Computers and Chemical Engineering 90 (2016) 151–160

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Application of N-phase algebraic slip model and direct quadrature method of moments to the simulation of air-water flow in vertical risers and bubble column reactor

K. Swiderski[a,b,*], C. Narayanan[a], D. Lakehal[a]

[a] ASCOMP AG, Technoparkstrasse 1, 8005 Zurich, Switzerland
[b] Institute of Fluid Dynamics, D-MAVT, ETH Zurich, Switzerland

A R T I C L E I N F O

Article history:
Received 25 September 2015
Received in revised form 14 April 2016
Accepted 16 April 2016
Available online 25 April 2016

Keywords:
DQMOM
Multiphase flow
Algebraic slip model
Population balance
Bubble column
Pipe flow

A B S T R A C T

In the present work the Direct Quadrature Method of Moments (DQMOM) has been implemented into the commercial CFD code TransAT. DQMOM has recently become a very attractive approach for solving population balance equation (PBE) due to its capability of representing the most interesting properties of the population, eg. Sauter mean diameter, void fraction, number of particles. The DQMOM technique was coupled with the turbulent N-phase Algebraic Slip Model (ASM) model in order to extend the model to handle dispersed phase populations such that each class has its own velocity field. The results compared to experimental data show that the developed numerical model accurately predicts void fraction profile in a long riser within a bubbly flow regime. Moreover the model is used for the simulation of bubble column, proving that it accurately predicts the gas hold up and the Sauter mean diameter.

1. Introduction

In many industrial applications and in nature as well, bubbles are dispersed in a liquid continuum. The understanding and the modeling of dispersed flows physics is therefore of high importance for many applications including chemical engineering (bubble columns), water treatment (ozonation and purification), nuclear industry (steam generators, accidental depressurization), naval transport (skin drag reduction) and medicine or biotechnology (contrast agent, micro bubbles bursting, virus replication in cell structures), see e.g. (Latorre, 1997; Yadigaroglu et al., 2008; Hsiao et al., 2010; Ishikawa et al., 2013; Jakobsen, 2014; Dürr et al., 2015).

The dynamics of bubbly flows is very complex in nature. Typically various complex phenomena are present simultaneously, such as bubble collisions and coalescence or breakage. Almost all interactions between bubbles occur in the presence of turbulence or hydrodynamic mixing, which usually dictate their rate. Under such conditions, the assumption of constant bubble size may lead to incorrect predictions of gas-liquid multiphase flow behavior. The evolution and creation of bubbles of different sizes require the representation of the particle size distribution. This is typically achieved by the Population Balance Models (PBM) (Ramkrishna and Mahoney, 2002), where the statistical distribution of the dispersed phase can be tracked. The N-phase model with algebraic slip between phases (Manninen et al., 1996) as implemented in TransAT (Lakehal et al., 2013) needs to be extended in this regard. Since the N-phase model solves for the volume fraction of each phase, a natural way to extend it would be direct discretization of the distribution into a number of size bins with birth and death terms accounting for processes such as breakup, coalescence, growth, etc. (Frank et al., 2005; Yeoh et al., 2012; Krepper et al., 2008).

Among the other available PBM methods, such as the Method of Moments (MOM), Quadrature Method of Moments (QMOM) and their different variants (Marchisio and Fox, 2013), DQMOM (Marchisio and Fox, 2005) is chosen in this study. The main reason to not use the direct discretization method is the fact that moment-based methods are more efficient in capturing the distribution function. It has been shown that whereas 12–18 bins were required for the direct discretization method (Sanyal et al., 2005; Selma et al., 2010), equal or more accurate results were obtained with only 6 moments using the QMOM method. However, the QMOM method remains difficult to implement because the moment equations are directly solved, whose closure requires the recreation of the quadrature nodes and weights from the moments in order to

* Corresponding author at: ASCOMP AG, Technoparkstrasse 1, 8005 Zurich, Switzerland.
E-mail address: karols@ethz.ch (K. Swiderski).

http://dx.doi.org/10.1016/j.compchemeng.2016.04.023
0098-1354/

Nomenclature

C_D	Drag force coefficient
C_L	Lift force coefficient
C_{WL}	Wall force coefficient
D	Diffusivity [m^2s^{-1}]
Eo	Eötvös number
N	Total number of phases
N_c	Total number of classes
Pr	Prandtl number
Re	Reynolds number
R	Radius [m]
Sc	Schmidt number
S	Shear rate tensor [s^{-1}]
Y	Mass fraction
$\tilde{a}$	Breakage frequency [$m^{-3}s^{-1}$]
$\tilde{b}$	Daughter size distribution function
d	Diameter [m]
d_{32}	Sauter mean diameter [m]
g	Gravity acceleration [ms^{-2}]
j	Superficial velocity [ms^{-1}]
k	Turbulence kinetic energy [m^2s^{-2}]
k_V	Bubble shape factor
$\vec{n}$	Normal vector
p	Pressure [Pa]
t	Time [s]
u	Velocity coordinate [m/s]
x	Spatial coordinate [m]
y_w	Wall distance [m]

