Chinese Journal of Chemical Engineering 23 (2015) 1737–1745

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Fluid Dynamics and Transport Phenomena

A dual-scale turbulence model for gas–liquid bubbly flows☆

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ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 19 March 2015
Accepted 10 May 2015
Available online 25 September 2015

Keywords:
Two-fluid model
Dual-scale turbulence model
Shear-induced turbulence
Bubble-induced turbulence
Bubbly flow

ABSTRACT

A dual-scale turbulence model is applied to simulate cocurrent upward gas–liquid bubbly flows and validated with available experimental data. In the model, liquid phase turbulence is split into shear-induced and bubble-induced turbulence. Single-phase standard k-ε model is used to compute shear-induced turbulence and another transport equation is added to model bubble-induced turbulence. In the latter transport equation, energy loss due to interface drag is the production term, and the characteristic length of bubble-induced turbulence, simply the bubble diameter in this work, is introduced to model the dissipation term. The simulated results agree well with experimental data of the test cases and it is demonstrated that the proposed dual-scale turbulence model outperforms other models. Analysis of the predicted turbulence shows that the main part of turbulent kinetic energy is the bubble-induced one while the shear-induced turbulent viscosity predominates within turbulent viscosity, especially at the pipe center. The underlying reason is the apparently different scales for the two kinds of turbulence production mechanisms: the shear-induced turbulence is on the scale of the whole pipe while the bubble-induced turbulence is on the scale of bubble diameter. Therefore, the model reflects the multi-scale phenomenon involved in gas–liquid bubbly flows.

1. Introduction

Bubbly flows occur in a great variety of natural phenomena and industrial applications. Knowledge of the characteristics of such flow is of great importance in designing multiphase systems, but gaining full understanding of the flows is difficult for the complex physics involved and the existing multi-scale phenomena. Hence, the CFD simulation is an important tool for predicting hydrodynamics in the systems and scaling up the apparatuses. Suitable CFD models should account for such effects as turbulence, phase interaction and multi-dimensionality.

The Euler–Euler two-fluid framework of interpenetrating continua is the widely used approach to simulate two-phase flows [1,2]. In this model, conservative equations of mass, momentum and energy written for each phase are derived by an ensemble averaging method, and other equations are needed to close the turbulent stresses, such as in k-ε, k-ω, and RSM turbulence models. However, these turbulence models are all well developed and validated only in single phase flows, and their applications to multiphase flows remain open questions for the complexity of multiphase turbulence.

In bubbly flows, bubbles significantly affect the liquid turbulence structure and intensity [3]. Therefore, a turbulence model taking into account the effect of bubbles is vital for predictive CFD simulations for bubbly flows. Sato *et al.* [4] modeled the bubble-induced turbulence through simply adding an extra bubble-induced contribution to single-phase turbulent viscosity. However, this method does not directly predict bubble-induced turbulent kinetic energy and dissipation. Another approach is directly reflected by adding source terms to the liquid turbulent kinetic energy and dissipation transport equations [5–8]. The additional turbulent kinetic energy production rate is equal to the energy loss by the bubbles due to interface forces; in the turbulent dissipation transport equation, the destruction of bubble-induced turbulence is modeled through dividing the production rate by a characteristic time scale. Nevertheless, the time scale is mainly based on dimensional analysis and no consensus has reached due to the complexity of turbulence in bubbly flows. Morel [5] chose the time scale $(d_B^2/\varepsilon_L)^{1/3}$ based on bubble diameter and turbulent dissipation; the bubble time scale d_B/u_{rel} was selected by Troshko and Hassan [6] and the turbulence time scale k_L/ε_L by Politano *et al.* [7]. However, Rzehak and Krepper [8] indicated that the mixed time scale of $d_B/\sqrt{k_L}$ gave better prediction. In addition, Chahed *et al.* [9] introduced a separate transport equation for non-dissipative pseudo-turbulence induced by the displacements of the bubbles. However, the limitations of the model are the consideration of fluctuations from the perturbation of the flow only in the vicinity of the bubbles and the assumption of ideal equilibrium between turbulent production and dissipation in the bubble wakes.

