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DEM numerical investigation of wet particle flow behaviors in multiple-spout fluidized beds

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HIGHLIGHTS

- A modified DEM (Discrete Element Method) approach has been applied.
- A force analysis of wet particles in single and double spout fluidized bed has been performed.
- The particle flow behaviors in single and double spout fluidized bed have been investigated with cohesive liquid.
- The effect of liquid contents on gas-solid hydrodynamic characteristics has been found.
- The relative humidity of air has been considered to validate the accuracy of the model.

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ABSTRACT

Spout fluidized beds are important for industrial processing, and multiple-spout fluidized beds play an important role in chemical reactions. However, particle flow behaviors in multiple-spout fluidized beds are not well known in wet particle systems. In this study, the flow behaviors of particles were investigated in dry and humid multiple-spout fluidized beds using a discrete element method (DEM). The simulated spout fluidized beds are similar to the ones used in the Buijtenen et al.'s experiment (published in Chemical Engineering Science, 2011, 66(11): 2368–2376). In the reference, particle flow behaviors were measured and investigated by PIV and PEPT in multiple spout fluidized beds. In this work, the simulated results are compared with the experimental data in single and double spout fluidized beds from Buijtenen et al., and the time-averaged particle velocities are compared to validate the simulation method. In contrast, simulated results with a liquid content of 1% in the bed showed good agreement with the data in the experimental results with an air relative humidity of 50%. Different liquid contents of the particles were applied to investigate the particle flow behaviors in wet granular systems. The liquid bridge force had a strong influence on the flow behaviors of the particles in the dense region, which resulted in different hydrodynamic characteristics between the dry and wet particles. In addition, the drag force dominated the particle flow behavior in the dry and wet particle systems. Moreover, in a wet granular system, the mass particle fluxes decreased, and the fluctuation of the pressure drops increased with an increasing influence of the liquid bridge force on the particles. Furthermore, with an increasing liquid content, the energy fluctuation of the particles weakened gradually with less active motions. A comparison of the hydrodynamic flow behaviors in single-spout and double-spout fluidized beds was carried out as well. Comparisons of the solid circulation rate and the colliding characteristics between single-spout and double-spout fluidized beds were conducted. Particularly, a comparison of the mixing characteristics demonstrated that the particles were mixed more completely in a double-spout fluidized bed. Therefore, the double-spout fluidized bed could provide more adequate space for mass and heat transfer under the same condition. This was important in providing a theory for designing the industrial reactor.

1. Introduction

Spouted beds have gained increased recognition in recent years. They have been widely used for the production of particles through

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Nomenclature

C	granular temperature [$m^2\ s^{-2}$]
d_p	particle diameter [m]
DEM	discrete element method
$\boldsymbol{F}_c$	contact force [N]
$\boldsymbol{F}_{gp}$	particle drag sink term [$N\ m^{-3}$]
$\boldsymbol{F}_{lb}$	liquid bridge force [N]
$\boldsymbol{g}$	gravitational acceleration [$m\ s^{-2}$]
H	distance between particles [m]
HSD	Hertzian Spring Dashpot
I_p	moment of inertia [$kg\ m^2$]
k_n	spring stiffness [N m]
LSD	Linear Spring Dashpot
m_p	particle mass [kg]
M	mixing index [–]
N	numbers [–]
PEPT	positron emission particle tracking
PIV	particle image velocimetry
$\boldsymbol{r}_p$	the position of particle center [m]
R	particle radius [m]
Re	Reynolds number [–]
t	time [s]
$\boldsymbol{T}_p$	torque [N m]
$\boldsymbol{u}_g$	gas velocity [m/s]
$\boldsymbol{v}_p$	particle translational velocity [m/s]
V_{lb}	liquid bridge volume [m^3]
V_p	particle volume [m^3]

Subscripts

avg	average
A	area
c	contact
cell	cell numbers
cp	capillary
g	gas phase
f	fraction
lb	liquid bridge
n	normal direction
neg	negative
p	solid phase
r	relative parameter
t	tangential direction

