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Parallel CFD–DEM modeling of the hydrodynamics in a lab-scale double slot-rectangular spouted bed with a partition plate

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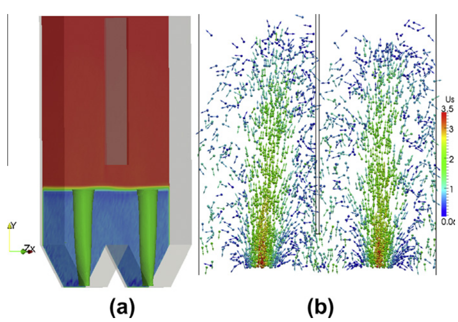
HIGHLIGHTS

- 3D modeling of the hydrodynamics in a lab-scale multiple-spouted bed is performed.
- Millions of the particles are tracked individually with the parallel CFD–DEM coupling.
- Two parallel fountains are formed without information exchanging in fountain region.
- Distribution properties of the hydrodynamics show strong dependence on the slot shape.
- Spout–annulus interaction intensity is the strongest in conical region and reduces along axis.

GRAPHICAL ABSTRACT

(a) 3-D view of the spout–annulus interface; (b) instantaneous snapshot of particle distribution in fountain.



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ABSTRACT

This paper presents a numerical modeling of the gas–solid motion in a 3-D lab-scale double slot-rectangular spouted bed with a partition plate under the parallel framework of CFD–DEM coupling approach. Solid motion is tracked with the discrete element method, while the gas motion is solved by the k–ε turbulence model. The bed has two uniform chambers with the diverging base and two parallel slots lying in the bottoms of these two chambers. A total of 2,590,000 glass particles have been tracked with 112 CPUs in a cluster. The distributions of the gas–solid hydrodynamics are investigated initially. Then, the interaction between the spout and the annulus is explored. Finally, the effect of the plate height on the gas–solid motion of the bed is discussed. The results show that the insertion of the partition plate leads to the formation of two parallel fountains without information exchanging and the enlargement of the pressure drop. A velocity peak of the fluid phase or solid phase appears in the central region of each individual chamber. Furthermore, large vertical solid flux appears in the central region of each chamber and shows a distribution strongly related to the slot shape. The slot shape influences the spout–annulus interaction boundary, whereas this effect diminishes obviously with increasing the bed height. Spout–annulus interaction intensity shows the strongest in the conical region of bed and reduces along the axial direction. Finally, the plate height exerts little effect on the solid velocity and voidage distributions.

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1. Introduction

Due to its ability to operate the irregular particles and the high gas–solid contacting efficiency, the spouted bed has been successfully applied in many applications, such as the coating, drying, combustion, gasification, granulation and pyrolysis [1–6]. However, the wide utilization of the spouted bed in the large-scale industrial processes is limited due to the difficulty in the scale-up procedure, such as the instability of the system to obtain steady spouting and the lack of a better understanding on the hydrodynamics of the large apparatus [7]. To overcome the limitation of

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Nomenclature

d_p	particle diameter, m
$\mathbf{f}_c$	contact force, N
$\mathbf{f}_{cnij}$	normal contact force, N
$\mathbf{f}_{ctij}$	tangential contact force, N
$\mathbf{f}_d$	drag force, N
$\mathbf{f}_p$	far field pressure force, N
$\mathbf{g}$	gravitational acceleration, m/s^2
H_p	plate height, m
I	particle moment of inertia, $kg{\cdot}m^2$
k	turbulent kinetic energy, m^2/s^2
k_n	spring coefficient in normal direction, N/m
k_t	spring coefficient in tangential direction, N/m
m	particle mass, kg
N	number of time interval for statistic
p	pressure, Pa
$\mathbf{r}$	position, m
$\mathbf{R}$	particle radius, m
Re_p	particle Reynolds number
$\mathbf{S}_p$	particle drag sink term, N/m^3
$\mathbf{T}_p$	particle torque, N m
$\mathbf{u}$	velocity vector, m/s
U_{sp}	superficial gas velocity, m/s
$\mathbf{V}$	particle velocity, m/s
ΔV	volume of current computational cell, m^3
V_p	particle volume, m^3