Subscripts:

b	Bubble
c	Class index
d	Dispersed
f	Fluid
i,j,k,l	Vector index
l	Liquid
m	Mixture
t	Turbulent

Superscripts:

d	Drift
m	Mixture
s	Slip
td	Turbulent dispersion

Greek letters:

α	Volume fraction
$\tilde{\beta}$	Coalescence kernel [m^3s^{-1}]
ξ	Abscissa, node [m]
ω	Weight [m^{-3}]
ν	Kinematic viscosity [m^2s^{-1}]
μ	Dynamic viscosity [Pa s]
ρ	Density [kg m^{-3}]
σ	Surface tension [N m^{-1}]
ε	Turbulence dissipation rate [m^2s^{-3}]

close the terms with higher order moments. Also, the velocity field associated with a given moment is difficult to interpret if it depends strongly on the internal coordinate of the population balance equation; as it is typically in case of bubbles of widely different sizes.

DQMOM, on the other hand, directly solves for the nodes and weights of the quadrature approximation instead of the chosen moments, and is therefore easier to implement, still offering good accuracy at acceptable computational effort (Cheung et al., 2013). This is important in the N-phase context wherein the population balance might need to be solved for multiple dispersed phases.

It is worth mentioning that DQMOM was originally developed for homogeneous systems (no spatial gradients of particle size of each class) and its application to inhomogeneous systems poses several challenges. One of the critical issues of DQMOM is the problem of zero weights, which makes it not possible to calculate the dispersed phase size when solving for the weighted abscissa. For practical problems, zero weights (or number density) can occur naturally due to segregation of particles due to the flow or due to condensation of bubbles. Another issue is the condition where two particle classes converge to the same size making one of them redundant. This leads to ill-conditioning of the system. This paper presents the implementation of monovariate DQMOM into TransAT with all the necessary improvements for handling inhomogeneous flows, such as dealing with the ill-conditioning of the system due to the above mentioned phenomena. The method is then successfully applied to the simulation of complex flows such as vertical risers and bubbles columns which are of direct industrial relevance.

2. Mathematical model

In order to describe the dynamics of N-phase flows an Algebraic Slip Model (ASM) extended to N-phases is used in the present work. Within this framework the DQMOM method is used to capture the most important properties of the dispersed phase like bubble size, void fraction or interfacial area. In this study, only the population of one of the phases is represented using DQMOM.

2.1. N-phase algebraic slip model

Multiphase gas-liquid flows can be tackled using either interface tracking methods (ITM) or phase-average models, for both laminar and turbulent flows. Specifically, the Level-Set approach, the phase-field variant and the Volume-of-Fluid methods can be employed as ITM's. In the context of phase-average models, eg. the mixture (homogeneous) approach applied to gas-liquid systems, transport equations are solved for the mixture quantities rather than for the phase-specific quantities, unlike in the two-fluid model. This implies that one mixture momentum equation is solved for the entire flow system, reducing the number of equations to be solved in comparison to the two-fluid model. In many situations however, the model must be employed with a prescribed closure law for the interphase slip velocity and associated stresses. In this case, the model is known as homogeneous ASM.

The N-phase approach is an extension of the homogeneous ASM introduced above, and is invoked in situations involving more than two fluid phases. The N-phase approach could as well be used in the two-fluid flow context. In the homogeneous ASM framework, the N-phase features a modified scheme where mass conservation and energy equations are solved for each phase to better cope with interphase mass transfer, whereas the momentum is solved for the mixture. Further, the model can be used either under its homogeneous form or by adding an algebraic slip velocity to separate the phases.

The N-phase ASM represents multiphase flow in an ensemble averaged sense, where the involved phases move at different or equal velocities under the assumption of equilibrium within short spatial length scales (Manninen et al., 1996). The model also requires that the relaxation time for dispersed phase is short in comparison with changes in the flow, therefore Stokes number «1. This condition is generally met when dispersed phase particles are small or carrier fluid viscosity is high. Thus the model is suitable for modeling rising bubbles in a liquid. The model is given in the