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Advanced Wall Boiling Model with Wide Range Applicability for the Subcooled Boiling Flow and its Application into the CFD Code

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1. Introduction

Subcooled boiling is one of the crucial phenomena for the design, operation and safety analysis of a nuclear power plant. It occurs due to the thermally non-equilibrium state in the two-phase heat transfer system. Many complicated phenomena such as a bubble generation, a bubble departure, a bubble growth, and a bubble condensation are created by this thermally non-equilibrium condition in the subcooled boiling flow. However, it has been revealed that most of the existing best estimate safety analysis codes have a weakness in the prediction of the subcooled boiling phenomena in which multi-dimensional flow behavior is dominant. In recent years, many investigators are trying to apply CFD (Computational Fluid Dynamics) codes for an accurate prediction of the subcooled boiling flow.

In the CFD codes, evaporation heat flux from heated wall is one of the key parameters to be modeled for an accurate prediction of the subcooled boiling flow. The evaporate heat flux for the CFD codes is expressed typically as follows,

$$q_e'' = \frac{\pi D_d^3}{6} \rho_g h_{fg} f N'' \qquad (1)$$

where, D_d, f, N'' are bubble departure size, bubble departure frequency and active nucleation site density, respectively.

In the most of the commercial CFD codes, Tolubinsky[1] bubble departure size model, Kurul&Podowski[2] active nucleation site density model and Ceumem-Lindenstjerna bubble departure frequency model are adopted as a basic wall boiling model. However, these models do not consider their dependency on the flow, pressure and fluid type.

In this paper, an advanced wall boiling model was proposed in order to improve subcooled boiling model for the CFD codes.

2. Advanced Wall Boiling Model for the CFD Codes

In the present work, state-of-the art bubble departure size and active nucleate site density models were explored for the enhancement of prediction ability of wall boiling model.

Klausuner et al. [3] proposed a mechanistic force balance model at for the prediction of both bubble departure and lift-off sizes in the nucleate boiling condition of refrigerant R113. They applied the model successfully in the wide range flow conditions such as in the both horizontal and vertical channels under the pool and flow boiling. Many investigators also tried to improve the model to achieve a general applicability for various fluids.

In the present work, Klausuner's force balance model was explored for the replacement of Tolubinsky model. The force balance model is expressed along the flow and lateral direction as follows (See Fig.1),

$$\sum F_x = F_{sx} + F_{dux} + F_{sL} + F_h + F_{cp} \qquad (2)$$

$$\sum F_y = F_{sy} + F_{duy} + F_{qs} + F_b \qquad (3)$$

Here, bubble departure occurs when above force balance of F_x or F_x is violated. In the highly subcooled flow, bubble condensation is expected on the top of the growing bubble. To take into account of it, the bubble condensation model was developed and implemented into original force balance model. Details of each modeling are summarized in the Table.1

For the improvement of the active nucleation site density model, Hibiki et al.'s [4] model was adopted as a new advanced wall boiling model. Detailed description on the model is available from their original paper.

To ensure a wide range applicability, the new advanced wall boiling model was evaluated separately according to flow conditions such as pressure, temperature and flow rate. One example is bubble departure size model shown in Fig. 2. In the figure, the other bubble departure models were also plotted for the comparison. As shown in the figure, the force balance model follows well expected trends on the liquid velocity and pressure.

3. Implementation into CFD code and Assessment

The advanced wall boiling model was implemented into the user FORTRAN files of the STAR-CD 4.12 [5]. For the validation of the present model, benchmark calculations were carried out against DEBORA experimental data which are available from open literatures [6]. In this experiment, R-12 flows upwardly inside a vertical pipe having an internal diameter equal to 19.2mm. The whole pipe can be divided axially into three parts: the adiabatic inlet section (1 m length), the heated section (3.5 m length) and the adiabatic outlet section (0.5 m length). The phasic density ratio of the DEBORA test is equivalent to that of steam-water around 90~170 bars

4. Assessment Result

For the benchmark calculation of advanced wall boiling model, 2D grid which consists of 20 radial and 100 axial nodes is prepared based on the grid size study. A total of 13 data sets are assessed by using STAR-CD in the present work.

Fig. 3 shows one of comparisons of predicted void fraction against experimental data and it confirms that the newly proposed advanced wall boiling model is successfully developed and implemented. As shown in the figure, original wall boiling model over-predicts local void fraction and advanced wall boiling model improves it. All of the other calculations also showed that the advanced wall boiling model shows better prediction capability than the original one

5. Conclusion

In the present paper, a new advanced wall boiling model which consists of Klasusner force balance model for bubble departure size and Hibiki active nucleation site model was proposed for the improvement of subcooled boiling model of CFD codes.

