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

Analysis of particle rotation in fluidized bed by use of discrete particle model

Run-Jia Liu [a,b], Rui Xiao [a,*], Mao Ye [b,*], Zhongmin Liu [b]

[a] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, College of Energy and Environmental Engineering, Southeast University, Nanjing 210096, China
[b] National Engineering Laboratory for MTO, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China

ARTICLE INFO

Article history:
Received 3 November 2017
Received in revised form 11 March 2018
Accepted 31 March 2018
Available online xxxx

Keywords:
Fluidized bed
DPM
Magnus lift force

ABSTRACT

The particle rotation was found important in the fluidized bed when the heterogeneous structures appeared. Some researches show that Magnus lift force might play an pivotal role in fluid-solid system, especially when the particles have fast rotation speed. As the Magnus lift force is acted at the single particle level, a pseudo two-dimensional discrete particle model (DPM) was used to investigate the influence of Magnus lift force in fluidized bed. The rotational Reynolds number (Re_r) bases on the angular velocity and the diameter of the spheres is used to characterize the rotational movement of particles. We studied the influence of Magnus lift force for particles with rotational Reynolds number in the range of 1–100. Our results show that the influence of Magnus lift force is enhanced with a higher Re_r. Magnus lift force affects the movement of particles in both radial and axial directions while Re_r is high. However, in low Re_r case it can be neglected in computational simulation model. This indicates the introduction of Magnus lift force may improve the discrete particle model only in high Re_r case and Magnus effect should be considered in real gas-solid two phase system when the particle rotational speed is high.

1. Introduction

Recent years have seen a rapid growth of interests in detailed particles motion in a wide variety of natural and industrial processes. Particle motion possesses significant influence on the hydrodynamics in these processes. For example, in industrial fluidized beds such as circulating fluidized bed (CFB) risers, the particles experience not only translational but also rotational motion due to the frequent particle-particle collisions and the relative velocity between solids and the surrounding airflow [1]. Particle rotation appears to have effect on the linearity of the motion and may play a part in the mechanism of particle entrainment in conveyed solid-gas system [2].

Some experimental methods was used to track particle rotation and analyzed relevant influence factors such as particle size, average particle collision velocity, particle collision rate and particle number density [3]. Other researchers tried to obtain the angular velocity by use of the digital imaging method. For example, with a high-speed digital camera system, Wu et al. [3,4] measured the averaged particles rotational velocity in a cold CFB riser. They found the mean rotational velocity for particles with a density of 2400–2600 kg/m^3 and size of 0.5 mm was about 300 rev/s whilst the highest rotational velocity could be up to 2000 rev/s. The study on particle rotation, however, still presents a big challenge since the direct measurement of particle angular velocity is, if not impossible, extremely hard.

Relatively more contributions have been made to numerical study of particle in solid-gas two-phase flows [5]. In the interesting work by Kajishima et al. [6], they found that, due to the reverse direction of lift force in the shear flows, the irrotational particles could be easily absorbed into clusters but rotational ones might escape. Similar conclusion can be found by Wang et al. [7] who argue that particle rotation reduce the cluster size. Sun et al. [8] found that the multi-fluid model taking the particle rotation into account could better capture the bubble dynamics and time-averaged bed behavior in fluidized bed. Despite the significance of particle rotation in solid-gas two-phase flows found in the aforementioned studies, much are yet to be understood on how the particle rotation affects hydrodynamics.

It is widely accepted that the rotational particles experience a Magnus lift force, which is perpendicular to the plane constituted by particle translational and rotating velocities. The Magnus lift force was first discovered by Newton in 1671 [9], and the Magnus effect in particle systems has since been a subject to many investigations [10–13]. Oliver [10] attempted to explain some

---

[*] Corresponding authors.
E-mail addresses: ruixiao@seu.edu.cn (R. Xiao), maoye@dicp.ac.cn (M. Ye).

https://doi.org/10.1016/j.apt.2018.03.032
0921-8831/

Please cite this article in press as: R.-J. Liu et al., Analysis of particle rotation in fluidized bed by use of discrete particle model, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.03.032

Nomenclature

C_d	drag coefficient, [–]
d_p	particle diameter, mm
$F_{ab,n}$	normal contact force, N
$F_{ab,t}$	tangential contact force, N
$F_{cont,a}$	contact force, N
$F_{dra,a}$	drag force, N
F_L	lift force, N
$F_{mag,a}$	magnus lift force, N
g	gravity acceleration, m/s^2
p	pressure, Pa
Re	Reynolds number, [–]
Re_r	rotational Reynolds number, [–]
k	spring stiffness, N/m
m_a	particle mass, kg
n_{ab}	normal unit vector, [–]
N_{part}	number of particles, [–]
n	number of fluctuant particles, [–]
I_a	moment of inertia, kg m^2
S_p	source term symbol, $kg/(m^2/s^2)$
t	time, s
T_a	particle torque, N m

