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Unified modeling of bubbly flows in pipes, bubble columns, and airlift columns

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HIGHLIGHTS

- A closure model for bubbly flow is proposed.
- Including bubble forces and bubble-induced turbulence.
- It allows to treat different geometries and boundary conditions in a unified manner.
- Specifically bubbly flow in a pipe, a bubble column and an airlift column are considered.

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ABSTRACT

Multiphase CFD simulation is a valuable tool in process engineering which is particularly useful to study new reactor concepts and their scale-up from laboratory to production scale. Simulations of bubbly flows up to industrial dimensions are feasible within the Eulerian two-fluid framework of interpenetrating continua. However, for practical applications suitable closure models are needed which describe the physics on the scale of individual bubbles or groups thereof. The quest for such models with a broad range of applicability allowing predictive simulations is an ongoing venture.

A set of closure relations for the fluid dynamics of bubbly flow has been collected that represents the best available knowledge and may serve as a baseline for further improvements and extensions. It is shown that this model is applicable to bubbly flows in different systems, namely pipes, bubble columns, and airlift columns. While these systems have been considered individually before, the novelty of the present work lies in their unified treatment by a single model.

1. Introduction

The purpose of computer-aided process engineering (CAPE) is to assist the development and operation of complex processes involving chemical or physical change (Joshi and Ranade, 2003). Computational fluid dynamics (CFD) simulations are a means to study in detail unit operations, such as mixing, reaction, separation or combinations thereof, performed in a specific type of equipment. In particular scale-up studies and the evaluation of concepts for process intensification in an early design phase promise high benefits in terms of identifying energy- and resource-efficient solutions which are expensive to assess by conventional semi-empirical methods (Ranade, 1995; Sundaresan, 2000; Joshi, 2001; Jakobsen et al., 2005; Dudukovic, 2010).

CFD simulations of dispersed bubbly flow on the scale of technical equipment are feasible within the Eulerian two-fluid framework of interpenetrating continua. However, accurate numerical predictions rely on suitable closure models describing the physics on the scale of individual bubbles or groups thereof. A large number of works exists, in each of which largely a different set of closure relations is compared to a different set of experimental data. For the limited range of conditions to which each model variant is applied, reasonable agreement with the data is mostly obtained, but due to a lack of comparability between the individual works no complete, reliable, and robust formulation has emerged so far. Moreover, the models usually contain a number of empirical parameters that have been adjusted to match the particular data that were used in the comparison. Predictive simulation, however, requires a model that works without any adjustments within the targeted domain of applicability.

As a step towards this goal, an attempt has been made to collect

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Nomenclature

Notation Denomination

A_I	interfacial area density (dimensionless)
C_B	bubble-induced turbulence coefficient ((1981_Sato) model) (dimensionless)
C_D	drag coefficient (dimensionless)
C_L	lift coefficient (dimensionless)
C_{TD}	turbulent dispersion coefficient (dimensionless)
C_{VM}	virtual mass force coefficient (dimensionless)
C_W	wall force coefficient (dimensionless)
C_μ	shear-induced turbulence coefficient (k–ε model) (dimensionless)
d_B	bubble diameter (volume equivalent sphere) (m)
$d_\perp$	bubble diameter perpendicular to main motion (m)
D	pipe or column diameter/width (m)
Eo	Eötvös Number (dimensionless)
F_D	drag force (N m^{-3})
F_L	lift force (N m^{-3})
F_{TD}	turbulent dispersion force (N m^{-3})
F_{VM}	virtual mass force (N m^{-3})
F_W	wall force (N m^{-3})
g	acceleration of gravity (m s^{-2})
G	mass flux (kg s^{-1} m^{-2})
H	measurement position (m)
J	volumetric flux=superficial velocity (m s^{-1})
k	turbulent kinetic energy (m^2 s^{-2})
L	length of domain (m)
Mo	Morton Number (dimensionless)
p	pressure (Pa)
r	radial coordinate (m)
R	pipe or column radius/half-width (m)
Re	Reynolds number (dimensionless)
s	hydrodynamic wall roughness (m)
t	time (s)
$\boldsymbol{u}$	velocity (m s^{-1})
u_τ	friction velocity (m s^{-1})
U	velocity scale (m s^{-1})
V	volume (m^3)
x	axial coordinate (m)
y	distance to the wall (m)
z	spanwise coordinate (m)
α	volume fraction (dimensionless)
δ	viscous length scale (m)
ε	turbulent dissipation rate (m^2 s^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
τ_W	wall shear stress (N m^{-2})

