International Journal of Multiphase Flow 85 (2016) 236–244

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Prediction of mono-disperse gas–liquid turbulent flow in a vertical pipe

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ARTICLE INFO

Article history:
Received 17 September 2015
Revised 17 April 2016
Accepted 9 June 2016
Available online 20 June 2016

Keywords:
Two-fluid model
Gas–liquid flow
Gas volume fraction
Low Reynolds number model
Bubble induced turbulence

ABSTRACT

A two-fluid model in the Eulerian–Eulerian framework has been implemented for the prediction of gas volume fraction, mean phasic velocities, and the liquid phase turbulence properties for gas–liquid upward flow in a vertical pipe. The governing two-fluid transport equations are discretized using the finite volume method and a low Reynolds number $k-\varepsilon$ model is used to predict the turbulence field for the continuous liquid phase. In the present analysis, a fully developed one-dimensional flow is considered where the gas volume fraction profile is predicted using the radial force balance for the bubble phase. The current study investigates: (1) the turbulence modulation terms which represent the effect of bubbles on the liquid phase turbulence in the k–ε transport equations; (2) the role of the bubble induced turbulent viscosity compared to turbulence generated by shear; and (3) the effect of bubble size on the radial forces which results in either a center-peak or a wall-peak in the gas volume fraction profiles. The results obtained from the current simulation are generally in good agreement with the experimental data, and somewhat improved over the predictions of some previous numerical studies.

1. Introduction

Two-phase flow, where one component is distributed as droplets, bubbles or particles throughout a continuous phase, is relevant to many engineering applications. In particular, gas–liquid flow occurs in many industrial applications within the petrochemical, chemical and nuclear industries. For example, bubble columns, where the flow of bubbles is driven by buoyancy, are often used to facilitate reactions in chemical engineering applications. Gas–liquid flow in a pipe is of special interest within the nuclear industry due to the boiling heat transfer which takes place within reactor systems. It encompasses different flow regimes, such as bubbly, slug, churn and annular flow, which depend on the operating and flow conditions. Each of these flow regimes can be characterized by their corresponding gas-phase volume fraction (Shaikh and Al-Dahhan, 2007). Among the different gas–liquid flow regimes, the bubbly flow regime is most widely encountered in industrial applications including the nuclear industry. From a design viewpoint, it would be advantageous for engineers to have access to computational tools capable of predicting the behavior of such flows.

Computational fluid dynamics (CFD) is currently able to provide realistic predictions for many single-phase flows. Recently, it has been applied to multiphase flows by using the volume of fluid or level-set method to track the temporal and spatial development of the gas–liquid interface. However, these techniques require relatively large computational resources and are often impractical for modeling large industrial systems. An alternative approach is provided by the Eulerian–Eulerian two-fluid model, which requires significantly less computational effort than interface-tracking methods, since it represents both phases as inter-penetrating continua with the local composition defined by the volume fraction field. Most importantly, it avoids having to resolve the details of the local interface and its complex evolution in time and space. The two-fluid model has been successfully applied to multiphase flows as a tool for predicting the spatial- and time-average flow properties (Monahan and Fox, 2009). Although it shows significant promise, application of the two-fluid model to gas–liquid flows also includes some on-going challenges, such as modeling the effect of the dispersed gas-phase on the continuous liquid-phase turbulence, the development of appropriate interphase momentum exchange correlations and improved wall treatments for the liquid phase.

Limited experimental data is available for validating computational models of gas–liquid flow in a vertical pipe. Lucas et al. (2005) measured the gas volume fraction and bubble size distributions for bubbly flow in a vertical pipe for air–water flow using a high resolution wire-mesh sensor. In addition to studying the transition from the wall-peaking to the center-peaking case for the bubbly flow regime, they also measured the gas volume fraction profile for the slug flow regime. Their database is useful

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.06.010
0301-9322/

Nomenclature

C_D	drag force coefficient
C_L	lift force coefficient
C_W	wall (lubrication) force coefficient
C_{TD}	turbulent dispersion force coefficient
$C_{D,\,Eo}$	turbulent dispersion force coefficient based on modified Eotvos number (m^2/s^2)
d_b	gas bubble diameter (m)
d_H	long axis bubble diameter (m)
D	pipe diameter (m)
Eo	Eotvos number
F^D	drag force (N/m^3)
F^L	lift force (N/m^3)
F^W	wall (lubrication) force (N/m^3)
F^{TD}	turbulent dispersion force (N/m^3)
$F^{TD,\,Eo}$	turbulent dispersion force based on modified Eotvos number (N/m^3)
g	gravitational acceleration (m/s^2)
k	turbulence kinetic energy (m^2/s^2)
P	pressure (N/m^2)
r	radial variable (m)
R	pipe radius (m)
Re	Reynolds number (flow)
Re_b	bubble Reynolds number
u_τ	friction velocity (m/s)
u_z	liquid phase mean velocity (m/s)
v_z	gas phase mean velocity (m/s)
y	distance from the wall (m)