Greek symbols

β	inter-phase momentum transfer coefficient, $kg/(m^3\ s)$
σ_{nij}	normal displacements between particle *i* and particle *j*, m
σ_{tij}	tangential displacements between particle *i* and particle *j*, m
ε_g	void fraction
ε_t	turbulent dissipation rate, m^2/s^3
ε_p	solid concentration
μ	gas dynamic viscosity, kg/(m s)
μ_p	friction coefficient between particles or particle–wall
μ_t	gas turbulence viscosity, kg/(m s)
ρ_g	gas density, kg/m^3
$\boldsymbol{\omega}$	particle angular velocity, 1/s
η_n	Damping coefficients in normal direction, kg/s
η_t	damping coefficients in tangential direction, kg/s

Subscript

sc	contact force
cell	computational grid cell
d	drag force
g	gas phase
k	kinetic energy
p	particle phase
t	turbulence

Abbreviation

CFD	computational fluid dynamics
CPU	central processing unit
DEM	discrete element method
2-D	two dimensional
3-D	three dimensional

the conventional spouted bed, modification in the spouted bed has been applied for the purpose of optimum operation, such as the spout-fluid bed, the slot-rectangular spouted bed, the spouted bed with draft tube and the multiple-spouted bed. Due to the great flexibility, easy design and construction simplicity, the multiple-spouted bed shows a promising direction for the scale-up of the spouted bed.

Many experimental works have been conducted to investigate the hydrodynamics in the multiple-spouted bed. Murthy and Singh [8] performed an experiment in the multiple-spouted bed having 2, 3 and 4 spout cells under different operation conditions to measure the minimum spouting velocity of the system. Albina [9] investigated the emission of the pollutants from the multiple-spouted bed and the spout-fluid fluidized bed. The results demonstrated that the lower emission of CO in the multiple-spouted bed can be obtained with under-bed feeding as compared with that of over-bed feeding of the rice husk fuel. Gong et al. [10] conducted an experiment in a spouted bed with multiple air nozzles to study the particle hydrodynamics and the effect of air flow on the pressure drop of the multiple-spouted bed. The results illustrated that three distinct spouting stages can be observed with enlarging the gas hold-up. Chen et al. [11] carried out an experiment in a slot-rectangular spouted bed with slots of the same area but in different length/width ratio to study the slot configuration on the local flow behavior of the system. Hu et al. [12] explored the flow patterns and transitions in the spouted bed with multiple air nozzles. They pointed out that the turbulent exchange or mixing of particles among the nozzles can be captured due to the interaction of the spouting gases from different nozzles. Ren et al. [13] experimentally investigated the flow patterns and transition in a visible multiple-spouted bed.

Besides the experimental work, numerical simulation has been used in the modeling of two-phase dense flow with the development of the computational technology [14–18]. The methods adopted to model the two-phase dense flow can be mainly divided into two types: the Eulerian–Eulerian method and the Eulerian–Lagrangian method. The main difference between these two approaches lies in the way of dealing with the tracking of the solid phase. The solid phase is treated as continuous media in the Eulerian–Eulerian method, while it is tracked individually in the Eulerian–Laraingian approach. Due to the ability to obtain the detailed hydrodynamics without disturbing the flow field, numerical investigations on the important characteristics of the spouted bed have been carried out by many researchers [19–21]. However, few reports exist on the exploration of the gas–solid flow behaviors in the multiple-spouted bed.

van Buijtenen et al. [22] carried out the numerical and experimental studies to evaluate the effect of multiple spouts on the bed hydrodynamics in a pseudo-2D triple-spout fluidized bed. They noted that the presence of multiple spouts in a spout fluidized bed highly affects the flow behavior of each other. Thus, the flow behavior in the multiple-spouted beds cannot be researched by solely investigating the single-spout fluidized beds. Recently, Li et al. [23] simulated the 2-D gas–solid flow in a multiple-spouted bed with the Eulerian–Eulerian approach to study the hydrodynamics of the solid phase, and the effects of the superficial velocity and bed thickness on flow behavior in a multiple-spouted bed.

Since the 3-D natural flow behavior of the gas–solid motion in the spouted bed, the ability to model the hydrodynamics in a lab-scale apparatus is important for understanding the detailed solid migration mechanism in the system. On the other hand, for

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