Chemical Engineering Science 170 (2017) 139–153

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Settling/rising of a foreign particle in solid-liquid fluidized beds: Application of dynamic mesh technique

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HIGHLIGHTS

- Performed CFD simulations of solid liquid fluidised bed using Euler-Euler approach.
- Used dynamic mesh for simulating the foreign particle motion.
- 3D simulations predicted the settling/rising velocity better than 2D simulations.
- Discussed the turbulence interactions of particles/bubble with liquid bubbles.

ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 26 January 2017
Accepted 30 January 2017
Available online 4 February 2017

Keywords:
Fluidization
Moving object
Settling
Rising bubble
Classification velocity
Dynamic mesh

ABSTRACT

The modeling of moving objects has been the focus of many studies and has succeeded to attract sufficient attention by researchers. However, commonly used modeling approaches such as discrete element modeling (DEM), direct numerical simulations (DNS) lack simplicity and have been computationally intensive. In the present work, simple method of dynamic mesh in the framework of computational fluid dynamics has been employed. Eulerian-Eulerian simulations of a monodisperse solid-liquid fluidized bed (SLFB) have been carried out. A foreign particle (settling particle or rising bubble) was inserted in the system to study the effect of turbulence in SLFB on the motion of settling particle. The operating and geometrical parameters have been chosen based on the experiments performed by Ghatage et al. (2013). The results showed that the model can satisfactorily predict the settling velocity for low voidage fluidization in 2D as well as 3D simulations. Computational fluid dynamics (CFD) simulations at higher values of superficial liquid velocity showed liquid bubbles confirming the transition to heterogeneous regime. These liquid bubbles directed the settling particle to move zig-zag resulting in lower settling velocity. The size and number of the bubbles increase with an increase in the liquids velocity indicating increased heterogeneity. However, CFD predicted larger and higher number of bubbles than experimentally noted. This resulted in an increase in the deviation of predicted settling velocities from experimentally observed with an increase in superficial liquid velocity. In case of bubbles, it was observed that the dynamic mesh method is greatly dependent on the regime of operation in the column and works only in the range of low voidage when the fluidized bed is homogeneous and does not contain liquid bubbles.

1. Introduction

Fluidized beds are widely used in chemical, petrochemical and allied industries. They provide efficient contact between fluid and solid phases and, hence, are preferred for carrying out various gas-solid, liquid-solid and gas-liquid-solid processes. One of the key parameters which affect the equipment performance is relative velocity or classification velocity of one phase with respect to another when the fluidized particles are characterized by wide range of terminal velocities. In the design of such multiphase fluidized beds, it is important to understand the phase distributions as well as motion of the various phases relative to one other.

In the published literature, many researchers have characterized the turbulence in multi-particle systems. Joshi (1983), Grbavcic and Vukovic (1991), Grbavcic et al. (1992, 2009), Van

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http://dx.doi.org/10.1016/j.ces.2017.01.064

Nomenclature

C_D	drag coefficient, –
$C_{D\infty}$	drag coefficient in infinite medium, –
C_V	virtual mass coefficient, –
d_B	bubble diameter, m
d_P	diameter of particle comprising fluidized bed, m
d_{PD}	diameter of foreign particle, m
D	column diameter, m
e_{SS}	solid-solid interaction restitution coefficient, –
e_{WS}	solid-wall interaction restitution coefficient, –
F_z	interphase force, N/m^3
g	gravitational acceleration, m/s^2
H	column height, m
k	turbulent kinetic energy, m^2/s^2
K	wall correction factor, –
l	characteristic turbulence lengthscale, m
L	length, m
n	Richardson-Zaki index, –
P	pressure, N/m^2
R	radial co-ordinate in 3D simulations, $\sqrt{(X)^2+(Y)^2}$, m
Re	liquid Reynolds number, $DV_L\rho_L/\mu_L$, –
$Re_{B\infty}$	Reynolds number based up on the terminal settling velocity of the particle, $d_BV_{B\infty}\rho_L/\mu_L$ –
Re_P	particle Reynolds number, $d_PV_R\rho_L/\mu_L$, –
$Re_{P\infty}$	Reynolds number based up on the terminal settling velocity of the particle, $d_PV_{S\infty}\rho_L/\mu_L$ –
St	Stokes number, $St=\frac{[(\rho_P/\rho_L)+C_V]}{[(3/4)(C_{D\infty}/d_P)V_{S\infty}]}\frac{u'_r}{\ell}$, –
u	superficial velocity, m/s
U_{mf}	minimum fluidization velocity, m/s
u_r'	rms turbulent velocity in radial direction, m
v_P	volume of particle, m^3

