Interfacial Area Transport Equation for a Subcooled Boiling Flow on the CUPID Code

Ik Kyu Park, Jungwoo Kim, Hyoung Kyu Cho, Han Young Yoon, Jae Jun Jeong
Korea Atomic Energy Research Institute,1045 Daedeok-daero, Yuseong-gu, Daejeon, Republic of Korea, 305-353
**Corresponding author: gosu@kaeri.re.kr*

1. Introduction

In the two-fluid model, the volumetric interfacial area, also called the interfacial area concentration, is a very important quantity which determines the intensity of inter-phase mass, momentum and energy transfers. The accurate modeling of the local interfacial area concentration (IAC) is the first step to be taken for the development of reliable two-fluid model closure relations. In this paper, the implementation of the interfacial area transport equation into CUPID code [1] was introduced, and the validation against experiments was also presented.

2. Methods and Results

2.1 Interfacial Area Transport Equation

For a multi-dimensional calculation of the IAC (interfacial area concentration), an IAC transport equation for a boiling flow was derived as follows [2].

$$\frac{\partial a_i}{\partial t}+\nabla\cdot\left(a_i \underline{u}_g\right)=\frac{2}{3}\frac{a_i}{\alpha_g\rho_g}\left[\Gamma_{i,g}-\alpha_g\frac{d\rho_g}{dt}\right]+\phi_{CO}+\phi_{BK}+\phi_{PH} \quad (1)$$

where ϕ_{CO}, ϕ_{BK}, and ϕ_{PH} mean the source terms of the IAC transport equation by a bubble coalescence, a bubble breakup, and a nucleation, respectively. The first term on the right-hand side of Eq. (1) means a bubble size variance due to a condensation heat transfer or a pressure drop. The coalescence by a random collision and the breakup by a turbulent impact are considered for the second and the third terms on the right-hand side of Eq. (1), respectively as follows [2].

$$\begin{aligned}\phi_{CO}&=-\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2\frac{1}{2}\frac{\eta_c n}{T_c}=-\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2\frac{1}{2}\frac{\eta_c n}{T_{cf}+T_{ci}}\\&=\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2 K_{c1}\frac{\varepsilon^{1/3}\alpha_v^2}{D_{sm}^{11/3}}\frac{1}{g(\alpha_v)+K_{c2}\alpha\sqrt{We/We_c}}\exp\left(-K_{c3}\sqrt{\frac{We}{We_c}}\right)\end{aligned} \quad (2)$$

$$\begin{aligned}\phi_{BK}&=\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2\frac{\eta_b n}{T_b}=-\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2\frac{1}{2}\frac{\eta_b n}{T_{bf}+T_{bi}}\\&=\frac{1}{3\psi}\left(\frac{\alpha_v}{a_i}\right)^2 K_{b1}\frac{\varepsilon^{1/3}\alpha_v(1-\alpha_v)}{D_{sm}^{11/3}}\frac{1}{1+K_{b2}(1-\alpha)\sqrt{We/We_c}}\exp\left(-\frac{We}{We_c}\right)\end{aligned} \quad (3)$$

where ψ is bubble shape factor, $1/36\pi$ for a spherical bubble, and η, n, and T are the interaction efficiency of neighboring bubbles, bubble number density, and the interaction time. Subscripts, c, cf, ci, b, bf, and bi indicate coalescence, free traveling from bubble generation to coalescence, interaction for a coalescence, breakup, free traveling from bubble generation to bubble breakup, and interaction for the breakup process. ε, D_{sm}, and We are the turbulence dissipation, Sauter mean diameter of bubbles, and a Weber number. The turbulence dissipation can be obtained from the $k-\varepsilon$ turbulence model. $g(\alpha_v)$ is a modification factor defined as $1-(\alpha/\alpha_{\max})^{1/3}$. The coefficients in the equations are designated as K_{c1}= 2.86, K_{c2} = 1.922, K_{c3} = 1.017, We_c = 1.24 , $\alpha_{\max}$ = 0.52 , K_{b1} = 1.6, K_{b2} = 0.42.

The last term on the right-hand side of Eq. (1) denotes an increase of the IAC by a bubble nucleation at the heated wall, that is, the boiling source term in the interfacial area transport equation. Similarly to the evaporative heat flux, it is composed of a product of the active nucleate site density (N''), the bubble departure diameter (D_d) and the bubble departure frequency (f), as presented in Eq. (4).

$$\phi_{ph}=\pi D_d^2\frac{N''\,f A_H}{V_{cell}} \quad (4)$$

where D_d, N'', f, A_H, V_{cell} are bubble departure diameter, the active nucleate site density, the bubble departure frequency, the area of heated surface, the volume of a unit cell. The bubble departure diameter, the bubble departure frequency, and the active nucleate site density are given as follows [3].

