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CFD-DEM STUDY OF THE GAS-SOLIDS FLOWS IN A FLUIDIZED BED WITH AN IMMERSED CYLINDER: COMPARISON OF PSEUDO-2D AND 3D MODELS

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ABSTRACT

In this work, a numerical study of the gas-solids flow in a 3D gas-fluidized bed with an immersed horizontal cylinder is performed using the combined computational fluid dynamics (CFD) and discrete element method (DEM). In order to investigate the wall effect, a sensitivity study of bed thickness is performed first to obtain the critical bed thickness at which the bed can be regarded as 3D. Then pseudo-2D and 3D flow characteristics are compared at the same gas inlet velocity. The effect of different structures on heat transfer between bed and an immersed cylinder is examined by comparing the values of heat transfer coefficients. The differences of the flow structure between pseudo-2D and 3D are reproduced and may be due to wall frictions and three dimensional affects. The wall shear stress in pseudo 2D is larger than that in 3D and results in larger pressure drop. Furthermore, the contribution of drag forces in bed thickness-direction to the total drag force is very small in pseudo-2D compared to in 3D. These differences of solids flow patterns result in difference heat transfer coefficient between bed and immersed cylinder.

Keywords: Gas-solids flow, computational fluid dynamics, discrete element method, bed thickness, three dimensional, and two dimensional.

INTRODUCTION

Bubbling Fluidized Beds are widely used many years in chemical and industrial processes due to their performances as characterized by good solid mixing, high efficiency of heat transfer, and fast chemical reaction. Moreover, their applications as heat treating furnaces become increasing popular in recent years as an alternative to other environmentally hazardous processes using oils, molten salts, and molten leads.

The heat transfer between bed and immersed surface is the most important process in heat treatment process. It is generally accepted that the relatively high heat transfer is the result of scrubbing action or contact of solids with the heat transfer surface. These actions depend heavily on hydrodynamics process in fluidized bed system. As a consequence, an accurate characterization of the heat transfer can be made only when the hydrodynamics and underlying mechanisms of the transport are well understood.

Previous experimental studies of hydrodynamics in fluidized bed with immersed surface frequently used pseudo-2D (thin bed thickness) for following reasons: (i) saving construction cost and (ii) making direct observation of flow structures and measurement easier. However, the use of pseudo-2D experimental fluidized bed might not exhibit proper three dimensional affects. Peeler and Whitehead (1982) briefly reviewed and concluded that there are quite different behaviours of the region of gas-solids flows near cylinder between pseudo-2D and 3D fluidized bed.

Information of macroscopic flow around tube is very useful to assess the bulk behaviors of gas and solid flows around tube. However, information of microscopic flow such as local density and frequency of solids-cylinder contact, particle and gas velocity around tube or cylinder are difficult to obtain using photographical and other conventional experimental method. In recent years, numerical methods have been developed to overcome this difficulty. This is mainly achieved by combining computational fluid dynamic (CFD) and discrete element method (DEM) or often called CFD-DEM approach (Tsuji et al., 1993; Xu and Yu, 1997).

Due to expensive computational cost, most of previous simulations using CFD-DEM approach for this system were conducted using 2D model (2D CFD – 2D or 3D DEM models) (See Rong et al., 1999; Zhao et al., 2008; 2009; Hou et al., 2010). Nonetheless, this does not fully represent the reality because the fluid and solids motions as well as particle-fluid interactions are naturally 3D, particularly with the presence of immersed surfaces.

This work aims to develop 3D CFD-DEM model for fluidized bed with an immersed cylinder and to understand the underlying mechanisms of different gas-solids structures between pseudo-2D and 3D fluidized bed. Due to wall effects, a sensitivity study of bed thickness is performed first to obtain the critical bed thickness at which the bed can be regarded as 3D. Then pseudo-2D and 3D flow characteristics are compared and analyzed. The effect of different structures on heat transfer between bed and an immersed cylinder is then examined by comparing the values of heat transfer coefficients between cylinder and bed.

MODEL DESCRIPTION

The CFD–DEM developed at our lab has been well documented in the literature (Xu and Yu, 1997; Zhu et al., 2007). Chu and Yu (2008); Chu et al. (2011) have extended the CFD-DEM code by using Fluent, a commercial CFD software package, as a platform and incorporating a DEM code into Fluent through its User Defined Functions (UDF). This approach has been successfully used in the recent studies of various complicated fluid-solid flow system.

Zhou et al. (2009) have extended CFD-DEM approach by taking into account a comprehensive model of heat transfer mechanisms to study the heat transfer in packed and fluidized beds. To reduce the computational cost that is inherent in their proposed model, they developed a new computational method by introducing a correction coefficient as the function of Young's modulus used in DEM (Zhou et al., 2010). They demonstrated that this extended CFD-DEM approach can be a useful tool to study the coupled gas-solids flow and heat transfer in fluidized beds and is used in this work.

