International Journal of Heat and Mass Transfer 98 (2016) 799–813

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Computation and validation of the interphase force models for bubbly flow

Qinggong Wang [a,b], Wei Yao [a,*]

[a] Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology, Beijing 100094, China
[b] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 18 March 2016
Accepted 19 March 2016

Keywords:
Bubbly flow
Interphase forces
Model validation
Numerical simulation

ABSTRACT

The interphase forces play a crucial role in gas–liquid two-phase flow modeling as they construct the mechanical equilibrium between phases and determine the phase distribution pattern across/along the flow channel. In this work, the predictive features of different correlations for the interphase forces were analyzed, and corresponding simulations were conducted to validate the accuracy of each correlation. Three experimental cases with a wide range of bubble Renolds number (Re_b) were considered in the modeling validation in order to verify the predictive ability of each model on different bubbly flow regimes. The models differences were clarified. The results showed that there was no standard models that could be universally used for all flow conditions. Selection of the correlations for the drag force, lift force and wall lubrication force should take in account of the bubble regimes and the flow patterns in different Re_b ranges. Changes of the turbulence dispersion force model and the turbulent model showed minor influences on the phase distribution in the simulated results, but variation of the turbulent viscosity model significantly affected the turbulent structure in the gas–liquid flow. The optimal models for different Re_b ranges had been determined in the simulated results. Based on the results in this work, a modeling strategy route was finally summarized for easier selection of the interphase force models in arranging/optimizing simulations. The strategy route can also be used as the validating steps for new interphase models proposed for bubbly flows.

1. Introduction

Gas–liquid flow occurs in a variety of industrial applications and ordinary life. It behaves as the transporting medium in isothermal flows such as gas–oil transportation pipelines and sewage disposal systems and behaves as heat/mass transfer medium in chemical reactors, nuclear reactors, powder plant boilers, evaporators and condensers etc. In most cases, the gas phase and liquid phase are strongly interactive and they combine an instantaneously deformable interface. Due to the complexity of interface, a series of interfacial problems have been unresolved to date and they are still the key points in studies of gas–liquid flow, including the phase distribution pattern, inter-phase interaction mechanism and the microscopic turbulent structure etc. [1,2].

Over the last decades, both experimental and simulation methods have been used for gas–liquid flow studies. The experimental method requires a complete system and accurate data acquisition tools. Physical distributions of void fraction, pressure drop, interfacial area concentration, bubble diameter and bubble shapes can be obtained from the macro-scale experimental results [3–5]. Differently, the simulation method builds the gas–fluid system using computational dynamics. A proper set of conservation equations are required to describe the basic flow, phase interaction and heat and mass transfer processes. With fast advances in the computer technology, the computational fluid dynamics (CFD) gains an increasing interest in multiphase flow analysis and prediction [6]. Currently, the two-fluid model is considered as the most detailed macroscopic two-phase flow model and has been widely used for two-phase flow analysis [7–10]. In applying this model for two-phase flow, one key aspect is to provide proper closure relations for the interfacial exchange terms that appears in the balance equations. Accurate modeling of the interphase forces determines the degree of mechanical equilibrium between phases, and then determines the phase distribution pattern across the transversal section of the flow channel.

A complete description of the phase interaction mechanism should take into account the interphase forces like drag force, lift force, wall effect force, virtual mass force and the turbulence

---

* Corresponding author.
E-mail addresses: wangqinggong@qxslab.cn (Q. Wang), yaowei@qxslab.cn (W. Yao).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.064
0017-9310/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

$\vec{v}$	velocity vector (m/s)
t	time (s)
p	pressure(Pa)
$\vec{g}$	gravity acceleration (m/s^2)
$\vec{F}$	interphase force (N)
k	turbulence kinetic energy (m^2/s^2)
K	interphase momentum exchange coefficient
X_{gl}	covariance of the velocities of the phases (m^2/s^2)
C	coefficient
d	diameter (m)
D	pipe diameter (m)
Re	Renolds number
Re_ω	vorticity Renolds number
Eo	Eötvös number
U_t	terminal velocity
Mo	Morton number
Sr	shear rate
D_t	dispersion scalar
Sc	Schmidt number
y_w	distance to the nearest wall (m)
j	superficial velocity (m/s)
z	measurement location (m)

Greek symbols

α	volume fraction
ρ	density (kg/m^3)
ε	turbulence dissipation rate (m^2/s^3)
ω	specific turbulence dissipation rate (1/s)
μ	viscosity (m^2/s)
τ_p	characteristic time (s)
σ	surface tension coefficient (N/m)

