# A Validation of CUPID Code for a Subcooled Boiling Test

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

## 1. Introduction

The Korea Atomic Energy Research Institute has been developing a three-dimensional thermal-hydraulic code, called CUPID, which was motivated from practical needs for the realistic simulation of two-phase flows in nuclear reactor components [1]. This paper presents the implementation of the subcooled boiling model into the CUPID code and some assessment results. The closure relations for the subcooled boiling model are turbulence model, interfacial non-drag force, interfacial condensation, wall evaporation model, bubble departure diameter, and so on.

## 2. Mathematical Model

### *2.1 Governing Equations*

The governing equations of the two-fluid, three-field model are similar to those of the time-averaged two-fluid model derived by Ishii and Hibiki [2]. The continuity, momentum, and energy equations for the k-phase are given by

$$\frac{\partial}{\partial t}(\alpha_k\rho_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k)=\Gamma_k \tag{1}$$

$$\begin{aligned}\frac{\partial}{\partial t}(\alpha_k\rho_k\underline{u}_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k\underline{u}_k)=-\alpha_k\nabla P+\nabla\cdot[\alpha_k\tau_k]+\alpha_k\rho_k\underline{g}\\ +P\nabla\alpha_k+M_k^{mass}+M_k^{drag}+M_k^{VM}+M_k^{non-drag}\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial}{\partial t}[\alpha_k\rho_k e_k]+\nabla\cdot(\alpha_k\rho_k e_k\underline{u}_k)=-\nabla\cdot(\alpha_k q_k)+\nabla\alpha_k\tau_k:\nabla\underline{u}_k\\ -P\frac{\partial}{\partial t}\alpha_k-P\nabla\cdot(\alpha_k\underline{u}_k)+I_k+Q'''_k\end{aligned} \tag{3}$$

where, $\alpha_k$, $\rho_k$, $u_k$, $P_k$, $\Gamma_k$, $I_k$ are the k-phase volume fraction, density, velocity, pressure, and an interface mass transfer rate, and energy transfer rate, respectively. $M_k$ represents the interfacial momentum transfer due to a mass exchange, a drag force, a virtual mass, and non-drag forces.

To consider a turbulence effect, the k-ε turbulence model was also implemented. The classical lift force, a wall lubrication force by Antal, et al. [3] and a turbulent dispersion force derived by Lopez de Bertodano [4], were implemented as non-drag forces. For a multi-dimensional calculation of the IAC (interfacial area concentration), an IAT equation for a boiling flow was derived as follows [5].

$$\frac{\partial a_i}{\partial t}+\nabla\cdot(a_i\underline{u}_g)=\frac{2}{3}\frac{a_i}{\alpha_g\rho_g}\left[\Gamma_{i,g}-\alpha_g\frac{d\rho_g}{dt}\right]+\phi_{CO}+\phi_{BK}+\phi_{PH} \tag{4}$$

### *2.2 Wall Boiling Model*

In the subcooled boiling flow, the amount of vapor generation can be computed by a wall heat flux partitioning model. The mechanism of a heat transfer from the wall consist of the surface quenching $q_q$, evaporative heat transfer $q_e$, and single phase convection $q_c$ which are basically included in the CFX-4 code as follows.

$$q_q=\left(\frac{2}{\sqrt{\pi}}\sqrt{t_w k_f\rho_f C_{pf}}\,f\right)A_{2f}\left(T_w-T_f\right) \tag{5}$$

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

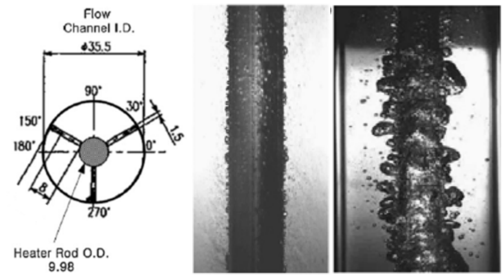
$$q_c=h_c A_{1f}\left(T_w-T_f\right) \tag{7}$$

The heat flux partitioning model adopted in the CUPID code is summarized in Table 1.

Table 1. Wall heat flux partitioning model

| Parameter | Model |
|---|---|
| Active nucleate site density | $N''=[185(T_w-T_{sat})]^{1.805}$ |
| Bubble departure diameter | $D_d=0.208\theta\sqrt{\sigma/(g\Delta\rho)}$ |
| Bubble departure frequency | $f=\sqrt{4g(\rho_f-\rho_g)/(3D_d\rho_f)}$ |
| Bubble waiting time | $t_w=0.8/f$ |
| Bubble influence factor | $K=4$ |
| Hat transfer coefficient | $h_c=St\cdot\rho_f C_{pf}u_f$ |

## 3. Validation



(b) (c)

Fig. 1 Test Section of SUBO Facilities (a) Cross-section (b)Wall Voidage at L/Dh=30 (c)Vapor Generation at L/Dh=79.

