International Journal of Multiphase Flow 54 (2013) 31–42

Contents lists available at SciVerse ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Modeling of bubble coalescence and break-up considering turbulent suppression phenomena in bubbly two-phase flow

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ARTICLE INFO

Article history:
Received 13 November 2012
Received in revised form 4 January 2013
Accepted 2 March 2013
Available online 14 March 2013

Keywords:
Interfacial area concentration
Coalescence
Break-up
Turbulent suppression phenomena
Turbulent eddy size
CFD

ABSTRACT

New mechanistic bubble coalescence and break-up models considering turbulent suppression phenomena, which can possibly occur in the high liquid velocity condition of turbulent bubbly two-phase flow, are presented. The energy exchange mechanism between a turbulent eddy and interfacial structure was taken into account in the efficiency terms. Numerical simulations of turbulent bubbly flow were conducted in a CFD code to evaluate the newly developed models, in comparison with other advanced models coupled with a bubble-induced turbulent effect for one-group interfacial area transport equation. Local measurements of the bubble characteristics on the bubble size evolution along a vertical pipe flow were performed at KAERI-VAWL test facility using the five-sensor conductivity probe method to provide database for models validation. Results from the calculation clearly show the improvements of the newly developed models.

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1. Introduction

In the advanced two-fluid model currently used in many general computational fluid dynamic codes and more specific nuclear thermal–hydraulics analysis codes, the interfacial area concentration is a very important quantity that determines the intensity of inter-phase mass, momentum, and energy transfer. The interfacial area transport equation has been developed intensively to describe the temporal and spatial evolution of the two-phase geometrical structure in a two-phase flow (Ishii, 1975; Ishii and Hibiki, 2006). In the interfacial area transport equation, the development of physical models for bubble coalescence and break-up source terms requires the consideration of bubble size distribution as well as the dynamic interaction between bubbles or bubble and liquid turbulence. The break-up and coalescence kernel of Prince and Blanch (1990) and Luo and Svendsen (1996) have been widely used in the open literature.

For a one-group interfacial area transport equation, where the bubbles can be assumed to be equivalent in diameter, three mechanistic models of bubble coalescence and break-up have been proposed by Prof. Ishii's group (Wu et al., 1998; Ishii and Kim, 2001; Hibiki and Ishii, 2002). These models, which were developed based on Prince and Blanch's (1990) kernel, consist of at least four adjustable parameters, which would certainly be a function of the overlap of the excluded volume, the bubble deformation, the bubble velocity distribution, and the ratio of eddy size to bubble size. However, the adjustable parameter was assumed a constant for simplicity and was determined experimentally by one-dimensional approach for an adiabatic air–water bubbly flow. This obviously brings up the following experimental issue: how to adjust all these parameters as independently as possible by considering experiments where a single physical phenomenon is of importance (Delhaye, 2001).

Yao and Morel (2004) found some shortcomings of the previous models in the collision frequency term, and theoretically proposed a new model taking into account the free traveling time and interaction time separately. This model was validated under both subcooled boiling (DEBORA data) and adiabatic flow conditions (DEDALE data), and compared with Wu et al. (1998), Ishii and Kim (2001) and Hibiki and Ishii's (2002) models.

Recently, Kumbaro (2004), Chen et al. (2005), and Cheung et al. (2007) reported difficulty in simulating a bubbly flow with the implementation of bubble coalescence and break-up models. Kumbaro (2004) found that both Prince and Blanch (1990) and Luo and Svensen's (1996) models overestimate the coalescence rate, and that Prince and Blanch's (1990) model over-predicts the coalescence rate by a larger margin. It is systematically necessary to use a scaling coefficient in order to agree with the experimental data. Chen et al. (2005) also found similar trends. The coalescence rate was found to be about one-order of magnitude higher than the breakage rate in their works. For an engineering estimation and

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0301-9322/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.03.001

maintaining the balance of two terms, they enhanced the breakages by a factor of 10. This adjusted factor implies a lack of a physical mechanistic approach in modeling the bubble coalescence and break-up. Unfortunately, this adjusted factor was also adopted by Cheung et al. (2007) in the assessment of the bubble coalescence and break-up models of Wu et al. (1998), Hibiki and Ishii (2002), and Yao and Morel (2004).

Nguyen et al. (2012) pointed out that the bubble coalescence and break-up models of Yao and Morel (2004) are strongly dependent upon the turbulent energy dissipation rate. Considering the turbulent enhancement phenomena in bubbly two-phase flow, they found that the implementation of bubble-induced turbulence (BIT) models with source terms in the standard k–ε equations can improve the prediction results of Yao and Morel's (2004) model under low superficial liquid velocity and high void fraction conditions. However, the BIT approach failed to predict the bubble size under a high superficial liquid velocity condition. For these cases, the bubble Sauter mean diameter is strongly underestimated and the interfacial area concentration is strongly overestimated, especially at the region close to the wall. As explained in Nguyen et al. (2012), the predicted values of turbulent kinetic energy generation and dissipation rate are very large due to a high liquid velocity gradient near the wall boundary, and they might lead to a strong overestimation of bubble break-up source term in the interfacial area transport equation. Within the author's best knowledge, the turbulent suppression phenomena have not taken into account in the modeling of bubble coalescence and break-up yet. The importance of the mechanisms involved in these phenomena has been stressed by Serizawa and Kataoka (1990) for a better understanding of the complex nature of a bubbly two-phase flow. In the previously published models for bubble break-up source term, the whole turbulent kinetic energy of single eddy was considered as the possible energy for bubble break-up process, and a fractional loss of liquid turbulent eddy energy which is converted to and maintained as surface energy due to surface distortion has not been taken into account. Moreover, the turbulent eddy scale is an important factor for two bubbles keeping in contact with each other in the beginning step of a coalescence event. Therefore, the distribution of turbulent eddy size should be taken into account in the modeling of contact time between bubbles.