☆ Supported by the National Natural Science Foundation of China (U1162125, U1361112) and the National High Technology Research and Development Program of China (2011AA05A205).
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http://dx.doi.org/10.1016/j.cjche.2015.09.003

For macroscopic simulations of vegetated flows, King *et al.* [10] proposed a dual-scale turbulence model to evaluate different turbulence generation mechanisms: turbulence produced by large-scale shear and small-scale stem wakes. In this model, the standard k-ε turbulence model was applied to simulate large scale shear-induced turbulence and one-equation turbulence model was used to describe wake turbulence. In bubbly flows, there are also two kinds of turbulence production mechanisms: large-scale shear-induced turbulence and small-scale bubble-induced turbulence. Notwithstanding the similarity between vegetated flows and bubbly flows, whether the model proposed by King *et al.* [10] for vegetated single-phase flows can be applied to simulating turbulence in gas–liquid bubbly flows remains unknown.

The objective of the present research is to apply the dual-scale turbulence model proposed by King *et al.* [10] to turbulent bubbly flows. The model is validated with experimental results, and the multi-scale turbulence structure in bubbly flows is also discussed. The model is compared with other turbulence models to illustrate its advantages. Moreover, the parameter sensitivity of the dual-scale turbulence model is investigated.

2. Overview of Models

The Euler–Euler two-fluid model is used to simulate the gas–liquid pipe flows. The conservation of mass for each phase is given by

$$\frac{\partial(\alpha_i\rho_i)}{\partial t}+\nabla\cdot(\alpha_i\rho_i\boldsymbol{u}_i)=0. \tag{1}$$

The conservation of momentum for each phase is

$$\frac{\partial(\alpha_i\rho_i\boldsymbol{u}_i)}{\partial t}+\nabla\cdot(\alpha_i\rho_i\boldsymbol{u}_i\boldsymbol{u}_i)=-\alpha_i\nabla p+\nabla\cdot\left[\alpha_i\left(\boldsymbol{T}_i+\boldsymbol{T}_i^{Re}\right)\right]+\boldsymbol{F}_i+\alpha_i\rho_i\boldsymbol{g}. \tag{2}$$

The total interfacial forces $\boldsymbol{F}_{\rm i}$ are formulated based on appropriate consideration of different sub-forces interacting between phases. As Lahey and Drew [11] demonstrated, the total interfacial forces are given by the drag, lift, wall force and turbulent dispersion force:

$$\boldsymbol{F}_i=\boldsymbol{F}_i^{\rm drag}+\boldsymbol{F}_i^{\rm lift}+\boldsymbol{F}_i^{\rm wall}+\boldsymbol{F}_i^{\rm td}. \tag{3}$$

The drag force between gas and liquid phase is given by

$$\boldsymbol{F}_{\rm G}^{\rm drag}=-\frac{3C_{\rm D}}{4d_{\rm B}}\rho_{\rm L}\alpha_{\rm G}|\boldsymbol{u}_{\rm G}-\boldsymbol{u}_{\rm L}|(\boldsymbol{u}_{\rm G}-\boldsymbol{u}_{\rm L}). \tag{4}$$

Some researchers analyzed the energy dissipation mechanisms of gas–liquid flows in bubble columns and proposed the drag models based on Energy-Minimization Multi-Scale (EMMS) methods [13–16]. The drag model suggested by Ishii and Zuber [12] distinguishes bubble shape regimes and is widely used in the simulations of gas–liquid flows [5–8]:

$$C_{\rm D}=\max\left(C_{\rm D,sphere},\ \min\left(C_{\rm D,ellipse},C_{\rm D,cap}\right)\right) \tag{5}$$

with

$$\begin{aligned}C_{\rm D,sphere}&=\frac{24}{Re}\left(1+0.1Re^{0.75}\right)\\ C_{\rm D,ellipse}&=\frac{2}{3}\sqrt{Eo}\\ C_{\rm D,cap}&=\frac{8}{3}.\end{aligned} \tag{6}$$

