \vec{g} + \nabla\left[\alpha_g \mu_g \left(\nabla \vec{u_g}\right)\right] + \left(\Gamma_{gl}\vec{u_l} - \Gamma_{lg}\vec{u_g}\right) + F_{gl}^d \quad (4)$$

Energy equation of liquid phase

$$\frac{\partial \rho_l \alpha_l H_l}{\partial t} + \nabla.\left(\rho_l \alpha_l \vec{u_l} H_l\right) = \nabla\left[\alpha_l k_l^e \left(\nabla T_l\right)\right] + \left(\Gamma_{gl} H_l - \Gamma_{lg} H_g\right) \quad (5)$$

Energy equation of vapor phase

$$\frac{\partial \rho_g \alpha_g H_g}{\partial t} + \nabla.\left(\rho_g \alpha_g \vec{u_g} H_g\right) = \nabla\left[\alpha_g k_g \left(\nabla T_g\right)\right] + \left(\Gamma_{lg} H_g - \Gamma_{gl} H_l\right) \quad (6)$$

The interfacial force F^d_{lg} appearing in Eqs. (1), (3) and (5) is formulated through appropriate consideration of drag force affecting the interface between each phase. Note that for the gas phase, $F^d_{gl} = \square F^d_{lg}$ [2].
Interphase momentum transfer between gas and liquid due to drag force is given by [2]

$$F_{lg}^d = \frac{1}{8} C_D a_{if} \rho_l \left|\vec{u_g} - \vec{u_l}\right| \left(\vec{u_g} - \vec{u_l}\right) \quad (7)$$

where a_{if} is the interfacial area per unit volume. The drag coefficient CD has been correlated for several distinct Reynolds number regions for individual bubbles according to Ishii and Zuber [2, 9].
Interfacial area concentration is defined as the interfacial area between two phases per unit mixture volume. The interfacial area can be calculated by using an algebraic relationship between a specified bubble diameter (d_b) and the interfacial area concentration (a_{if}). The algebraic interfacial area models are derived from the surface area to volume ratio, A_b, of a spherical bubble[10] :

$$A_b = \frac{\pi d_b^2}{\frac{1}{6}\pi d_b^3} = \frac{6}{d_b} \quad (8)$$

For a dispersed phase, g, with volume fraction, α_g, the particle model estimates the interfacial area concentration, (a_{if}) as

$$a_{if} = \alpha_g A_b = \frac{6\alpha_g}{d_b} \quad (9)$$

where db is calculated based on Sauter mean diameter [11].

The interfacial mass transfer rate due to condensation in the bulk subcooled liquid in Eqs. (2), (4) and (6) can be expressed as [2]:

$$\Gamma_{lg} = \frac{h a_{if} T_{sub}}{h_{fg}} \quad (10)$$

where h represents the inter-phase heat transfer coefficient modelled by widely used Ranz-Marshall correlation [12]. The wall vapour generation rate is modelled in a mechanistic manner by considering the total mass of bubbles detaching from the heated surface as [2]

$$\Gamma_{gl} = \frac{q_e}{h_{fg}} \quad (11)$$

C. Heat flux partitioning model

The first and most well-known wall partitioning boiling model is the RPI model, which was formulated by Kurul and Podowski [13] of the Rensselaer Polytechnic Institute. The Eulerian two-phase model and RPI wall boiling model have been used by many researchers [2, 5-8, 14-16] to investigate the subcooled flow boiling of a pure base fluid numerically. The total wall heat flux is calculated as follows [2, 3, 17]:

$$q = q_e + q_a + q_c \quad (12)$$

The wall heat flux component due to evaporation which occurs at the nucleate boiling region can be determined from [2]

$$q_e = N_a f \left(\frac{\pi D_{bd}^3}{6}\right) \rho_g h_{fg} \quad (13)$$

where N_a, f, D_{bd} and h_{fg} are the active nucleation site density, the bubble frequency, departing bubble diameter and the latent heat, respectively.
The wall heat flux component contributed by surface quenching is formulated accordingly. As liquid comes in contact with the hot surface, the heat is transferred to liquid mainly based on transient conduction which can be determined from [2]

$$q_q = \left(\frac{2}{\sqrt{\pi}} \sqrt{k_l \rho_l C_{p,l} f}\right) A_q \left(T_w - T_l\right) \quad (14)$$

where A_q denotes the fraction of the wall area that is in contact with the fresh liquid and is cooled down by transient conduction. This area is calculated from [2]

$$A_q = N_a \left(K \frac{\pi D_{bd}^2}{4}\right) \quad (15)$$

Heat transfer due to turbulent convection can be defined based on local Stanton number as [2]

$$q_c = St \rho_l C_{p,l} u_l \left(1 - A_q\right)\left(T_w - T_l\right) \quad (16)$$

where u_l is adjacent liquid velocity and

$$St = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}} \quad (17)$$

where Nu, Re and Pr are the local Nusselt, Reynolds and Prandtl numbers.
The correlations for calculations of the active nucleation site density and the bubble departure

diameter are given in Table I and Table II respectively. The Cole correlation [18] for bubble departure frequency is calculated as

$$f = \sqrt{\frac{4g\left(\rho_l - \rho_g\right)}{3D_{bd}\rho_l}} \quad (18)$$

Table I: Empirical correlations for nucleation site density [2].