From this point of view, this study aims at developing bubble coalescence and break-up models taking into account the turbulent suppression phenomena. The original contact time in the bubble coalescence model, which is solely derived from a dimensional analysis, was extended by selecting the turbulent eddy size as a characteristic length, and taking into account the fragmentation process of a turbulent eddy. The fractional loss of liquid turbulent eddy energy was included in the efficiency term of the break-up model. The resulting models, and Yao and Morel's (2004) models coupled with a BIT approach, were evaluated using the in-house EAGLE (Elaborated Analysis of Gas–Liquid flows Evolution) code. Local measurements of bubbles such as void fraction, bubble/liquid velocities, interfacial area concentration and bubble size were performed at three axial elevations in the KAERI-VAWL test facility using the five-sensor conductance probe method to provide database for validating the prediction results. Experimental data of Hibiki et al. (2001) have also been used in the present study. Results from the calculation clearly show the improvements of the newly developed models.

2. One-group interfacial area transport equation

The volumetric interfacial area transport equation, which can describe the temporal and spatial evolution of the two-phase geometrical structure, for an adiabatic bubbly flow is given by

$$\frac{\partial a_i}{\partial t}+\nabla\cdot(a_i\vec{u}_g)=\frac{2}{3}\frac{a_i}{\alpha}\left[\frac{\partial\alpha}{\partial t}+\nabla\cdot(\alpha\vec{u}_g)\right]+\frac{36\pi}{3}\left(\frac{\alpha}{a_i}\right)^2(\varphi_{CO}+\phi_{BK}) \quad (1)$$

The first term on the right hand-side of Eq. (1) is the term for a bubble size variation from a pressure drop. The second and third terms are the variance of the interfacial area concentration from the coalescence and break-up phenomena. As summarized clearly in Yao and Morel (2004), the coalescence and break-up terms induced by turbulence can be written in the following general forms:

$$\phi_n^{CO}=-f_c\eta_c=-\frac{1}{T_c}n\eta_c,\quad \phi_n^{BK}=f_b\eta_b=\frac{1}{T_b}n\eta_b, \quad (2)$$

where f_c is the total collision frequency between two bubbles, f_b is the total collision frequency between bubble and turbulent eddy, T_c and T_b are the coalescence and break-up times of a single bubble, η_c and η_b are the coalescence and break-up efficiencies. The bubble number per unit volume n is given as

$$n=\frac{\alpha}{\pi d_s^3/6}=\frac{1}{36\pi}\frac{a_i^3}{\alpha^2} \quad (3)$$

where the bubble Sauter mean diameter is calculated by

$$d_s=\frac{6\alpha}{a_i}. \quad (4)$$

The available bubble coalescence and break-up models in the open literature are summarized in Table 1.

3. Modeling of bubble coalescence and break-up considering turbulence suppression phenomena

3.1. Turbulence suppression phenomena

Turbulent kinetic energy is one of most important variables in two-phase flow since it is a measure of turbulence intensity, which is a ratio of the root-means-square of the turbulent velocity fluctuation and the mean velocity. In the experiments of two-phase flow turbulence, one interesting phenomenon has been observed particularly in bubbly flow regime, which is "turbulence suppression". Serizawa and Kataoka (1990) and Kataoka et al. (1993) defined "turbulence suppression" as phenomena in which the local turbulent kinetic energy in a two-phase flow becomes smaller than that in a single phase flow for the same averaged liquid flux somewhere in the radial position of the pipe. In relation to the turbulence suppression, "turbulence augmentation" is defined as the phenomena in which the local turbulent kinetic energy in two-phase flow is larger than everywhere in the radial position of the pipe. The transition between turbulence suppression and turbulence augmentation is defined as the boundary where the turbulence suppression phenomenon is no more observed. Based on their experimental observations and the previously published works, a turbulence suppression/augmentation map was qualitatively obtained in a j_f–j_g diagram, where turbulent augmentation occurs in a small liquid flux, and turbulence suppression occurs in a large liquid flux (see Fig. 1).

Many experimental investigations in the open literature have also confirmed Serizawa–Kataoka's observation. Hibiki and Ishii (1999, 2001) performed the local measurements of bubble parameters using the double sensor probe method as well as the liquid velocity and turbulent intensity using hot-film anemometry for vertical upward bubbly air–water flows in a round tube with an inner diameter of 25.4 mm and 50.8 mm. Their findings supported the Serizawa–Kataoka's observation, while the phenomena of turbulent intensity enhancement were observed for a high void fraction condition regardless of the superficial liquid velocity. Shawkat et al. (2008) also showed that turbulence suppression was

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