The bed should be wide enough for structures to freely evolve and grow across the bed. Rectangular bed geometry is applied in the simulation. The bed width (y-direction) and height (z-direction) are 120 and 640 mm respectively while the depth (x-direction) varies as 15, 25, 40, 60, and 80 mm. The inlet-cylinder clearance is 90 mm. To save computational time, coarse particle with diameter of 2.5 mm is used. Other simulation conditions are summarized in Table 1. The simulation is started with the random generation of particles without particle overlaps

Table 1. Operational parameters used in the simulations

Solid phase	
Initial bed height	114 mm
Particle density	2600 kg/m^3
Rolling friction coef.	0.005 mm
Sliding friction coef.	0.3
Damping friction coef	0.15
Poisson's ratio	0.3
Young's Modulus	1 x 10^7 N/m^2
Initial temperature	298 K
Specific heat capacity	830 J/(kg.K)
Thermal conductivity	18.9 W/(m.K)
Time step	5 x 10^{-6}
Gas phase	
Gas density	1.225 kg/m^3
Gas viscosity	1.8 x 10^{-5} kg/m s
CFD cell type	Unstructured Hexahedral
Initial temp.	298 K
Specific heat capacity	1006.43 J/(kg.K)
Thermal conductivity	0.0242 W/(m.K)
Time step	5 x 10^{-5}

from the bed top, followed by gravitational settling process for 0.6 s. Then gas is imposed uniformly at the bottom to fluidize the bed at superficial velocity of 1.723 m/s. Outflow condition is applied at the top while the bed and cylinder walls are set to no slip condition. Cylinder temperature keeps constant at 373 K and walls are treated as adiabatic. Simulation time is set to 5 s. Unless otherwise specified, all the time-averaged properties are taken from 2.4 - 5 s.

RESULTS

In this part, it is shown that the flow features from simulation results qualitatively agree with those from experimental observation. Four distinct stages of bubble transit past the cylinder (Peeler & Whitehead, 1981) are reproduced using pseudo-2D model as shown in Fig.1: (a) dense phase movement preceding bubble arrival, (b) bubbles approaches to the cylinder, (c) bubble envelopes the cylinder and (d) bubble departure and reappearance. The expansion of the envelope around the cylinder shows that gas pass from the bubble to the envelope before the bubble itself make contact with the cylinder (Fig. 1b). The same description has been reported by Clift et al. (1993).

Three flow regimes around cylinder (Glass & Harrison, 1964) are also reproduced: (i) void formation on the upstream of the cylinder (Fig. 1b and 1c), (ii) defluidized region at the downstream of the cylinder (Fig. 1c & 1d), and (iii) small bubble chain formation at the end of cylinder horizontal diameter (Fig. 1b).

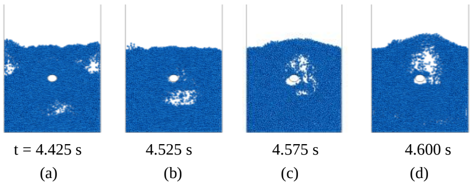


Figure 1: Snapshot of bubble transit past the cylinder

In order to find critical bed thickness, sensitivity of bed thickness is examined using some parameters at bed scale (pressure drop and bed height), bed averaging (mean specific kinetic energy of particle) and micro scale (particle-cylinder contact density) as criterions. Bed height is calculated as average height of particles whose positions are at the top of the bed. Particle contact density is defined as the number of particles in contact with cylinder per square cm of circumferential area of cylinder.

Fig. 2 shows the relationship of pressure drop, bed height, and mean particle specific kinetic energy for different bed thickness. High pressure drop corresponds to thin bed thickness (Fig. 2a). It may due to wall friction effect. There are no significant differences of pressure drop for bed thickness of 40, 60, and 80 mm. The inconsistent trend of pressure drop toward bed thickness was also reported by Kathuria & Saxena (1987). Bed height reaches maximum at 40 mm bed thickness then decreases slightly until constant for bed thickness larger than 60 mm (Fig. 2b). Fig. 2c shows that particle kinetic energy increases with the increase of bed thickness and is constant when the bed thickness is larger than 60 mm. The averaged PCD decreases steeply from 15 mm to 25 mm bed thickness then decreases slightly from 25 to 60 mm (Fig. 2d). No significant change of averaged PCD is observed for bed thickness larger than 60 mm.

