International Journal of Heat and Mass Transfer 115 (2017) 741–752

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Review

Bubble-induced turbulence modeling for vertical bubbly flows

Avinash Vaidheeswaran [a,*], Takashi Hibiki [b]

[a] National Energy Technology Laboratory, 3610 Collins Ferry Rd, Morgantown, WV 26505-2353, United States
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, United States

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 19 August 2017
Accepted 21 August 2017

Keywords:
Bubble-induced turbulence
Two-fluid model
Bubbly flows
LES
RANS

ABSTRACT

Eulerian two-fluid model (TFM) has been the workhorse for several applications involving vertical bubbly flows due to its computational efficiency especially when applied to large-scale systems. The constituent phases are treated as interpenetrating continuous media, and the stress terms are usually modeled using Large Eddy Simulation (LES) and Reynolds Averaged Navier Stokes (RANS) approaches. Turbulence in the liquid phase plays an important role in determining the void fraction distribution. Besides, turbulence parameters are used in the closure models for interfacial terms which would determine heat and mass transfer or species composition in a given system. Hence, it is necessary to model the turbulence field accurately. LES-TFM approach has produced reasonably accurate results, albeit the sub-grid scale modeling of interfacial terms remains to be validated. There is a lack of a universal approach to model turbulent bubbly flows using RANS-TFM, and the research in developing the transport equations and closure terms is extensive. At present, the choice of one model over the other is mostly ad hoc, and a systematic analysis is required to determine their applicability. In the current review, the different BIT models and their applications have been summarized. Further, some of the shortcomings in the existing approaches are identified and recommendations for future work are made based on the analysis.

Contents

1. Introduction

Turbulent bubbly flows are ubiquitous in engineering applications including chemical reactors, bioreactors, nuclear reactors, heat exchangers, and oil and gas pipelines. It is known from the experiments [1–7] that the liquid velocity profiles vary in vertical bubbly two-phase flows depending on the morphology of bubbles and flow conditions. For finely dispersed flows at low superficial gas velocities, the bubbles migrate to the wall [4,8,9] resulting in a steeper velocity gradient in the near-wall region. At higher gas concentrations, as larger bubbles are formed from coalescence, they migrate towards the center, and the velocity profile would resemble that of single phase flows. There is a strong interdependence between void fraction, liquid velocity, and turbulence field, which eventually determine the heat and mass transfer char-

---

* Corresponding author.
E-mail address: avinash.vaidheeswaran@gmail.com (A. Vaidheeswaran).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.075
0017-9310/

Nomenclature

Latin

a_i	interfacial area concentration [$\mathrm{m^{-1}}$]
C_D	coefficient of drag [–]
C_{VM}	coefficient of virtual mass [–]
D_b	bubble diameter [m]
g	acceleration due to gravity [$\mathrm{m\,s^{-2}}$]
I	identity tensor
j	volumetric flux [$\mathrm{m\,s^{-1}}$]
k	turbulence kinetic energy [$\mathrm{m^2\,s^{-2}}$]
M_{2i}^{D}	momentum transfer due to drag [$\mathrm{kg\,m^2\,s^{-2}}$]
M_{2i}^{VM}	momentum transfer due to virtual mass [$\mathrm{kg\,m^2\,s^{-2}}$]
P	rate of turbulence production [$\mathrm{kg\,m^{-1}\,s^{-3}}$]
p	pressure [$\mathrm{N\,m^{-2}}$]
Q	volumetric flow rate [$\mathrm{m^3\,s}$]
r_ρ	density ratio [–]
Re	Reynolds number[–]
S_{ki}	rate of interfacial turbulence kinetic energy production [$\mathrm{kg\,m^{-1}\,s^{-3}}$]
$S_{\varepsilon i}$	rate of interfacial turbulence kinetic energy dissipation [$\mathrm{kg\,m^{-1}\,s^{-3}}$]
u	velocity [$\mathrm{m\,s^{-1}}$]
u^+	non-dimensional velocity [–]
u_*	friction velocity [$\mathrm{m\,s^{-1}}$]
y^+	non-dimensional distance from the wall [–]