the best available description for all aspects known to be relevant for adiabatic bubbly flows in which only momentum is exchanged between liquid and gas phases. Apart from interest in its own right, results obtained for this restricted problem also provide a good starting point for the investigation of more complex situations including heat and mass transport, phase change, and chemical reactions.

Aspects requiring closure for the case under consideration are: (i) the exchange of momentum between liquid and gas phases, (ii) the effects of the dispersed bubbles on the turbulence of the liquid carrier phase, and (iii) processes of bubble coalescence and breakup that determine the distribution of bubble sizes. All of these aspects are coupled and therefore in principle have to be considered as a whole.

At the same time it is highly desirable to validate the individual sub-models of this complex coupled problem separately. To this end we use a step-by-step procedure in which we first consider situations where a fixed distribution of bubble sizes may be imposed. In this way the sub-models for bubble forces (i) and bubble-induced turbulence (ii) can be validated independently of bubble coalescence and breakup processes (iii). The latter will be added later on in a second step building on the already established sub-models for the former.

In the present contribution the baseline model referred to above is applied to several different configurations commonly encountered in chemical engineering applications, namely bubbly flows in pipes, bubble columns, and airlift columns. Since in all of these systems the small scales are governed by the same physics it is expected that they can be treated in a unified manner using the same set of closure relations. By comparison of simulation results to experimental data taken from the literature this is shown to be the case within a certain accuracy and the model is validated for all of these configurations.

In this way a starting point for the prediction of flow phenomena is obtained. Expanding the range of applicability as well as the achieved accuracy is a continuously ongoing development effort. From the observed level of agreement between simulation and experiment issues requiring further investigation can be identified. This includes both the need for further model development and the need for CFD-grade experimental investigations.

2. Description of the baseline model

The conservation equations of the Euler–Euler two-fluid model have been discussed at length in a number of books (e.g. Drew and Passman, 1998; Yeoh and Tu, 2010; Ishii and Hibiki, 2011), while the extension to treat multiple bubble size and velocity classes (inhomogeneous MUSIG model) have been presented in several research papers (e.g. Frank et al., 2008; Krepper et al., 2008). A broad consensus has been reached, so this general framework will not be repeated here. Closure relations required to complete the model, in contrast, are still subject to considerable variation between researchers. Here, the baseline model that has emerged from previous work (Rzehak et al., 2012; Rzehak and Krepper, 2013a,b; Ziegenhein et al., 2015; Rzehak and Krepper, 2015; Liao et al., 2016) is adopted. This model has been validated for a number of different test cases including bubbly flow in pipes and bubble columns. Details of the model are given in Section 2.1 for the bubble forces and in Section 2.2 for bubble-induced turbulence.

2.1. Bubble forces

Concerning momentum exchange between liquid and gas phase we consider drag, virtual mass, lift, wall, and turbulent dispersion forces. The correlations are expressed in terms of the dimensionless numbers, namely the Reynolds number $Re=|\mathbf{u}_G-\mathbf{u}_L|d_B\nu_L^{-1}$, the Eötvös number $Eo=(\rho_L-\rho_G)gd_B^2\sigma^{-1}$, and the Morton number $\mathrm{Mo}=(\rho_L-\rho_G)\rho_L^2 g\nu_L^4\sigma^{-3}$.

2.1.1. Drag force

The drag force reflects the resistance opposing bubble motion relative to the surrounding liquid. The corresponding gas-phase