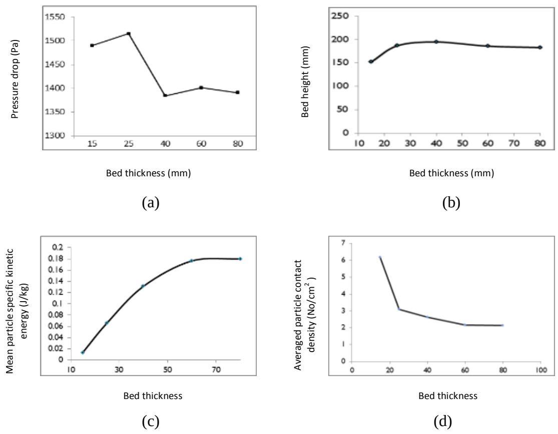
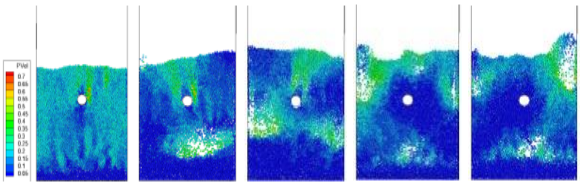


Figure 2: Sensitivity of (a) pressure drop, (b) bed height, (c) particle kinetic energy, and (d) particle-cylinder contact density on bed thickness

It can be seen from Fig. 2 that the change of parameter values is less sensitive for bed thickness larger than 60 mm. Hence, it can be concluded that under simulation conditions, the bed thickness of 60 mm can be considered as critical bed thickness for 3D bed. Bed thickness of 15 or lower is considered as pseudo-2D. Bed thickness of 25 and 40 mm can be regarded as transition from pseudo-2D to 3D bed. From experimental observation of freely fluidized bed, Wu et al (1999) suggested that for spherical particle, a 20 mm-bed thickness is adequate to neglecting wall (bounding) effect as long as the ratio of bed thickness to particle diameter is greater than 7. However, with the presence of tube or cylinder, a 20 mm front-rear wall separation is inadequate to describe the three dimensional nature of the bed. A larger distance is required to reduce the effect of high particle concentration at the ends of cylinder (near front and rear wall).

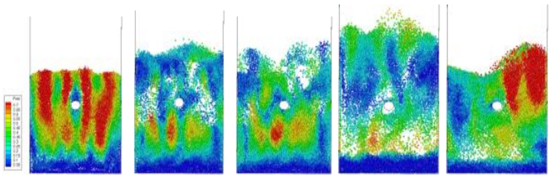
Fig. 3 and Fig. 4 respectively describe the solids flow pattern for pseudo-2D (bed thickness = 15 mm) and 3D (bed thickness = 60 mm) bed at macroscopically steady state. Unlike pseudo-2D, the flow structures for 3D cannot be seen clearly from front view. To be comparable, the 3D solids flow structure shown here is taken at the center volume of the bed with thickness of 15 mm (equal to bed thickness of pseudo-2D model). This depth is chosen to



t = 0.05 s　1.05 s　1.38 s　1.50 s　4.90 s

Figure 3: Solids flow patterns for pseudo-2D model

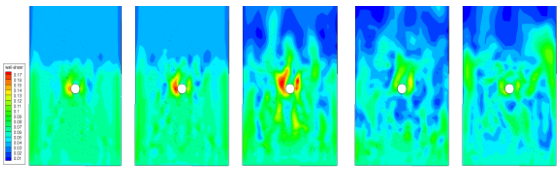
make sure that the front and rear wall effects can be neglected and only 3D behaviors are represented. The solids flow structures in pseudo-2D bed is macroscopically more stable than 3D bed (Fig. 3). After 1.5 s the bubble is generated at the center and move periodically. The bubbles also periodically appear and move near left and right walls. On the other hand, no periodic flow pattern is observed in 3D bed (Fig. 4). The appearances of gas void at upstream and defluidized cap at downstream in 3D bed are not as often as in pseudo-2D. It is shown in these figures that in general the particle velocity in 3D bed is much larger than that in pseudo-2D.



t = 0.05 s　0.90 s　1.38 s　2.30 s　4.90 s

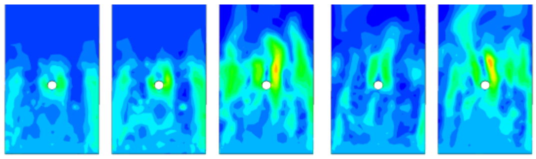
Figure 4: Solids flow patterns for 3D model

The differences of the solids flow patterns between pseudo-2D and 3D may due to wall frictions and three dimensional affects. The wall shear stress in pseudo 2D is larger than that in 3D and results in larger pressure drop (See Fig.5 and Fig. 6).