Greek

α	volume fraction [–]
ε	turbulence eddy dissipation [$\mathrm{m^2\,s^{-3}}$]
ν	kinematic viscosity [$\mathrm{m^2\,s^{-1}}$]
μ	dynamic viscosity [$\mathrm{kg\,m^{-1}\,s^{-1}}$]
ρ	density [$\mathrm{kg\,m^{-3}}$]
τ	shear stress [$\mathrm{kg\,m^{-1}\,s^{-2}}$]
ω	turbulence eddy dissipation frequency [$\mathrm{s^{-1}}$]

Subscripts

1,l	liquid phase
2,g,b	vapour phase
BI	bubble-induced
D	drag
i	interfacial
r	relative
t	turbulent
VM	virtual mass

Abbreviations

TFM	two-fluid model
BIT	bubble-induced turbulence
CFD	computational fluid dynamics
DES	detached eddy simulation
DNS	direct numerical simulation
IATE	interfacial area transport equation
LES	large-eddy simulation
LNS	limited numerical scales
PANS	partially-averaged Navier-Stokes
RANS	Reynolds-averaged Navier-Stokes
RSM	Reynolds stress model
SAS	scale adaptive simulation
SRS	scale resolving simulation
SST	shear-stress transport

acteristics for systems with phase change, and species composition for chemically reacting flows. Hence, it is important to predict the turbulence field accurately.

Turbulence modeling approaches in single-phase flows can be classified under scale resolving simulation (SRS) (which includes Large Eddy Simulation (LES), Detached Eddy Simulation (DES), and Partially Averaged Navier-Stokes method (PANS)), and Reynolds Averaged Navier-Stokes equations (RANS). Besides DES, there have been some developments in hybrid turbulence modeling approach using Limited Numerical Scales (LNS) method of Batten et al. [10], and Scale Adaptive Simulation (SAS) method of Menter and Egorov [11]. The choice among them is often made depending on the desired resolution and the scale of application. Some of the methodologies have been extended to dispersed bubbly flows as summarized in Table 1. The recently developed approaches including PANS [12], LNS [10], and SAS [11] are primarily restricted to single-phase flows and offer considerable potential for multi-phase flow systems.

Direct Numerical Simulation (DNS) would provide the highest resolution of the flow field around bubbles and has no dependence on modeling. However, the computational cost scales considerably with the Reynolds number, and hence cannot be adopted for industrial scale applications. One of the alternatives is to use Large Eddy Simulation (LES) which is capable of resolving the dynamically significant scales of motion. It is well-suited to handle a wider range of turbulent flows, and is less dependent on modeling compared to Reynolds Averaged Navier-Stokes (RANS) approach. The filtered phasic equations [20] (referred to as LES-TFM henceforth) obtained using first principles are similar to the two-fluid model (TFM) equations obtained by time-averaging [54], volume-averaging [55] or ensemble averaging [56]. It is common to impose a restriction on the filter length scale [57] based on the bubble size while using the LES-TFM, and the recommended value is $\Delta/D_b = 1.5$. Recently, Vaidheeswaran and Lopez de Bertodano [58] have obtained convergent predictions going well below this cut-off limit, which is inevitable when the computational domain imposes restrictions on the grid size. However, filtering of inter-phase momentum transfer terms remains open-ended.

TFM using RANS modeling (referred to as RANS-TFM henceforth) has been the most widely used approach for large scale applications even though it has a greater dependence on closure relations. It is worth pointing out that work including Buwa et al. [59] and Moraveji et al. [60] do not include the interfacial contributions to liquid phase turbulence and consider the single phase k-ε model [39] to be adequate. Even though the results obtained were satisfactory, neglecting BIT does not appear consistent with the physics of vertical bubbly flows.

The objective of the current review is to discuss the development and application of BIT models for vertical bubbly flows. The literature reported in this article is restricted to predicting turbulence in continuous phase. The dispersed phase turbulence is usually neglected since it is observed to scale with the continuous phase turbulence proportional to the density ratio $r_\rho = \rho_2/\rho_1$ ([1–3]), and for gas-liquid flows, $r_\rho \ll 1$. Some of the shortcomings of the existing approaches have been identified and recommendations are provided to improve the state-of-the-art in BIT modeling.

2. BIT modeling strategies

The Eulerian TFM consists of continuity, momentum and energy equations for the constituent phases. The readers may refer to Ishii and Hibiki [9] for details regarding the TFM and constitutive rela-