The non-drag lateral force consists of lift, wall force and turbulent dispersion force, and shows great influence on the lateral void fraction distribution in gas–liquid pipe flows [17–19]. The lift force arises from the interactions between bubbles and the shear stress in liquid, and is expressed as

$$\boldsymbol{F}_{\rm G}^{\rm lift}=-C_{\rm L}\rho_{\rm L}\alpha_{\rm G}(\boldsymbol{u}_{\rm G}-\boldsymbol{u}_{\rm L})\times(\nabla\times\boldsymbol{u}_{\rm L}). \tag{7}$$

The lift force depends on the bubble diameter and bubble shape as suggested by Tomiyama *et al.* [20], Hibiki and Ishii [21]. The lift force coefficient is positive for small spherical bubbles so that the lift force pushes the bubbles toward the wall in upward co-current pipe flows; however, it changes its sign for large bubbles of substantial deformation and drives the bubbles toward the pipe axis, resulting in core-peak void fraction profiles in the lateral direction. From the experimental observation of the trajectories of single bubble rising in a shear flow, the following correlation was derived for the lift force coefficient by Tomiyama *et al.* [20]:

$$C_{\rm L}\begin{cases}\min[0.288\tanh(0.121Re),f(Eo)] & Eo<4\\ f(Eo) & 4<Eo<10\\ -0.27 & Eo>10\end{cases}$$
$$\text{with}\ f(Eo)=0.00105Eo^3-0.0159Eo^2-0.0204Eo+0.474. \tag{8}$$

This correlation has been widely applied to simulate bubbly flows [7,8,22] and will also be used in the present simulations of gas–liquid pipe flows. The lift force coefficient changes its sign for water–air system at a bubble diameter of 5.8 mm.

The wall force is proposed by Antal *et al.* [17] to describe the interactions between bubbles and wall, and it drives bubbles away from the wall. The general form of the wall force is

$$\boldsymbol{F}_{\rm G}^{\rm wall}=\frac{2}{d_{\rm B}}C_{\rm W}\rho_{\rm L}\alpha_{\rm G}|\boldsymbol{u}_{\rm G}-\boldsymbol{u}_{\rm L}|^2\boldsymbol{n}_{\rm w} \tag{9}$$

where $\boldsymbol{n}_{\rm w}$ is the unit normal inward vector on the surface of the wall. The wall force coefficient $C_{\rm W}$ depends on the distance between the bubbles and the wall. An expression was derived by Antal *et al.* [17] based on potential flow as follows:

$$C_{\rm W}=-0.104-0.06u_{\rm R}+0.147\frac{d_{\rm B}}{2y}. \tag{10}$$

Based on experimental observation, Tomiyama *et al.* [23] proposed the following wall force coefficient model:

$$C_{\rm W}=f(Eo)\left(\frac{d_{\rm B}}{2y}\right)^2 \tag{11}$$

with

$$f(Eo)=\begin{cases}\exp(-0.933Eo+0.179) & 1<Eo<5\\ 0.007Eo+0.04 & 5<Eo<33\end{cases}. \tag{12}$$

For the small Morton number water–air system, Hosokawa *et al.* [24] extrapolated their results to the following correction:

$$f(Eo)=0.0217Eo. \tag{13}$$

The wall force models of Antal *et al.* [17] and Tomiyama *et al.* [23] are widely used; however, Rzehak *et al.* [25] compared the above mentioned 3 models and found that predictions with Hosokawa *et al.* [24] suggested great agreement. Thus, this model is chosen in the present simulations.

The turbulent dispersion force describes the force exerted on the bubbles because of turbulent fluctuations of liquid velocity. Burns *et al.* [26] derived the expression by Favre averaging the drag force as

$$\boldsymbol{F}_{\rm G}^{\rm td}=-\frac{3}{4}\frac{C_{\rm D}}{d_{\rm B}}\alpha_{\rm G}|\boldsymbol{u}_{\rm G}-\boldsymbol{u}_{\rm L}|\frac{\mu_{\rm L}^{\rm t}}{\sigma_{\rm TD}}\left(\frac{1}{\alpha_{\rm L}}+\frac{1}{\alpha_{\rm G}}\right)\nabla\alpha_{\rm G}. \tag{14}$$