APT 2046
20 August 2018
ARTICLE IN PRESS
No. of Pages 14, Model 5G

Advanced Powder Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Dynamic two-point fluidization model for gas–solid fluidized beds

Javad Aminian *, Kasra Farnagh

Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, A.C., Tehran, Iran

ARTICLE INFO

Article history:
Received 26 February 2018
Received in revised form 6 August 2018
Accepted 7 August 2018
Available online xxxx

Keywords:
Integrated hydrodynamic model
Fluidization regimes
Two-point switching
Spatiotemporal dynamics
OpenFOAM

ABSTRACT

In real fluidized beds various fluidization regimes may occur simultaneously resulting in quite distinct hydrodynamic characteristics in various regions of the bed. Classical approaches, generally, use a step drag function with a single switching point to distinguish dense and dilute regimes. In the present study, a new integrated hydrodynamic model (drag and viscosity) is developed using a smooth logistic function with two switching points dividing a fluidized bed into three dense, dilute and mixed regimes which is more in accordance with reality. Gas volume fraction at minimum fluidization velocity and particle Geldart's group are employed to decide switching between dense and dilute drag and viscosity models. A spatiotemporal dynamic algorithm is used to implement the integrated model into the open source CFD package OpenFOAM 2.1.1. Reasonable predictions of various hydrodynamic characteristics in three different experimental data sets demonstrate wide applicability of the new integrated hydrodynamic model to any fluidization regime.

1. Introduction

Gas–solid fluidization is a technology used in chemical and physical processes such as drying, mixing and chemical reactions. Enhanced heat and mass transfer in fluidized beds due to high mixing efficiency led to their widespread applications in many industries such as in combustion, gasification, granulation, polymerization and separation. The high mixing efficiency in these systems is directly related to hydrodynamic behavior of fluidization regimes. Therefore, development of accurate models to predict hydrodynamic behavior of fluidized beds and avoiding vital errors in design of bed structures is necessary. Furthermore, reliable modeling results can be used in scale-up processes and help saving time and money [1].

The complex physics of gas–solid fluidized beds embraces sophisticated phenomena such as turbulent mixing, interaction of heat and mass transfer and net production of various species in several chemical systems. To predict this complex behavior, accurate solution of governing equations including the momentum, heat and mass transfer equations with several source terms is essential. Among all, solution of the momentum transfer equation with interphase momentum exchange directly affects species and temperature fields in both dispersed and continuous phases. Therefore, accurate determination of interphase momentum exchange in the momentum conservation equation is the key modeling issue in prediction of gas–solid fluidized bed behavior.

Toward this end, computational fluid dynamics has become an effective and economical tool to investigate hydrodynamic behavior of gas–solid flow systems [2,3]. Researchers have focused on developing and testing new drag_viscosity models and their thermo-physical constitutive relations. Following to the development of computational techniques, attempts on creating more rigorous modeling tools restarted in this era. Broadly speaking, two phase gas–solid flow systems can be modeled using two different approaches namely the Eulerian-Lagrangian discrete particle model (DPM) or in some cases discrete element method (DEM) and the Eulerian-Eulerian two-fluid model (TFM) or in some cases multi fluid model. In both approaches, the gas phase is considered to be a continuous phase and is treated using the conventional Eulerian approach. In the former approach, modeling of dispersed phase is performing via the Lagrangian method by solving Newton's equation of motion for each dispersed particle, considering particle-wall and particle-particle interactions [1]. This approach is more suitable for modeling multi-phase systems with less than 10% dispersed phase volume fraction due to computational costs. In this field, internally circulating fluidized bed (ICFB) and circulating fluidized bed (CFB) are modeled using discrete element method (DEM) coupled with large eddy simulation [4]. A comprehensive investigation of the effect of hydrodynamic and time related physical parameters in a 3-D spouted bed using DEM approach has been performed by Luo et al. [5]. They have investigated time-averaged

* Corresponding author.
E-mail address: j_aminian@sbu.ac.ir (J. Aminian).

https://doi.org/10.1016/j.apt.2018.08.005

Please cite this article in press as: J. Aminian, K. Farnagh, Dynamic two-point fluidization model for gas–solid fluidized beds, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.08.005