Greek letters

β	interphase momentum exchange coefficient [–]
γ	surface tension [N/m]
δ	elastic deformation [m]
ε	volume fraction [–]
θ	contact angle [rad]
μ	friction coefficient [–]
ρ	density [kg/m^3]
σ	deviation [–]
τ	stress tensor [–]
φ	half-filling angle [rad]
ω	rotational velocity [$rad\ s^{-1}$]

granulation, and they have been applied in the production of detergents, pharmaceuticals, food, and fertilizers (Ye et al., 1992). The unique advantages, including enhanced heat and mass transfer rates and the high mixing rates of the particles (Sutkar et al., 2013), has initiated more investigations of spouted fluidized beds. To overcome the limitation of the conventional single spouted bed, it has been modified for the purpose of optimum operation to yield various types of beds including slot-rectangular spout bed, spout bed with a draft tube, and multiple-spout bed. Owing to its high flexibility, easy design, and construction simplicity, the multiple-spout bed is promising for scaling-up. Besides, for industrial production, the scale of multiple-spout fluidized beds is essential to apply adequate space for mass and heat transfer between the particles. However, the investigations mainly focused on single-spout fluidized beds, and the gas-solid hydrodynamic characteristics in multiple-spout fluidized beds were not very clear. Thus, the flow behaviors of the particles in a multiple-spout fluidized bed require further study.

The spout fluidized bed involves complex gas-solid two-phase flow behaviors. A wide range of operating conditions results in various fluidization states. Some researchers have investigated the flow behaviors in spouted beds. For experiments, Van Buijtenen et al. (2011b) investigated the collision properties of particles in a spout fluidized bed combining particle image velocimetry and digital image analysis. Luo et al. (2013) investigated solid dispersion and circulation properties in a 3D spouted bed with or without a draft tube. In addition, pressure drop fluctuation characteristics were researched by Duarte et al. (2009), Filla et al. (1983) and Zhong and Zhang (2005) further understanding of the fluidization conditions in a spout fluidized bed. In a simulated analysis, Link et al. (2004) investigated the flow behaviors of particles in a spout fluidized bed using a hard sphere discrete particle model. In addition, Kawaguchi et al. (2000) and Zhang et al. (2010) revealed mixing and flowing mechanisms in an incline-bottomed and flat-bottomed spouted bed, respectively. With regard to the multiple-spout fluidized bed, Yang et al. (2014) millions of particles by the parallel CFD-DEM coupling method, which is meaningful for the industrial processing. Deb and Tafti (2014) predicted the bubble characteristics in the fluidized bed with multiple jets. Wang et al. (2015) analyzed the mixing and segregation characteristics in a double spout fluidized bed. Besides, Saidi et al. (2015) investigated the gas-solid behaviors in the rectangular bed. As mentioned above, there have been a satisfactory number of experimental and simulated investigations on particle flow behaviors in spout fluidized beds. However, most of them are limited to the single-spout fluidized bed and double-spout fluidized bed, of which the latter system does not involve a cohesive liquid.

In fact, the presence of liquid is not neglected during industrial processing, such as a granular drying process in a spout fluidized bed (Zielinska and Markowski, 2007; Khadilkar et al., 2014). Additionally, the particle flow characteristics change owing to the effect of the cohesive liquid between the particles (Liao and Hsiau, 2010; Chou and Hsiau, 2011) Further understanding of the flow behaviors of the particles in a wet granular system is necessary and essential, especially in a double-spout fluidzied bed. This is limited in previous investigations.

Experiments are essential for investigating the gas-solid hydrodynamic characteristics; however, the results are limited to macro-motion parameters, including particle velocity and pressure drop. Thus, with the development of computational fluid dynamics, the simulation of multi-phase flow behaviors has become an effective way to further investigate the gas-solid hydrodynamic characteristics in a gas fluidized bed. Pain et al. (2001) and Lu et al. (2009) have researched gas-solid flow using a two-fluid model (TFM). However, the TFM was used in an industrial scale, and the motion of an individual particle could not be captured. In addition, Wang et al. (2009) proposed that the TFM failed to predict the bed expansion in fluidized beds. Therefore, a discrete element method (DEM) is widely used to calculate and capture gas-solid flow characteristics. For an in-depth study on particle systems, a modified soft