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Original Research Paper

DEM numerical simulation of wet cohesive particles in a spout fluid bed

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ABSTRACT

The dynamic behavior of wet cohesive particles is greatly different from that of dry particles in a spout–fluid bed. A modified discrete element model (DEM) for wet particles is established by adding an additional module to consider the presence of the liquid bridge. DEM simulations are conducted for the dry and wet granular systems and the geometry of the bed is the same as the experimental one of Link et al. The influences of drag models and liquid contents are investigated. It is found that the Koch–Hill drag model predicts a dominant peak, the same as the measured results of Link et al., in the frequency domain of the dynamic pressure drop under Case A. However, the Gidaspow drag model fails to catch this phenomenon. With an increase of the liquid content, the fluctuation range of the pressure drop increases firstly and then decreases rapidly under Case A, but it monotonically increases under Case B. In the spout–fluid bed, dead zones, where the particles are de-fluidized, appear at the corners. The inclined angle and the area of the dead zone expand with the increase of the liquid content, which makes the value of the final Lacey mixing index decrease.

1. Introduction

Spout–fluid beds combine the characteristics of spouted beds and fluidized beds and find a wide application in various industrial processes. It has a series of advantages, such as a strong interaction between particles and the fluid, an obvious improvement of the particle mixing, an effective restraint on the particle agglomeration, and a reduction of the de-fluidized zone at the bottom. In the last half-century, the subject of fluidization underwent a rapid development and all-around researches were carried out on the dry granular systems. However, studies on wet granular beds were just beginning and in-depth investigations were lack. Due to the liquid bridge between wet particles, the two-phase flow of wet granular systems is more complicated than that of dry systems. A de-fluidized phenomenon that the fluidization of particles becomes weak usually happens [1]. Some key problems, such as the interaction between wet particles and between a wet particle and a wall, and the multi-scale heterogeneous structure of the solid phase, need further study.

With a rapid development of the computer capacity and new numerical models, numerical simulation becomes an indispensable tool of investigating the complex behavior of the gas–solid two-phase flow [2–5]. The DEM model directly solves the motion of a single particle by the Newton's second law and, consequently, can easily cover the liquid bridge force between wet particles. Therefore, the DEM model becomes an effective tool to study the fluidization behavior of wet granular systems. According to the way of dealing with the particle collision process, the DEM model can be divided into two models: the hard-sphere model and the soft-sphere model [6]. However, it is difficult for the hard-sphere model with the assumption of instantaneous collisions to take the liquid bridge force into account.

On the other hand, the soft-sphere model is a time-driven approach, namely a constant time step in a numerical simulation. This makes the soft-sphere model become the first choice to handle the quasi-static problems of de-fluidization phenomena in wet granular systems. The soft-sphere model was originally proposed by Cundall and Strack [7], providing a powerful method for studying the hydrodynamic characteristic of the gas–solid two-phase flow in gas fluidized beds. Tsuji et al. [8] developed their model, described the collision of particles with a spring–dashpot–slider system, and firstly applied in a two-dimensional fluidized bed. Kawaguchi et al. [9] expanded it into the 3D coordinates. Muguruma et al. [10] investigated the dynamics of wet particles in a centrifugal rolling granulator. Lekhal et al. [11] and Radl

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Nomenclature

c_i	the local fraction of the sample particles (–)
$\bar{c}$	the average fraction of the sample particles
C_D	drag coefficient (–)
d	immersion height (m)
d_p	particle diameter (m)
e	coefficient of restitution (–)
$\boldsymbol{F}_{gp}$	rate of exchange of momentum between the particle and the gas phase (kg m^{-2} s^{-2})
$\boldsymbol{F}_{lb}$	liquid bridge force (N)
$\boldsymbol{F}_n$	normal contact force (N)
$\boldsymbol{F}_t$	tangential contact force (N)
$\boldsymbol{g}$	gravity (m s^{-2})
H	distance between particles or a particle and a wall (m)
$\boldsymbol{I}$	identity matrix (–)
I_p	moment of inertia (kg m^2)
k_n	normal spring stiffness (N m^{-1})
k_t	tangential spring stiffness (N m^{-1})
m_p	particle mass (kg m^{-3})
N_p	number of particles in the grid (–)
p	pressure (Pa)
$\boldsymbol{r}$	particle position (m)
R	particle radius (m)
Re	Reynolds number (–)
t	time (s)
T_p	torque (N m)
$\boldsymbol{u}_g$	gas phase velocity (m s^{-1})
U	superficial gas velocity (m s^{-1})
$\boldsymbol{v}_p$	particle velocity (m s^{-1})
$\boldsymbol{v}_r$	relative collision velocity (m/s)
V_p	particle volume (m^3)
V_z	vertical particle velocity (m/s)
V_{cell}	cell volume (m^3)
W_{tot}	total interfacial energy (J)