Nomenclature

A	Syamlal's model constant-Geldart group
Ar	Archemedes number
B	Syamlal's model constant-Geldart group
C_K	displacement parameter of logistic curve for momentum exchange coefficient
C_μ	displacement parameter of logistic curve for viscosity model coefficient
C_D	drag coefficient
d	particle diameter
e	restitution coefficient
F	logistic curve function
g	gravity acceleration
g_{0s}	radial distribution function (RDF)
H	bed height
H_0	static bed height
I	identity tensor
$K_{1,2}$	constants of force balance equation
K	momentum exchange coefficient
M_K	slope parameter of logistic curve for momentum exchange coefficient
M_μ	slope parameter of logistic curve for viscosity model coefficient
R	characteristic length scale (viscosity model)
S	half of strain rate tensor
t	time
U	inflow velocity
u_s, u_g, u_{cell}	superficial velocity
W	bed width
P	pressure

Greek letters

ρ	density
ε	volume fraction
$\in$	dissipation rate of turbulent kinetic energy
τ	stress tensor
μ	shear viscosity
∇	gradient
$\nabla.$	divergence
θ	granular temperature
$\varnothing$	sphericity coefficient

Subscripts

c	critical
g	gas phase
r	relative terminal
S	solid phase
mfp	mean free path
m	multi-particle
mf	minimum fluidization
sg	solid to gas phase exchange
ts	terminal and single particle
tm	terminal and multi-particle

Superscripts

f	frictional part
T	transpose of matrix
kc	kinetic and collisional part

Abbreviation

CFD	computational fluid dynamic
CVM	constant viscosity model
DPM	discrete particle model
DEM	distinct element method
KTGF	kinetic theory of granular flow
TFM	two fluid model

flow characteristics and the particle-scale details related to solid motion for a 3-D CFB elsewhere [6]. In the TFM approach, however, the dispersed phase is treated as a continuum which can penetrate into the continuous phase. In the both aforementioned approaches the kinetic theory of granular flows (KTGF), which is based on similarities between the flow of a granular material and gas molecules has employed to apply the inter-particle interactions [7]. The KTGF theory showed reasonable capability on predicting main features of the complex gas–solid fluidized beds [8].

One of the main source terms of the momentum conservation equation is the drag force which contains interphase momentum exchange coefficient (K_{gs}). This parameter has a significant effect on hydrodynamic modeling throughout the bed. The other important term in gas–solid momentum equations is the viscous stress tensor of solid phase which contains solid viscosity (μ_s). Plenty of classical correlations have been proposed for calculation of momentum exchange coefficients such as the Ergun [9], We-Yu [10], Gidaspow [11] and Syamlal-O'Brien [12] drag models as well as for solid viscosity such as the Gidaspow [11] and Sinclair [13] viscosity models.

To model dense fluidization regime, usually the Ergun part of the Gidaspow drag equation is used to estimate the hydrodynamic parameters. For dilute fluidized beds, however, Wen and Yu developed a drag model which was suitable for gas volume fraction (ε_g) larger than 0.8 [10]. Syamlal and O'Brien have extended the Wen-Yu approach to a more general expression applicable to a wider range of gas volume fractions [12]. The Gidaspow drag model [11] is a combination of Ergun and Wen-Yu drag models via a constant switching point of $\varepsilon_g = 0.8$. In a systematic study it was shown that proper choice of a viscosity model for a specific drag model has a great impact on the predicting hydrodynamic characteristics of different fluidization regimes [14]. In particular, for dense and dilute fluidization regimes, the Gidaspow [15] and Sinclair [16] viscosity models have been prescribed, respectively.

According to Fig. 1 gas–solid fluidized systems can be divided into four fluidization regimes based on the competition between inlet gas velocity and the minimum fluidization velocity (the gas velocity at which fluidization begins). If the inflow gas velocity (u_g) is much lower than the minimum fluidization velocity (U_{mf}), dense or packed bed regime can be established. When the inlet gas flows at a higher rate than required for minimum fluidization, a suspension of solids and bubbles appears and acts like a fluid (bubbling bed). If fluid velocity increases still further, then turbulent motion of particle clusters of various sizes and shapes can be observed [1]. In the turbulent regime, when the voids break up at the top surface, solid particles are thrown into the free board dilute region. When gas flow velocity increases even further, solid volume fraction decreases significantly and dilute region recognizes almost throughout the bed.

It has been shown that different fluidization regimes show quite distinct hydrodynamic characteristics through a single fluidized bed. According to Fig. 1, the turbulent fluidization regime which is the most common fluidization regime in industrial gas–solid fluidized beds is a chaotic combination of solid clustering, bubbling, slugging and dilute regimes. In other words, physical behavior of fluidized systems is somehow that various regimes with different

Please cite this article in press as: J. Aminian, K. Farnagh, Dynamic two-point fluidization model for gas–solid fluidized beds, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.08.005