Subscripts

q	phase symbol
g	gas phase
l	liquid phase
gl	transfer of quantities between gas and liquid
dr	drift
VM	added-mass
b	bubble
D	drag
L	lift
WL	wall lubrication
TD	turbulence dispersion

related forces [7]. The interphase forces can be illustrated as Fig. 1. The drag force results from the viscous force acting on the bubble surface and the pressure differences caused by the bubble shape. The drag acts as the resistance between the two phases and depends on the bubble Renolds number, terminal velocity and the turbulence intensity of the continuous phase [11]. The rest forces can be classified to the non-drag forces. The lift force is complex and may originate from three sources. These sources are the shear of fluid caused by non-uniform pressure distribution resulting from unbalanced slip velocities, the forced rotation of the bubbles caused by collision with a wall, by inter-particle collisions or simply because of the shear of fluid, and the vortical force caused by vortex shedding. The lift force is significant for the large density ratios in gas–liquid bubbly flows. It makes bubbles tend to be pushed towards the wall, leading to void fraction peaking close but away from the wall for vertical co-current up flow in a pipe [12]. For vertical co-current down-flow in a pipe, lift forces act away from the wall leading to a large flat void fraction profile in the center of the pipe [13,14]. In addition, surface tension prevents bubble from approaching the wall very closely and results in low gas void fraction near the wall. This phenomenon is modeled as a wall lubrication force that pushes the bubbles away from walls [15]. Hence, the wall lubrication only acts within area having a close distance to the solid wall. The virtual mass force represents a force due to inertia of the bubbles when they are accelerated in the liquid phase. The virtual mass force is proportional to relative acceleration of phases and is significant for the case of bubbly flow through narrow constriction [16]. For steady state flows, the virtual mass force is usually neglected in two-fluid modeling.

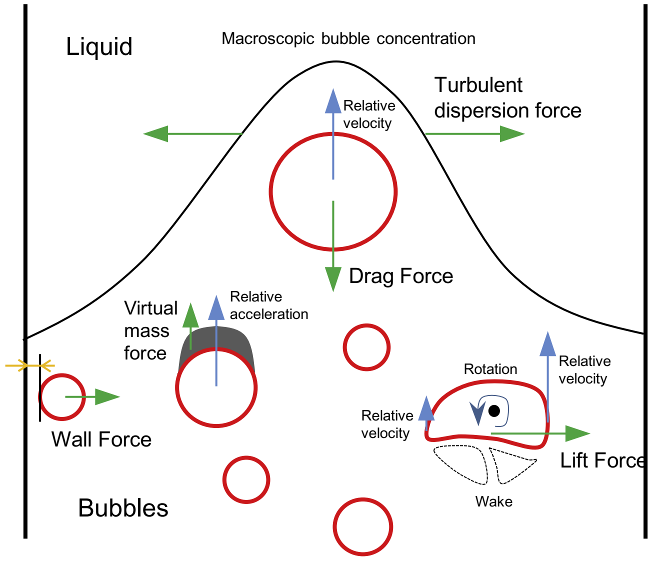

Fig. 1. Illustration of the interphase forces in bubbly flow.

Besides the above forces, another important aspect that should be taken into account is the turbulence effects. In bubbly two phase flow, the turbulence comes from two parts. One is the traditional turbulent effect arises from the viscosity of the continuous phase. This part is generally related to the physical property of the liquid phase and its modeling is similar to that of the single phase flow. However, for two-phase bubbly flows, existence of the dispersed phase introduces an interaction between the turbulent eddies and bubbles. The standard turbulence equations can be modified to consider the existence of the bubble phase and an additional bubble-induced contribution is considered in the inter-phase interaction [17,18]. The bubble-induced turbulence is modeled as the turbulent dispersion force. As the drag, lift and wall lubrication forces are also related to the turbulent structure in the flow channel, all these forces are not independent but interactive with each other. Consequently, they together determines the macroscopic phase distribution in the gas–liquid flows.

Due to the complicated flow structure, accurate prediction of bubble behavior and phase distribution in gas–liquid flow is not an easy task. Hence, the accuracy of constitutive correlations for the inter-phase forces are of great importance in two-phase flow modeling. For each force, a series of correlations have been proposed by different authors within their experimental ranges. However, it's hard to distinguish them and make a proper choice for a specified problem without a good understanding of their predictive features. It brings difficulties to modify or improve the interphase