U	fluid velocity, m/s
u_x	fluid velocity at X-direction, m/s
u_y	fluid velocity at Y-direction, m/s
u_z	fluid velocity at Z-direction, m/s
υ_a	particle normal velocity, m/s
υ_{ab}	relative velocity, m/s
V	volume of fluid cell, m^3
V_a	volume of particle, m^3

Greek symbols

ε	porosity, [–]
η	damping coefficient, N s/m
ρ_g	gas density, kg/s^3
δ_n	overlap, m
δ_t	tangential displacement, m
$\bar{\tau}$	viscous stress tensor, kg/m s^2
Θ_a	angular displacement, [–]
μ_f	friction coefficient, [–]
μ_g	dynamic viscosity, Pa s
ω	rotational speed, 1/s

phenomena and behavior of particle in tubes by using Magnus effect. White and Schulz [13] studied the motion of spherical glass microbeads (of diameter 350 um and density 2.5 g/cm^3) in a wind tunnel, and found that their results could be well explained by the Magnus effect. Lukerchenko [12] found the existence of Magnus effect in solid particle saltation over rough bed in a numerical study, and Huang et al. [11] further demonstrated the trajectories of saltating grains could be influenced by the Magnus effects. Dandy and Dwyer [14] compared the Magnus lift force and drag force acting on a particle over a wide range of Reynolds number, and showed the magnitude of the Magnus lift force was far less than that of drag force. You et al. [15] also think that for a small size particle, even if the speed reaches 10^6 rev/min, the lift force can be neglected as compared with the drag force. However, in a very recent work Zhou and Fan [16] studied the solid-fluid interaction by use of an immersed boundary lattice Boltzmann simulations, and their results suggest that the Magnus force might become even larger than the drag force in case of high Reynolds number and low solid volume fraction in particulate flows.

A natural question thus is whether the influence of particle rotation, especially the Magnus lift force, can be ignored or not in fluidized bed reactors. In this work, we aim at the study of Magnus lift force on the hydrodynamics of fluidized beds by use of discrete particle model. The underlying inspiration is that the discrete particle model can be used as an efficient learning tool for solid-gas interaction at particle level. According to Zhou and Fan [16], the Magnus effect is more pronounced for high Re and low solid volume fractions. Therefore in this research we will focus on the particle rotation and Magnus effect in circulating fluidized bed (CFB) risers. Our results show that the influence of Magnus lift force is enhanced with a higher Re_r. Magnus lift force affects the movement of particles in both radial and axial directions while Re_r is high. However, in low Re_r case it can be neglected in computational simulation model. This indicates the introduction of Magnus lift force may improve the discrete particle model only in high Re_r case and Magnus effect should be considered in real gas-solid two phase system when the particle rotational speed is high.

2. Mathematical model

The DPM-code was originally developed by Kuipers et al. and has been validated and extensively applied in various solid-gas two-phase systems [17–19].

2.1. Gas phase

The gas flow is described by the volume-averaged Navier-Stokes equation [20]:

$$\frac{\partial(\varepsilon\rho_g)}{\partial t} + (\nabla \cdot \varepsilon\rho_g u) = 0 \tag{1}$$

$$\frac{\partial(\varepsilon\rho_g u)}{\partial t} + (\nabla \cdot \varepsilon\rho_g uu) = -\varepsilon\nabla p - S_p - \nabla \cdot (\varepsilon\bar{\tau}) + \varepsilon\rho_g g \tag{2}$$

where ε presents the porosity, g the gravity acceleration, ρ_g the gas density, u the gas velocity, $\bar{\tau}$ the viscous stress tensor, and p the pressure of the gas phase. Based on the Newton's third law, the equivalent of that force must be acting on the mesh cell that the particle resides in. So the Magnus effect on gas phase should have been considered in Eq. (2). The solution in our study is to correct source term S_p. The source term S_p is:

$$S_p = \frac{1}{V}\int\sum_{a=0}^{N_{part}}[F_{dra,a} + F_{mag,a}]\delta(r - r_a)dV \tag{3}$$

where V is the volume of fluid cell, V_a the volume of particle, υ_a the particle velocity, and N_{part} the number of particles. The δ-function is to ensure the reaction force acts as a point force at the position of the particle [21]. $F_{dra,a}$ and $F_{mag,a}$ are drag force and Magnus lift force which will be discussed in Section 2.2.3. To solve the pressure linked equation, the SIMPLE algorithm is used in this research [22].

2.2. Particle phase

In the DPM model, the Newton's second law is used to track the velocity and position of each particle:

Please cite this article in press as: R.-J. Liu et al., Analysis of particle rotation in fluidized bed by use of discrete particle model, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.03.032