Greek symbols

α_g	gas volume fraction
α_l	liquid volume fraction
ε	dissipation of turbulence kinetic energy (m^2/s^3)
ρ_g	density of gas phase (kg/m^3)
ρ_l	density of liquid phase (kg/m^3)
μ_{eff}	effective viscosity of liquid phase ($N{\cdot}s/m^2$)
μ_g	dynamic viscosity of gas phase ($N{\cdot}s/m^2$)
μ_l	dynamic viscosity of liquid phase ($N{\cdot}s/m^2$)
ν	kinematic viscosity (m^2/s)
μ_{BIT}	bubble induced turbulent viscosity ($N{\cdot}s/m^2$)
μ_t	turbulent viscosity of liquid phase ($N{\cdot}s/m^2$)
σ	surface tension of liquid phase (N/m)

Subscripts

b	bubble
g	gas phase
l	liquid phase

for the validation of computational models which account for the various forces acting on the bubbles, as well as bubble coalescence and break-up. The evolution of gas–liquid flow structure in a large vertical pipe was investigated by Prasser et al. (2007) using a high resolution wire-mesh sensor for the bubbly, slug and churn turbulent flow regimes. They also studied the influence of the physical properties of the fluid by comparing results for experiments of air–water to steam-water mixtures at high pressure. Ohnuki and Akimoto (2000) investigated the transition characteristics of upward air–water flow in a large vertical pipe to examine the dependency on the pipe size. They found the flow conditions at which bubble coalescence begins are almost the same as for small-scale pipes, and that churn flow is dominant in large vertical pipes for the conditions where small-scale pipes exhibit slug flow. Whereas drag forces dominate the momentum exchange in the flow direction, the lift force strongly influences the radial distribution of bubbles and changes sign depending on the bubble diameter resulting in the radial separation of small and large bubbles (Krepper et al., 2005).

A number of computational studies have also considered the case of gas–liquid flow. Vitankar et al. (2002) predicted the gas volume fraction and liquid phase mean velocity profiles for bubble columns with a center-peak volume fraction profile using an iterative procedure with a low Reynolds number $k-\varepsilon$ model. They prescribed a general form and also used a drift-flux model for prediction of the gas volume fraction profile, also known as the hold-up profile. They extended their one-dimensional (1-D) model for the prediction of pressure drop for the case of two-phase gas–liquid flow in bubble columns. One benefit of a 1-D analysis is that it readily facilitates an assessment of the effects of individual models, both for the turbulence and multiphase transport, using experimental data compared to a fully three-dimensional flow where the measurements are both more complicated and difficult to obtain. Although a number of 1-D models are documented in the literature, some critical modeling issues remain such as: the appropriate closure model for the turbulent and interphase correlation terms, modeling of the radial movement of bubbles, and the overall interphase momentum and energy balances, as noted by Vitankar et al. (2002). Ekambara et al. (2005) performed simulations to predict the flow pattern in cylindrical bubble column reactors for one-, two- and three-dimensional flows using a k–ε model, and observed good agreement with experimental measurements for the axial liquid phase velocity and gas volume fraction profiles, especially for the three-dimensional flow. For the fully developed flow case in a vertical pipe, the non-drag forces, i.e. the lift, wall or lubrication, and turbulent dispersion forces act on the gas bubbles perpendicular to the flow direction and determine the gas volume fraction profile (Lucas et al., 2001). These forces are also responsible for the bubble coalescence or bubble break-up (Lucas et al., 2005). The lift and wall force plays the dominant roles in determining the gas volume fraction profile as noted by Krepper et al. (2005).

The present study focuses on modeling mono-disperse gas–liquid turbulent bubbly flow in a vertical pipe using the Eulerian two-fluid model. For this fully developed flow scenario, a 1-D computational model is used to predict the volume fraction profiles, mean phasic velocities, and turbulence properties based on a two-equation eddy viscosity model. The analysis implements a bubble induced turbulence model together with a conventional eddy viscosity model. Results are presented for the case of flow patterns characterized by both center-peak and wall-peak gas volume fraction profiles. The remainder of the paper documents the computational method, discusses the simulated results and presents some conclusions related to the underlying models which are relevant for future studies.

2. Computational method

2.1. Two-fluid model

The governing Reynolds-Averaged Navier–Stokes (RANS) equations for the mean velocity fields are obtained by averaging the conservation of mass and momentum equations for each phase, resulting in a so called Eulerian–Eulerian formulation. The two-fluid model treats both the gas and liquid phases as interpenetrating continua, and uses the local volume fraction of each phase to characterize the spatial distribution of the two phases. Coupling between the two phases is achieved through the pressure and interfacial transfer terms in the momentum equations. The two-fluid model is most appropriate when the dispersed phase is finely distributed in the corresponding continuous phase. For a turbulent gas–liquid flow, the relative motion between the phases is important in terms of interfacial energy and mass transfer, and