# Assessment of Turbulence Models for Isothermal Vertical-upward Bubbly Flows

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## 1. Introduction

EAGLE (Elaborated Analysis of Gas-Liquid Evolution) code was developed by KAERI for a multi-dimensional analysis of two-phase flow with the implementations of non-drag force, turbulence models, and the interfacial area transport equation [1]. The code structure was based on the two-fluid model and the Simplified Marker And Cell (SMAC) algorithm was modified to be available for an isothermal bubbly two-phase flow simulation. In the Euler/Eulerian approach simulating bubbly flow, the influence of the bubbles on the turbulence of the liquid has to be modeled correctly since the liquid turbulence strongly influences the models describing bubble coalescence and bubble breakup in any interfacial area transport equation [2].

In the present paper, two common concepts for modeling the influence of bubbles on liquid turbulence quantities implemented in k-ε turbulence model are described and analyzed. Simulation were done using EAGLE code and compared with gas volume fraction distributions and turbulence parameters obtained from experimental data of Hibiki et al (2001).

## 2. Concept of bubble induced sources for turbulence kinetic energy and eddy dissipation

The k-ε equations for two-phase flow are similar to the single phase ones with the difference of adopting the phase average and calculation with phase fractions. The k-ε consider the turbulence parameters in liquid phase ($\alpha_f$ liquid fraction) and account for the bubble-induced turbulence (BIT) via a source term $\Phi_k$ , $\Phi_\varepsilon$ as follows:

$$\frac{\partial(\alpha_f \rho_f k)}{\partial t} + \nabla\cdot\left(\alpha_f \rho_f \vec{u}_f k\right) = \nabla\cdot\left[\alpha_f\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \alpha_f P - \alpha_f \rho_f \varepsilon + \alpha_f \Phi_k \tag{1}$$

$$\frac{\partial(\alpha_f \rho_f \varepsilon)}{\partial t} + \nabla\cdot\left(\alpha_f \rho_f \vec{u}_f \varepsilon\right) = \nabla\cdot\left[\alpha_f\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla k\right] + \alpha_f \frac{\varepsilon}{k}\left(C_{\varepsilon 1} P - C_{\varepsilon 2}\rho_f \varepsilon\right) + \alpha_f \Phi_\varepsilon \tag{2}$$

$$\mu_T = C_\mu \rho_f \frac{k^2}{\varepsilon} \tag{3}$$

The constants in the above equations were chosen by optimizing the calculation results to fit a wide range of turbulent single-phase flows; nevertheless the same constant values are used in two-phase flows. The most used set of these values is [3]:

$$C_{\varepsilon 1} = 1.44,\ \ C_{\varepsilon 2} = 1.92,\ \ \sigma_k = 1.0,\ \ \sigma_\varepsilon = 1.3,\ \ C_\mu = 0.09$$

The bubble-induced turbulence source term $\Phi_k$ in turbulent kinetic equation (1) represents the interaction between the gas and the liquid phase at the interface between the two-phase. Most of BIT correlations that are found in the literature consider the work of the drag forces. In some correlations a contribution of non-drag forces is considered. The following expression for the bubble-induced turbulence source for turbulent kinetic energy was given by assuming that all friction work of a rising bubble is converted into turbulent kinetic energy:

$$\Phi_k = -\vec{F}_D \cdot \alpha_g \left|\vec{u}_g - \vec{u}_f\right| \tag{4}$$

where $\vec{F}_D$ is the drag force, $\alpha_g$ is the gas volume fraction, $\vec{u}_g$ is the gas velocity, and $\vec{u}_f$ is the gas velocity. Table 1 shows the literature work on $\Phi_k$.

| *Author* | $\Phi_k$ | |
|---|---|---|
| | *Work of drag forces* | *Other contributions* |
| *Morel (1997)* | $\frac{1}{\alpha_f}\lvert A_D\rvert\lvert u_r\rvert \quad \left(A_D = \frac{3}{4}\alpha_g C_D \frac{\lvert\vec{u}_r\rvert^2}{d_s}\right)$ | $\frac{1+2\alpha_g}{2\alpha_f}\left(\frac{D_g\vec{u}_g}{Dt} - \frac{D_f\vec{u}_f}{Dt}\right)\cdot$ |
| *Pfleger and Becker (2001)* | $C_k\lvert A_D\rvert\lvert u_r\rvert$ $\left(C_k = C_{\varepsilon 1}\right)$ | *None* |
| *Troshko and Hassan (2000)* | $\frac{1}{\alpha_f}\lvert A_D\rvert\lvert u_r\rvert$ | *None* |
| *Lahey (2005)* | $C_p(1+C_D^{4/3})\alpha_g \frac{\lvert\vec{u}_r\rvert^3}{d_s}$ $\left(C_p = 0.25\right)$ | *None* |
| *Star-CD* | $\frac{3}{4}\frac{C_D}{d_B}\frac{\alpha_g}{\alpha_f}\lvert\vec{u}_r\rvert\left\{2(C_t - 1)k - \frac{\nu_c^T}{\alpha_g\alpha_f\sigma_\alpha}u_r\cdot\nabla\alpha_g\right\}$ | *None* |

Unfortunately, there is no theoretical justification in the literature for the source of turbulence eddy dissipation. Most of previous works correlated $\Phi_\varepsilon$ with $\Phi_k$ and the relaxation time $\tau_{BIT}$ which is calculated on a dimensional background.