The advantages of the present wall boiling model are 1) it follows well the tendency on the change of flow conditions 2) it can be applicable to the wide range of flow conditions including nominal and postulated accidental conditions of nuclear power plant

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Acknowledgments

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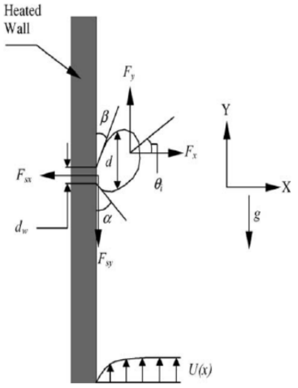
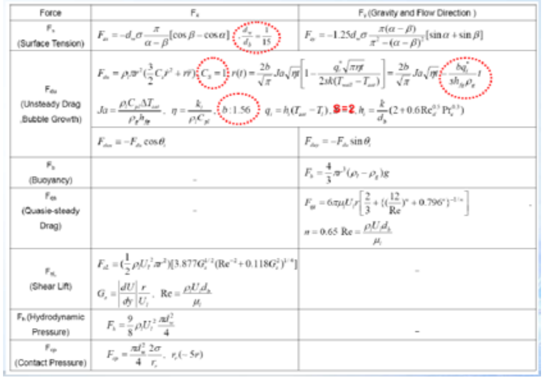


Fig. 2 Force of growing bubble

Table 1 Modeling of Force Balance Model



Force	F_x	F_y (Gravity and Flow Direction)
F_s (Surface Tension)	$F_{sx} = -d_w\sigma \frac{\pi}{\alpha-\beta}[\cos\beta - \cos\alpha]$, $\frac{d_w}{d_b} = \frac{1}{15}$	$F_{sy} = -1.25 d_w\sigma \frac{\pi(\alpha-\beta)}{\pi^2-(\alpha-\beta)^2}[\sin\alpha + \sin\beta]$
F_{du} (Unsteady Drag ,Bubble Growth)	$F_{du} = \rho_l \pi r^2 (\frac{3}{2}C_s \dot{r}^2 + r\ddot{r})$, $C_s = 1$, $r(t) = \frac{2b}{\sqrt{\pi}} Ja\sqrt{\eta t}\left[1 - \frac{q_i''\sqrt{\pi\eta t}}{2sk(T_{wall}-T_{sat})}\right] = \frac{2b}{\sqrt{\pi}} Ja\sqrt{\eta t} - \frac{bq_i''}{sh_{fg}\rho_g}t$ $Ja = \frac{\rho_l C_{pl}\Delta T_{sat}}{\rho_g h_{fg}}$, $\eta = \frac{k_l}{\rho_l C_{pl}}$, $b:1.56$ $q_i = h_i(T_{sat} - T_l)$, S=2, $h_i = \frac{k}{d_b}(2 + 0.6Re_d^{0.5} Pr_v^{0.3})$	
	$F_{dux} = -F_{du}\cos\theta_i$	$F_{duy} = -F_{du}\sin\theta_i$
F_b (Buoyancy)	-	$F_b = \frac{4}{3}\pi r^3(\rho_l - \rho_g)g$
F_{qs} (Quasie-steady Drag)	-	$F_{qs} = 6\pi\mu_l U_l r\left[\frac{2}{3} + \{(\frac{12}{Re})^n + 0.796^n\}^{-1/n}\right]$ $n = 0.65$ $Re = \frac{\rho_l U_l d_b}{\mu_l}$
F_{sL} (Shear Lift)	$F_{sL} = (\frac{1}{2}\rho_l U_l^2 \pi r^2)[3.877 G_s^{1/2}(Re^{-2} + 0.118G_s^2)^{1/4}]$ $G_s = \left\|\frac{dU}{dy}\right\|\frac{r}{U_l}$, $Re = \frac{\rho_l U_l d_b}{\mu_l}$	-
F_h (Hydrodynamic Pressure)	$F_h = \frac{9}{8}\rho_l U_l^2 \frac{\pi d_w^2}{4}$	-
F_{cp} (Contact Pressure)	$F_{cp} = \frac{\pi d_w^2}{4}\frac{2\sigma}{r_r}$, $r_r(\sim 5r)$	

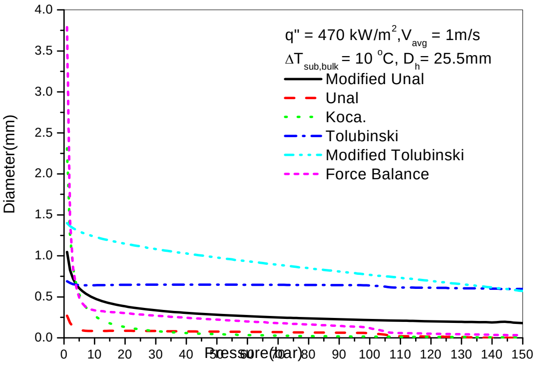


Fig. 2 Prediction of bubble departure diameter by force balance model

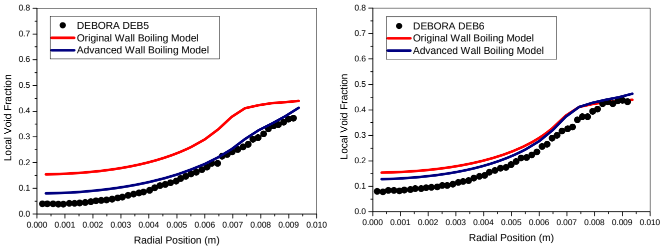


Fig. 3 Void fraction comparison : DEBORA DEB5 and DEB6 vs. STAR-CD prediction