Evaluation of the EAGLE code with one-group IATE in vertical-upward gas-liquid flow condition

V.T. Nguyen [a,b], B.U. Bae [b], C-.H. Song [a,b,*]
[a] *University of Science and Technology, 217 Gajungro, Yuseong, Daejeon, 305-350 ,Rep. of Korea*
[b] *Korea Atomic Energy Research Institute, Daedeok-daero 1045, Yuseong, Daejeon, 305-353, Rep. of Korea*
[*] *Corresponding author: chsong@kaeri.re.kr*

1. Introduction

The EAGLE (Elaborated Analysis of Gas-Liquid Evolution) code was developed based on the two-fluid model and aimed for a multi-dimensional analysis of two-phase flow with the implementations of non-drag force, standard k-ε turbulence models, and the interfacial area transport equation (IATE). The performance of EAGLE has been validated for sub-cooled boiling flows and showed good agreement with experimental data [1], [2]. In this paper, EAGLE code is evaluated with experimental data in adiabatic two-phase flow which has been measured with the vertical air-water loop (VAWL). VAWL has a cylindrical acryl type test section with 80 mm in diameter and 10 m in height. The main local parameters are the void fraction, bubble/liquid velocities, interfacial area concentration and bubble size at three axial elevations (L/D =12.2, 42.2, 100.7).

2. Code structure and constitutive relations

The EAGLE code adopts the two-fluid model, which is beneficial for treating the behavior of each phase separately and to consider a phase interaction term properly. For adiabatic flow condition, the conservation equations solved include the mass and momentum equations derived for each phases and the standard *k-ε* turbulence model for the continuous phase. The mass balance equation for a phase *k* is given as

$$\frac{\partial(\alpha_k\rho_k)}{\partial t}+\nabla\cdot(\alpha_k\rho_k \mathrm{u}_\mathrm{k})=0 \qquad (1)$$

The momentum equations are given as follows

$$\frac{\partial(\alpha_k\rho_k u_k)}{\partial t}+\nabla\bullet(\alpha_k\rho_k \mathrm{v}_\mathrm{k} u_k)=-\alpha_k\nabla p+\nabla\bullet\left[\alpha_k\left(\overset{=}{\tau}_k+\tau_k^T\right)\right] \qquad (2)$$
$$+\alpha_k\rho_k g+F_{ik}-\nabla\alpha_k\bullet\tau_{ki}$$

where $\overset{=}{\tau}_k$ and τ_k^T are molecular stress tensor and the turbulent stress tensor, respectively. F_{ik} denotes the term of an interfacial momentum transfer including the interfacial drag force, the wall lubrication force, the lift force, the turbulent dispersion force and the virtual mass force.

$$F_{ik}=F_{Dk}+F_{Wk}+F_{Lk}+F_{TDk}+F_{VMk} \qquad (3)$$

Selecting the proper models for interphase force is crucial for two-phase flow modeling. In this study, the interface drag model of Ishii and Zuber taken into account the effect of a multiparticle is adopted. Lift force on a bubble is induced by a rotational motion of the liquid phase as follow

$$F_{Lg}=-F_{Lf}=\alpha\rho_f C_L(u_g-u_f)\times(\nabla\times u_f) \qquad (4)$$

Here, the coefficient C_L is set to 0.01 and it can take 0.01 to 0.05 for a viscous flow. In contrast to the lift force, due to the surface tension, lateral force is formed to prevent bubbles attaching on the solid walls thereby results in a low gas void fraction at the vicinity of the wall area. In this study, the wall lubrication force model developed by Antal et al. (1991) was found to be proper. To consider turbulence assisted bubble dispersion, turbulent dispersion force is introduced in terms of Farve-averaged variables (Burns et al., 2004)

$$F_{TDg}=-F_{TDf}=\frac{3}{4}C_D\frac{\alpha\rho_f v_{t,f}}{d_b\,\mathrm{Pr}}\left|u_g-u_f\right|\nabla\alpha \qquad (5)$$

with C_D, $v_{t,f}$, and Pr is the drag force coefficient, turbulent kinematic viscosity of the liquid phase, and Prandtl number.

Liquid turbulence is estimated by the Standard *k-ε* model which is extended for two-phase flow with the implementation of bubble-induced turbulent source terms. The turbulent kinetic energy equation and the dissipation rate are formulated as follows.

$$\frac{\partial(\alpha_f\rho_f k)}{\partial t}+\nabla\cdot\left(\alpha_f\rho_f\vec{u}_f k\right)=\nabla\cdot\left[\alpha_f\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right] \qquad (6)$$
$$+\alpha_f P-\alpha_f\rho_f\varepsilon+\alpha_f\Phi_k$$

$$\frac{\partial(\alpha_f\rho_f\varepsilon)}{\partial t}+\nabla\cdot\left(\alpha_f\rho_f\vec{u}_f\varepsilon\right)=\nabla\cdot\left[\alpha_f\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla k\right] \qquad (7)$$
$$+\alpha_f\frac{\varepsilon}{k}\left(C_{\varepsilon1}P-C_{\varepsilon2}\rho_f\varepsilon\right)+\alpha_f\Phi_\varepsilon$$

$$\mu_T=C_\mu\rho_f\frac{k^2}{\varepsilon} \qquad (8)$$

The source terms for bubble-induced turbulence and the detail of coefficients can be found in [3].