Greek symbols

β	interphase momentum exchange coefficient (kg m^{-3} s^{-1})
γ	surface tension (N/m)
δ_n	normal overlap (m)
δ_t	tangential distance (m)
ε_g	gas phase void fraction (–)
ε_p	volume fraction of particles (–)
η_n	normal damping coefficient (N s m^{-1})
η_t	tangential damping coefficient (N s m^{-1})
θ	contact angle (rad)
μ_g	gas phase shear viscosity (Pa s)
μ_{lb}	viscosity of the liquid bridge (Pa s)
μ_s	friction coefficient (–)
ρ_g	gas phase density (kg m^{-3})
$\boldsymbol{\tau}_g$	viscous stress tensor (Pa)
φ	half-filling angle (rad)
ω_p	particle angular velocity (s^{-1})

et al. [12] carried out both an experimental and a numerical study on the characteristics of wet-particle mixing in a blade mixer. Anand et al. [13] numerically predicted the discharge dynamics of wet particles from a hopper. Liu et al. [14] conducted a DEM simulation of the mixing of wet particles within a drum.

Nevertheless, only a few literatures so far have reported on the numerical simulation of wet cohesive particles because the simulation of dry non-cohesive particles has been the major issue of the last few decades. Mikami et al. [15] developed a numerical simulation model for wet powder fluidization in the scope of investigation on cohesive powder behavior. The model was developed based on the discrete element method (DEM) with the inter-particle cohesive interaction due to liquid bridging. Muguruma et al. [16] made a numerical simulation of mono-sized spherical particle flows with a small amount of water in a centrifugal tumbling granulator by using discrete element method (DEM). A model for the inter-particle force due to a liquid bridge was applied to the present work because granulating processes are usually performed by adding binding liquid. Shi and McCarth [17] introduced a dynamic liquid transfer model for use in discrete element modeling (DEM) of heterogeneous particle systems. Sutkar et al. [18] presented a novel nonintrusive technique to investigate hydrodynamic and thermal behavior of gas–solid spout–fluidized beds with liquid injection. Buijtenen et al. [19] studied the effect of the inter-particle interaction on the bed dynamics, by considering a variable restitution coefficient. The study is done by using an extended discrete element method in a spout fluidized bed. Crüger et al. [20] developed a novel experimental setup based on two synchronized high-speed cameras capturing the collision behavior of a particle in three dimensions. The coefficient of restitution was measured for glass particles with two different diameters, at different relative velocities and liquid layer thicknesses, with a focus on small collision velocities and thin liquid layers, using both the improved (three dimensional) and the conventional (two dimensional) approaches to quantify the improvement of the new method's accuracy. As the mechanics of wet granular systems is still poorly understood, especially in a spout–fluid bed, the objective of the present work is to carry out numerical simulations of a wet spout–fluid bed. Firstly, a DEM method with the soft-sphere model for wet particles is established by compositing an additional module to account for the presence of the liquid bridge. Then, DEM simulations of dry and wet granular systems are carried out. Numerical results are compared to the measured data of Link et al. [21]. Finally, the influences of drag models and liquid contents are also investigated.

2. Description of two-phase flow

The DEM model is a kind of Euler–Lagrange method, in which the gas is treated as a continuous medium and the solid particles are considered discrete. There are three aspects to be constructed when modeling: the dynamics of the discrete particles, the control equations of the gas and the coupling between them.

The movement of each single particle is solved by the Newton's second law (Lagrange method) so as to track the position, velocity and other parameters of each particle at different moments. Based on the volume-averaged Navier–Stokes equations, a continuum model (Euler method) is applied to describe the local gas density and velocity. Finally, because the length scale of the hydrodynamics of the gas phase is larger than the particle diameters, a drag model is needed to consider the momentum exchange between the gas phase and the solid particles.

2.1. Wet particle dynamics

In wet granular systems, when the distance between a wet particle and a wall or between wet particles is close enough, a liquid bridge forms due to the presence of the interstitial liquid. The force from the interstitial liquid can be modeled by the concept of the