The bubble induced sources for turbulence eddy dissipation in equation (2) is obtained as below [4]:

$$\Phi_\varepsilon = C_{\varepsilon 3}\tau_{BIT}^{-1}\Phi_k \tag{5}$$

## 3. Concept of turbulence viscosity enhancement proposed by Sato

For two-phase flow, Sato (1981) considered the influence of bubbles by increasing the turbulent viscosity by

$$\mu_S = 0.6\rho_f \alpha_g |\vec{u}_g - \vec{u}_f| \tag{6}$$

Hence, the turbulence equation using Sato approach can be described as follows:

$$\frac{\partial(\alpha_f \rho_f k)}{\partial t} + \nabla\cdot(\alpha_f \rho_f \vec{u}_f k) = \nabla\cdot\left[\alpha_f\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \alpha_f P - \alpha_f \rho_f \varepsilon \tag{7}$$

$$\frac{\partial(\alpha_f \rho_f \varepsilon)}{\partial t} + \nabla\cdot(\alpha_f \rho_f \vec{u}_f \varepsilon) = \nabla\cdot\left[\alpha_f\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla k\right] + \alpha_f \frac{\varepsilon}{k}\left(C_{\varepsilon 1} P - C_{\varepsilon 2}\rho_f \varepsilon\right) \tag{8}$$

$$\mu_T = C_\mu \rho_f \frac{k^2}{\varepsilon} + 0.6\rho_f \alpha_g |\vec{u}_g - \vec{u}_f| \tag{9}$$

## 4. Data Assessment and Numerical Setup

Experiments performed by Hibiki et al. (2001) were chosen for the assessment of turbulence models implemented in EAGLE code following above approaches. In this experiment, local flow measurements such as gas void fraction, interfacial velocity, liquid velocity and turbulent intensity of vertical upward air-water flows in round tube with an inner diameter of 50.8 mm were performed at three axial locations of z/D = 6.0, 30.3 and 53.3 as well as 15 radial locations from r/R = 0-0.95 by using the double-sensor probe and the hot film probe. Four cases of wall-peaking void fraction were chosen for analysis in this paper. Due to the axial symmetry, numerical solution of the mathematical model was obtained on a 2D computational domain with a grid composed of 10 (radial) x 80 (axial) axisymmetric cells in a cylindrical coordinate. Local data at location z/D=6.0 was chosen for inlet conditions and the results were compared with experiment data at location z/D = 53.5. For turbulence assessment of bubbly two-phase flows and based on experiment data, it is reasonable to assume the constant bubble diameter along the tube.

## 5. Results and Discussions

The turbulent viscosity contributes directly to the calculation of the velocity gradient. The increase in turbulent viscosity decreases the velocity gradient. For using the BIT sources in k-ε equations, the turbulence kinetic energy was increased remarkably. The dissipation rate increases as well, however, not to the extent that keeps the turbulent viscosity unchanged. Hence, in Sato approach, even with the increase of additional term for turbulent viscosity, the velocity gradient is steeper than that in bubble-induced turbulent source approach (Fig.1).

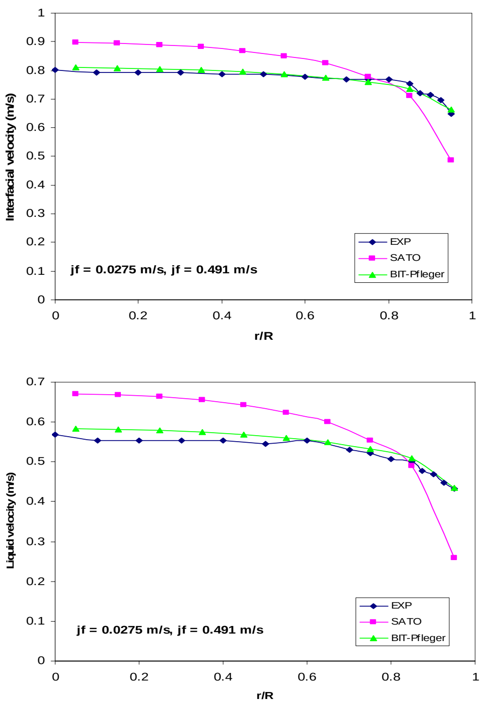


Fig.1 Interfacial and Liquid Velocity Profile

## 6. Conclusions

A k-ε turbulence model that considers the bubble-induced turbulence source term was implemented successfully into EAGLE code. The performance of EAGLE prediction has been assessed against Hibiki et al. (2001) experimental data.

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