V_L	superficial liquid velocity, m/s
V_R	classification velocity, m/s
V_{SD}	interstitial fluidization velocity for dense particle, m/s
V_{SDW}	bounded settling velocity for dense particle, m/s
V_{SW}	bounded settling velocity of fluidizing particle, m/s
$V_{S\infty}$	terminal velocity of particle, m/s
$V_{SD\infty}$	terminal settling velocity of heavy particle, m/s
X, Y	radial and axial co-ordinates respectively in 2D simulations, m
X, Y, Z	two radial and an axial co-ordinates respectively in 3D simulations, m

Greek letters

ε	turbulent dissipation rate, m^2/s^3
$\in$	fractional phase hold-up, –
$\epsilon_{L,\max}$	packing limit, –
ΔP	pressure drop, Pa
μ	viscosity of fluid, kg/ms
ρ	density, kg/m^3
τ	viscous stress tensor, N/m^2

Subscripts

B	bubble
D	dense particle
L	liquid
M	mixture
P	particle
S	solid
∞	infinite medium

der Wielen et al. (1996) have all studied the effect of turbulence on the settling velocity of a foreign particle in presence of monosized fluidized particles. Most of these studies are experimental and/or theoretical. Vos et al. (1990) measured classification velocity of foreign particle in fluidized bed of transparent particles using visualization technique. Authors used fluidized particles composed of gelatin which had a somewhat brownish but transparent appearance. Di Felice et al. (1991) have proposed a pseudo-fluid model for predicting the settling velocity of a large dense particle in a fluidized bed. The pseudo-fluid model considered a foreign particle settling in a pseudo-fluid consisting of fluid and small fluidized particles. Grbavcic et al. (1992) measured the effective buoyancy and drag for foreign large particles of varying density, settling/rising in a bed of small fluidized particles. Authors considered gravity, drag and buoyancy as the forces applied on the foreign particle. Van der Wielen et al. (1996) proposed a correlation for predicting hindered settling velocity based on mixture density, fluid density, foreign particle density, terminal settling velocity and Richardson-Zaki index of the foreign particle as:

$$\frac{V_{SD}}{V_{SD\infty}}=\left(\frac{\rho_{PD}-\rho_M}{\rho_{PD}-\rho_L}\right)^{n/4.8}\in_L^{0.79n-1} \tag{1}$$

Authors observed that the predictions of the correlation were in good agreement with the pseudo-fluid model proposed by Di Felice et al. (1991). Investigations have also been carried out for developing the relationship between the turbulence in multi-particle and the drag on a single introduced foreign particle (heavy particle/light bubble). However, these relationships have been largely empirical. Ghatage et al. (2013) have analyzed and reviewed the correlations. Authors discussed that the settling velocity of foreign particle decreases with increase in the superficial liquid velocity in SLFB. They observed classification velocities up to 20 percent of that of terminal settling velocity in quiescent liquid.

The hydrodynamics of the fluidized bed is generally modeled using two distinct approaches. The first is the most commonly applied Eulerian-Eulerian approach which is based on the continuum hypothesis, where motion for each phase is represented by the equations of continuity and motion for each phase. Another approach is the Eulerian-Langrangian approach, wherein the discrete element model (DEM) is capable of tracking every individual particle in the fluidized bed and computational fluid dynamics (CFD) model is used to simulate the flow field of the continuous fluid phase.

Computational studies on the settling/rising of foreign particles in SLFBs are scarce. Hu et al. (2001) used an arbitrary Langrangian-Eulerian (ALE) moving, unstructured mesh to study the movement of particles using the finite element method (FEM). The fluid flow and particle positions were updated explicitly; whereas particle motion was defined implicitly at each time step. The predicted sedimentation velocities of a particle in a pipe were found to be in excellent agreement with the experimental measurements. However, the study was computationally very intensive even for the case of pipe flow with no neighboring particles. Munster et al. (2012a,b) investigated the terminal settling velocity of a single particle in a fluid using FEM with fictitious boundary method (FBM). The adaptive aligning of the grid deformation allowed the tracking of particle motion through the fluid. They observed 10% deviation with experimental values of terminal settling velocity. Munster et al. (2012a,b) predicted the terminal settling velocity of dense and larger particle (d_P = 15 mm) in a fluid using FEM with fictitious boundary method (FBM) and the predictions were within 1%