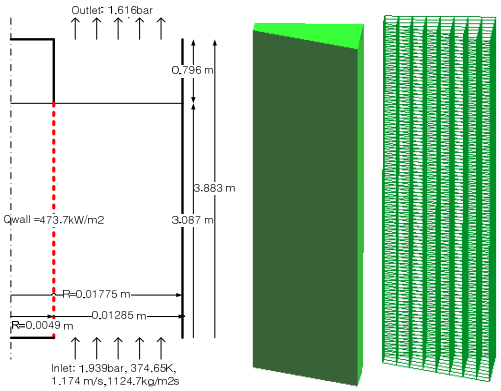
$$D_d=1.5\cdot10^{-4}\sqrt{\frac{\sigma}{g\Delta\rho}}\left[\frac{\rho_l c_{pl}(T_{wall}-T_{sat})}{\rho_g h_{lg}}\right]^{5/4} \quad (5)$$

$$f=\sqrt{\frac{4g(\rho_l-\rho_g)}{3D_{dt}\rho_l}}\ ,\quad N^{"}=[185(T_w-T_{sat})]^{1.805} \quad (6)$$

2.2 Validation of IAT against SUBO Test

The geometrical condition and the computational mesh for SUBO-BASE-RB test[4] are presented in Figure 1(a), (b), (c). The 2nd and 3rd parts of SUBO test section are used as CUPID calculation domain. The 2nd part is a heated region, and the 3rd part is a bubble condensation region. The calculation domain is an axi-symmetric geometry. The dotted line is the heated wall, the solid bold line is the wall. The radius of the heated wall is 0.0049 m, and that of test section wall is 0.01775 m. The calculation domain is the water region of from 0.0049 m to 0.01775 m. The left wall is a heated wall boundary, the right wall is a solid wall, and the top and bottom are set to inlet and outlet, respectively. The SUBO-BASE-RB test was selected for the base calculation set. The 374.65 K, 1.939 bar, 943.9 kg/m^3 water is injected into the inlet. The outlet was set to constant pressure boundary of 1.573 bar. The

heat flux from the heated wall is 473.7 kw/m^2.The calculation domain is a pillar with a fan-shape base area, of which inner radius and outer radius are 0.0049 m and 0.01775 m, respectively. 8x1x100 grids were used for r-,Θ -,z- coordinates as shown in Figure 1(c).



(a) (b) (c)

Fig. 1 Calculation Domain for SUBO test: (a)Schematic Diagram (b)Geometry (c) Mesh.

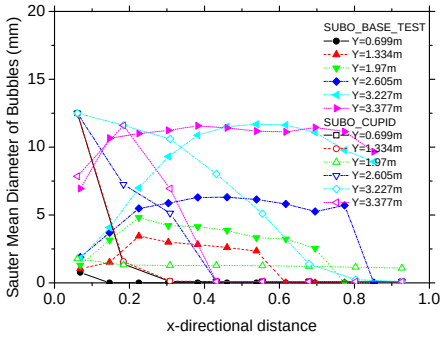


Fig. 2 Comparison of Bubble Diameter

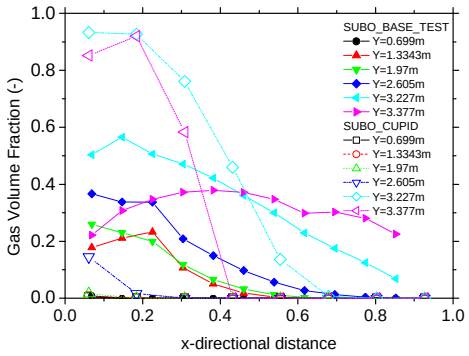


Fig. 3 Comparison of Gas Volume Fraction

The null transient calculation was done and the steady solution could be obtained at 10 seconds. In this calculation, the maximum bubble diameter was limited by the channel size and the Taylor bubble size. The calculated bubble diameters and gas volume fractions are compared to the measured ones in Figure 2 and Figure 3. The x-directional distance of those figures is the distance from the heated wall. The calculated gas volume fractions are high near the heated wall and very low at the outer solid wall. The calculated bubble diameters have also same distribution. The measured ones have the flat distribution for the x-directional distance. The calculated gas volume fraction is too low at middle level, but the fraction is too high at the higher level. This is induced by the poor heat partition: the subcooled boiling at the heated wall was too small and the prediction of the bubble departure from the heated wall by the current model was also poor. Thus, the heat partitioning model and the bubble departure model for the subcooled boiling region will be further studied. The non-drag force models will be also examined because the lateral gas distributions are primarily dependent upon non-drag forces.

3. Conclusions

The recent implementations of interfacial transport equation were introduced. The validation calculation of IAC transportation was done with SUBO-BASE-RB test. This calculation showed that the IAC transport equation works for the subcooled region. The heat partitioning model such as active nucleation site density, bubble departure model, etc should be further studied. After further validations against air-water flow tests and/or steam-water flow tests, these implementations can be adapted for a realistic simulation of transient two-phase flows.

ACKNOWLEDGEMENTS

This work was supported by Nuclear Research & Development Program of Nuclear Research and Development Program of the NRF (National Research Foundation of Korea) grant funded by the MEST (Ministry of Education, Science and Technology) of the Korean government (Grant code: M20702040002-08M0204- 00210).

REFERENCES

[1] J. J. Jeong, H. Y. Yoon, I. K. Park, H. K. Cho, H. D. Lee, Development and Preliminary Assessment of a Three Dimensional Thermal Hydraulics Code, CUPID, Nuclear Engineering and Technology, Vol. 42, No. 3, pp.279–296, 2010.
[2] W. Yao, C. Morel, Volumetric Interfacial Area Prediction in Upward Bubbly Two-phase Flow, International Journal of Heat and Mass Transfer, Vol. 47, pp. 307-328 2004.
[3] AEA, CFX-4 Solver Manual, UK , 1997.
[4] B. J. Yun, B. U. Bae, , D. J. Euh, G. C. Park, C. –H. Song, Characteristics of the Local Bubble Parameters of a Subcooled Boiling Flow in an Annulus, Nuclear Engineering and Design, doi:10.1016/j. nucengdes. 2009.11.014.