The IATE has been used by various studies for two-phase flow such as Ishii et al. (2002), Hibiki and Ishii (2002), Yao and Morel (2004), and Bae et al.(2009, 2010). For the adiabatic gas-liquid flow condition, the basic form of governing equation is as follows:

$$\frac{\partial a_i}{\partial t}+\nabla\cdot\left(a_i u_g\right)=-\frac{2}{3}\frac{a_i}{\rho_g}\frac{d\rho_g}{dt}+\phi_{co}+\phi_{bk} \qquad (9)$$

The first term on the right-hand side of Eq. (9) is the term for a bubble size variance due to a pressure drop. The second and the third term mean the variance of interfacial area concentration (IAC) by a coalescence and break-up, respectively. Recently, a commercial

CFD-code analysis of Cheung et al (2007) represented that the model of Yao and Morel showed a better agreement for an air/water adiabatic flow. Hence, the Yao and Morel's models for coalescence and breakup source term have been chosen for analysing of the EAGLE code.

3. Numerical details and boundary condition

The Simplified Marker And Cell (SMAC) algorithm with non-staggered grid was extended in EAGLE code for two-phase flow application. Analysis was conducted with a grid composed of 20 (radial) x 100 (axial) axisymmetric cells in a cylindrical coordinate. The sensitivity of grid size is also investigated in this study. At the inlet of the test section, as the diameter of the injected bubbles are unknown, uniformly distributed superficial liquid and gas velocities, void fraction and bubble size were specified in accordance with the flow condition described and based on drift-flux model. A zero gradient condition was taken into account at the outlet boundary.

4. Results

With the limitation of one-group IATE, numerical investigations were thus focused mainly on the bubbly flow regime. Fig. 1 shows typical results of void fraction, IAC, interfacial gas and liquid velocity distributions obtained from the breakup and coalescence models of Yao and Morel employed in one-group interfacial area transport equation and the experimental data measured in three dimensionless axial position L/D = 12.2, 42.2, and 100.7. In adiabatic gas-liquid bubbly flow, the void fraction peaking near the pipe wall represented the flow phase distributions caused by the typical "wall peak" behavior. From these results, it is observed that a well-developed wall peaking behavior was recorded in the experiment and also had been captured well by EAGLE code. As suggested by Cheung et al. (2007), the adopted wall lubrication model could be source of error causing the underestimated or overestimated void fraction at the wall. Another source of error is the uncertainties concerning the turbulence model which predicted the turbulent energy dissipation and coupled with the coalescence and breakup models.

5. Conclusions

Agreements were achieved for the void fraction, interfacial area concentration, bubble Sauter mean diameter and gas and liquid velocities against measurements. Although the discrepancies exist, encouraging results demonstrated the capability of the one-group IATE implemented in EAGLE code for modeling bubbly flow conditions.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Research & Development Program of the National Research Foundation (NRF) grant funded by the Korean government (MEST). (grant code: M20702040003-08M0204-00310)

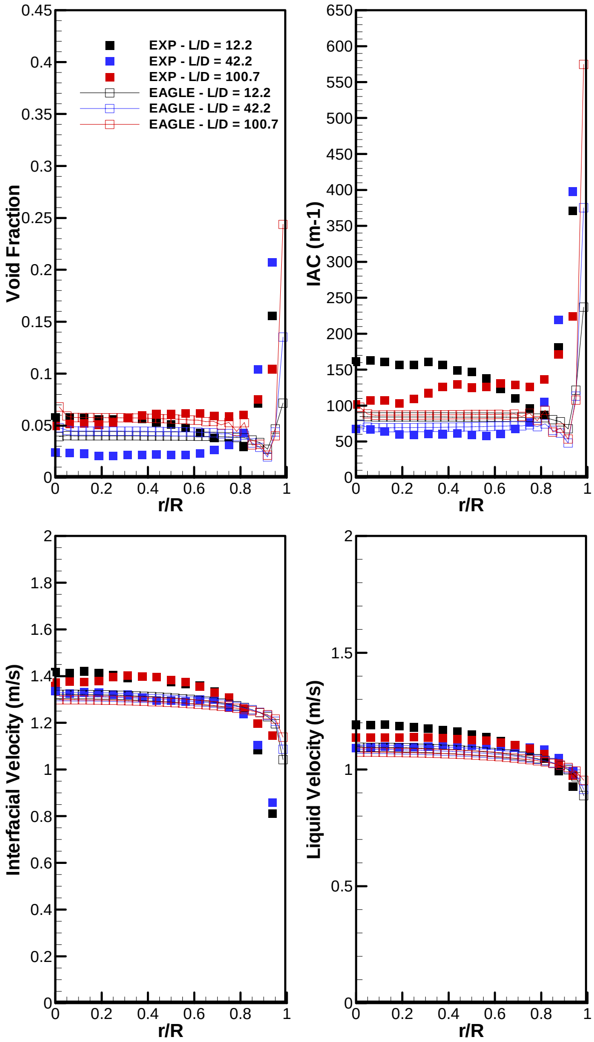

Fig 1. Typical results $\langle j_f \rangle = 1.0$ m/s, $\langle j_g \rangle = 0.053$ m/s

REFERENCES

[1] B.U. Bae, H.Y. Yoon, D.J. Euh, C.-H. Song and G.C. Park, "Computational Analysis of a Subcooled Boiling Flow with a One-group Interfacial Area Transport Equation", Journal of Nuclear Science and Technology, Vol. 45, No. 4, 2008, pp.341-351

[2] B.U. Bae, B.J. Yun, H.Y. Yoon, C.-H. Song, G.C. Park, "Analysis of subcooled boiling flow with one-group interfacial area transport equation and bubble lift-off model", Nuclear Engineering and Design, Vol. 240, Issue 9, 2010, pp. 2281-2294.

[3] V.T.Nguyen, B.U. Bae, B.J. Yun, D.J. Euh, C.H. Song, "Assessment of Turbulence Models for Isothermal Vertical-upward Bubbly Flows", Korea Nuclear Society Autumn Meeting, October 21-22, Jeju, Korea(2010)