The test section of SUBO test facilities is a vertically arranged annulus with an in-direct heater rod at the channel center as depicted in Fig. 1[6]. The inner diameter of the test section is 35.5mm, and the outer diameter of the heater rod is 9.98 mm. BASE-RB of

SUBO 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 geometrical condition and the computational mesh are presented in Figure 2(a), (b), (c). The 2nd and 3rd parts of SUBO test section are used CUPID calculation domain. The 2nd part is a heated region, and the 3rd part is a bubble condensation region. The calculation domain is an axis-symmetric geometry. 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. 12x1x100 grids were used for r-,θ-,z- coordinates as shown in Fig. 2(c).

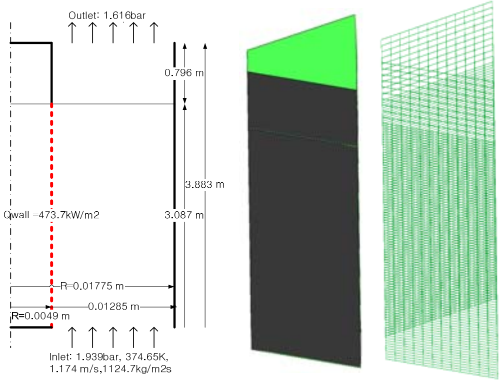


Fig. 2 Calculation Domain for SUBO test: (a)Schematic Diagram (b)Geometry (c) Mesh.

The null transient calculation was done and the steady solution could be obtained at 10 seconds. The calculated interfacial area concentration and gas volume fractions are compared to the measured ones in Fig. 3 and Fig. 4. The x-direction of those figures is the distance from the heated wall. The calculated gas volume fractions at the middle levels are very similar to measured ones. At the lowest level, the calculated void fraction is 0.1 while the measured void fraction is zero. This means that the current heat partitioning model overestimates the boiling heat transfer for the highly subcooled region. At the highest level, the calculated void fractions are lower than measured ones by about 0.15. The condensation predicted by the calculation is considered to be larger than that of the test.

The calculated interfacial area concentrations seem similar to measured ones. But, the peak values of the area concentration are smaller than measured ones near the heated wall, while the area concentrations are larger than measured ones far from the wall. The prediction error of the area concentration is somewhat larger than that of the void fractions. Thus, the interfacial area transport model needs to be improved for a better prediction of the interfacial area concentration.

## 3. Conclusions

This paper presents the implementation of the subcooled boiling model into the CUPID code and a assessment results. The subcooled boiling test, SUBO-Base-RB, was simulated for the validation of this implementation. This calculation showed that the implementation works properly but the further investigations are needed for the interfacial area transport source terms.

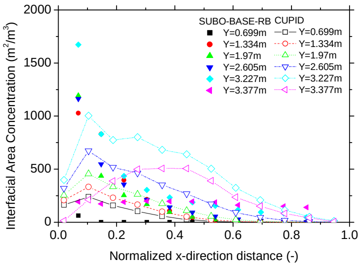


Fig. 3 Interfacial Area Concentration at SUBO-Base-RB.

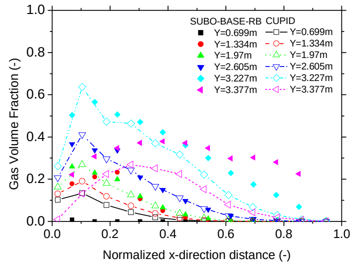


Fig. 4 Gas Volume Fraction at SUBO-Base-RB.

## ACKNOWLEDGEMENTS

This work was supported by the Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the South Korean government (MEST).(grant code: M M20702040002-08M0204-00210):

## REFERENCES

[1] J. J. Jeong, H. Y. Yoon, I. K. Park, H. K. Cho, and H. L. Heedong, Development and Preliminary Assessment of a Three-Dimensional Thermal Hydraulics Code, CUPID, NET, Vol. 42, No.3, P. 279, 2010.

[2] M. Ishii and T. Hibiki, Thermo-Fluid Dynamics of Two-Phase Flow, Springer Inc., New York, p. 217, 2006.

[3] S. P. Antal, R T. Lahey, J. E. Flaherty, "Analysis of Phase Distribution in Fully Developed Laminar Bubbly Two-Phase Flow, Int. J. of Multiphase Flow, 7, p.635, 1991.

[4] M. Lopez de Bertodano, Turbulent Bubbly Two-Phase Flow in a Triangular Duct, Ph. D., Thesis, Rensselaer Polytechnic Institute, Troy, NY, 1992.

[5] W. Yao, C. Morel "Volumetric Interfacial Area Prediction in Upward Bubbly Two-phase Flow," Int. J. Heat and Mass Transfer, Vol. 47, p. 307, 2004.

[6]B. J. Yun, B. U. Bae, D. J. Euh, G. C. Park, C.-H. Song, Characteristic of the Local Bubble Parameters of a Subcooled Boiling Flow in an Annulus, doi:10.1016/j.nucengdes. 2009.11.14.