Name	Correlation	Details
Lemmert - Chawla[19]	$N_a = \left[m\left(T_w - T_{sat}\right)\right]^n$	m=210, n=1.805
*Koca-Ishii [20]	$N_a = \frac{1}{D_{bd}^2} \times \left[\left(\frac{2\sigma T_{sat}}{\Delta T_{eff}\rho_g h_{fg}}\right)/\left(0.5\times D_{ab}\right)\right]^{-4.4} \times f(\rho^*)$	$\rho^* = \left(\rho_l - \rho_g\right)/\rho_g$, $f(\rho^*) = 2.157e-7\rho^{*-3.2}(1+0.0049\rho^*)^{4.}$ $\Delta T_{eff} = ST_{sup}$

*Koca-Ishii=Kocamustafaogullari & Ishii

Table II: Empirical correlations for bubble departure diameter [2].

Name	Correlation	Details
*Koca-Ishii [20]	$D_{bd} = 0.0012\left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{0.9} \times D_{LF}$	D_{LF} is equal to D_{bd} suggested by Fritz et al. [21]
*Tolub-Kostan [22]	$D_{bd} = D_{ref} \times \exp\left(-T_{sub}/\Delta T_{refd}\right)$	D_{ref}=1.3mm is suggested by Bartolomej et al. [23] ΔT_{refd}=53 °k is suggested by Krepper et al. [24]

* Kocamustafaogullari & Ishii= Koca-Ishii, Tolubinsky & Kostanchuk= Tolub-Kostan

D. Turbulence modeling

The turbulence stresses are modelled only for the liquid phase, whereas the vapour phase is assumed to be laminar [6]. Turbulence in the liquid phase is modelled using the standard k–□ model according to Launder and Spalding [25].

E. Boundary Conditions

The boundary conditions at the inlet are specified from the known inflow conditions. A constant heat flux is considered around the outer side of the wall of the pipe. A no-slip condition is applied for liquid and vapor phase velocity on the inner pipe surface. Due to the constraints of axis-symmetry, along the centreline of the pipe, gradient of axial velocity, temperature and volume fraction are equal to zero whereas the radial velocity is equal to zero.

F. Numerical methods

The numerical methods available in the commercial CFD package of ANSYS-Fluent V.15 has been used uses for the current study. Fluent uses a finite volume approach to convert the governing partial differential equations into a system of discrete algebraic equations. As discretization methods, a first-order upwind scheme are selected for the momentum, volume fraction, turbulent kinetic energy and turbulent dissipation rate equations whereas the first order upwind for energy equation is selected. The coupled algorithm is selected as the pressure-velocity coupling scheme. The scaled residuals for the velocity components and energy are set equal to 10^{-8} and 10^{-9}, respectively.

G. Simulation cases

Table III shows different simulation cases which have been investigated in the present study. The sensitivity test is done considering 4 combinations of the nucleation site parameters in the E-E CFD model to simulate water subcooled flow boiling (cases 1-4).

Table III: The simulation table for sensitivity test considering the effects of nucleation site parameters in the CFD model prediction

Simulation Cases	Model	Fluid	B.C.	Sensitivity test parameters
1-4	Two-Phase E-E model	water	G= 1445 (kg/m^{2}s), ΔT_{sub}=10 (°K) q″= 60 (KW/m^2)	Nucleation site parameters

E-E=Eulerian-Eulerian

III. RESULTS AND DISCUSSION

The meshing tool available in ANSYS is used to construct the computational mesh. A structured mesh based on a rectangular grid is used throughout the domain. A grid independence test was performed for the tube using water as working fluid to analyse the effects of grid size on the results. Four sets of mesh are considered, which are 8,872 nodes, 11,368 nodes, 13,846 nodes, and 15,306 nodes at G=1445 kg/m^{2}s, ΔT_{sub}=10^{o}K and q″=60 KW/m^2. By comparing the mesh configurations, in terms of average heat transfer coefficient, the corresponding changes are less than 1%. Therefore, the first grid case has been adopted to obtain an acceptable compromise between the computational time and the results accuracy.

A Sensitivity test has been done on the E-E CFD model prediction of water subcooled flow boiling using four different combinations of empirical correlations for active nucleation site density, bubble departure diameter and bubble frequency. The boiling heat transfer coefficient (BHTC) is predicted by the CFD model and this prediction is benchmarked against the Chen correlation [26]. The results of this sensitivity test are shown in Table IV. For the given boundary condition (G=1445 kg/m^{2}s, ΔT_{sub}=10^{o}K and q″=60 KW/m^2), the CFD model using the combination of Lemmert and Chawla correlation [19] for active nucleation site density, Tolubinsky and Kostanchuk [22] for bubble departure diameter and Cole correlation [18] for bubble frequency gives the least deviation of -4.67 % from Chen correlation.

Table IV: Sensitivity tests on the E-E two-phase CFD model prediction of water subcooled flow boiling using different combinations of bubble departure diameter (Dbd), bubble departure frequency (f) and Nucleation site density (Na) models

f	N_a	D_{bd}	T_{wall} (^oK)	h_{sim} ($w/m^2.{}^oK$)	Error (%)
Cole	Koca-Ishii	Tolub-Kostan	377.65	9264.25	-16.42
		Koca-Ishii	377.64	9265.82	-16.41
	Lemmert -Chawla	Tolub-Kostan	376.62	10309.16	-4.67
		Koca-Ishii*	375.57	11648.42	10.06

CONCLUSIONS

The subcooled flow boiling of water in a vertical heated pipe has been investigated numerically. The effect of nucleate boiling parameters on heat transfer prediction has been assessed. The E-E two-phase CFD model using the combination of Lemmert and Chawla correlation [19] for active nucleation site density, Tolubinsky & Kostanchuk [22] for bubble departure diameter and Cole correlation [18] for bubble frequency shows a good agreement with Chen correlation in prediction of BHTC of water subcooled flow boiling.

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