t = 0.003 s　0.005 s　0.050 s　1.380 s　4.900 s

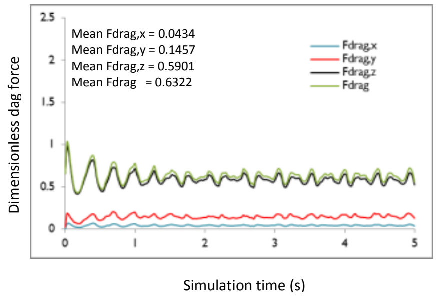
Figure 5: Wall shear stress for pseudo-2D model



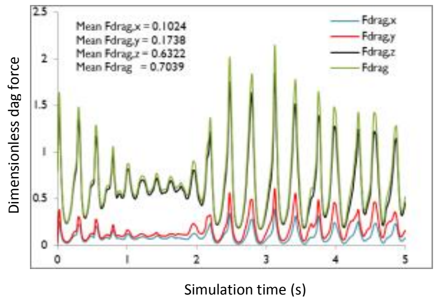
t = 0.003 s　0.005 s　0.050 s　1.380 s　4.900 s

Figure 6: Wall shear stress for 3D model

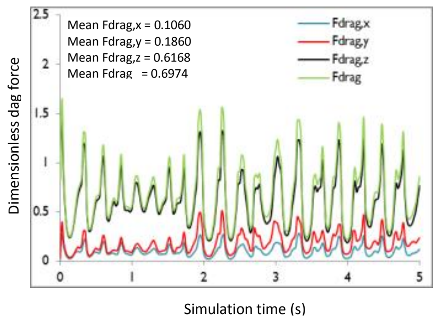
Furthermore, the contribution of drag forces in bed thickness-direction to the total drag force is very small in pseudo-2D compared to in 3D (see Fig. 7). Dimensionless drag force is defined as ratio of drag force and gravitational force. Accordingly, the gas and particle motions are almost two dimensional. On contrary, in 3D bed, the drag forces in bed thickness direction have significant contribution to generate the three dimensional motions of gas and particle motions. Therefore, it can be understood that in pseudo-2D bed, the macroscopic solids flow structures are more stable. In addition, the bubble formation and motions can be observed clearer than those in 3D bed.



(a)



(b)



(c)

Figure 7: Evolution of drag force for (a) pseudo-2D, (b) transition (bed thickness = 40 mm), and (c) 3D

Fig. 8 shows the time series (for three seconds simulation) of heat transfer coefficients (HTC) between bed and cylinder for bed thickness of 15 mm (pseudo-2D), 40 mm (transition), and 60 mm (3D). It is obvious from this figure that there is significant difference of HTC amplitudes between pseudo-2D and 3D models due to different flow structures. The average HTC in pseudo-2D bed is larger than in 3D due to more frequent contacts of

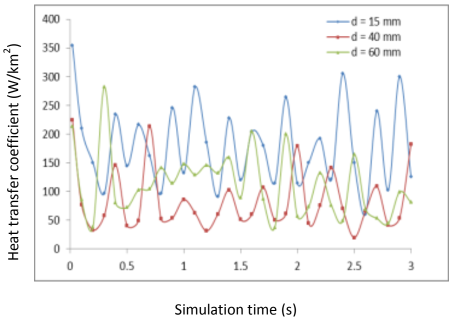


Figure 8: Evolution of heat transfer coefficients for different bed thicknesses

particle and cylinder in pseudo-2D bed (See Fig. 2d). At macroscopically steady state (after 2 s), no significant difference of HTC amplitude between transition and 3D models is observed.

CONCLUSIONS

It is found that under current simulation conditions, the critical bed thickness is 60 mm at which the wall effects can be neglected and the motions of gas and particle can be regarded as three dimensional. The model successfully captures the key flow features around cylinder in gas- fluidized bed, i.e. the defluidized cap region at cylinder downstream, gas cushion formation at cylinder upstream and small bubble chain formation at the right or left side of cylinder. The particle-gas interactions i.e. drag force and pressure gradient force play significant role in governing the flow structures in such this system, particularly for bubble formation and bubble motion. In pseudo-2D bed (bed thickness less than 15 mm), the bubble formation and motion are very obvious and clear to be observed from front view. The gas and particle motions are mostly in two dimensional directions due to small drag force in one direction. On contrary, the bubble formation and motions is not clearly observed in 3D bed. The flow structures are not as stable as those of pseudo-2D due to the six degree of freedom of gas and particle interactions. To sum up, the different flow structures between pseudo-2D and 3D beds are dominantly affected by wall frictions and the three dimensional interactions between gas and particles.

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