CFD Simulation and Optimization of Mixing Behaviors in a Spouted Bed with a Longitudinal Vortex

Feng Wu,† Jinhao Bai,‡ Jiejie Zhang,† Wenjing Zhou,§ and Xiaoxun Ma†‡

†School of Chemical Engineering, Northwest University, Xi’an 710069, China
‡Chemical Engineering Research Center of the Ministry of Education for Advance Use Technology of Shaanbei Energy, Xi’an 710069, China
§School of Chemical Engineering and Technology, Xi’an Jiaotong University, Xi’an 710049, China

ABSTRACT: The radial mixing characteristics of gas and solid phases in a cylindrical spouted bed with a pair of longitudinal vortex generators (LVGs) are numerically studied by a two-fluid model. The influence of the distance between the centers of two spheres (L) and the shape of LVGs on hydrodynamics in a spouted bed are discussed. The results show that the value of the coefficient of variation (CV) of the particle concentration can be significantly reduced by the longitudinal vortex produced in spouted beds. The particle concentration near the spout decreases first and then increases with the increase of L. When the shape of LVGs is cylindrical, a maximum increase of 188% for particle volume fraction is found near the spout region of the spouted bed. The strengthening effect on particles’ velocity achieves the best in annulus of the spouted bed, and CV of the particle concentration in the spouted bed reaches its minimum value with a pair of cylindrical LVGs.

1. INTRODUCTION

In the chemical and metallurgical industries, the spouted beds have been used in many applications such as coating, drying, mixing, and coal gasification.1,2 Many experimental testing and numerical simulations of spouted beds have been performed to determine the physics of gas–solid processes.3−9,9−29 Devahastin et al.3 experimentally developed a rotating jet annular spouted bed dryer for drying of particles in the falling rate period. Parise et al.4 studied the flow behavior of a slot-rectangular spouted bed of biomass particles with simultaneous injection of jet and pulsating airflow. Kiani et al.5 experimentally studied the mixing and segregation of binary mixtures of particles with different densities and sizes in a spouted bed. Recently, Breault et al.6,7 experimentally studied the flow behavior of gas and particles in a spouted bed under two different nozzle sizes. They also analyzed the spout characteristics and minimum spouting velocity of a flat-base spout-fluidized bed under different static heights. The pressure fluctuation of high-density zirconia particles (6200 kg/m³) in a three-dimensional (3D) conical spouted bed was studied by Rao et al.8 using a high strength microphone. Estiati et al.9 conducted a study on the influence of geometrical dimensions and structures of a restraint pipe and draft tube on entrainment, working pressure drop, working air flow rate, and maximum cycle time. The TFM approach has been widely used for simulating practical gas–solid flow behavior in spouted beds.10–18,50 Lan et al.19 numerically analyzed the effect of specularity coefficient and particle–wall restitution coefficient on hydrodynamics of spouted beds using a two-fluid model method. Wang et al.12 compared the experimental results and numerical simulations of hydrodynamics in a conical spouted bed. Jiang et al.13 numerically studied the hydrodynamics in a pressurized spouted bed with absolute pressure elevated to 1.0 MPa using three-dimensionally numerical simulation and TFM method. Hossein et al.14 numerically studied the gas–solid flow behavior and transient gas to particle heat transfer for spouted regime using the TFM approach. Du et al.15 investigated particle mixing and segregation in spouted beds with binary mixtures of particles by a numerical simulation method. Ludwig et al.16 verified the applicability of the two-fluid model for the description of gas–solid flow behavior in a circulating dilute spouted fluidized bed. Sun et al.17 investigated the hydrodynamics of ultrafine powders in a conical spouted bed with coarse particles using the TFM method, and the Perdew−Burke−Ernzerhof method was used to describe the particle number change. Wu et al.18 numerically simulated and optimized the gas–solid flow behavior in an integral multijet spout-fluidized bed using the TFM method.

The discrete element method (DEM) can capture more accurately the physics of gas–solid flow processes. However, with the increase of the number of particles, the computational cost of the DEM becomes higher. In recent years, a novel computational fluid dynamics (CFD)−DEM model coupling heat and mass transfer in a spout-fluidized bed with liquid injection has been built by Sutkar et al.20 Xu et al.22 analyzed the hydrodynamics of cohesive particles in a spouted bed by means of CFD−DEM. Golshan et al.24,25 numerically

Received: March 27, 2019
Accepted: April 25, 2019
Published: May 7, 2019
investigated the influence of bed geometry on the gas–solid flow behavior of slot-rectangular spouted beds by the CFD–DEM. A modified DEM was used by Takabatake et al. to simulate the effectiveness of the coarse-grain model in solid mixing in a spouted bed. Also, a coupled CFD–DEM method was adopted by Breuninger et al. to simulate the hydrodynamics of fine, cohesive powders in a spouted bed equipped with a Wurster tube.

Generally speaking, a conventional spouted bed is divided into three different regions: a spout at the center, a fountain region, and an annulus region between the spout and the column wall. The radial mixing of gas and particles between spout and annulus regions is not sufficient. The longitudinal vortex technique has been employed extensively to enhance the thermal efficiency of heat exchangers. described the application of the wing-type vortex generator technique in compact heat exchangers. The research progress of longitudinal vortex generators (LVGs) and nanofluids for heat transfer enhancement is reviewed by Ahmed et al. studied the mixing characteristics in the T-shaped channel with LVGs mounted on the bottom of the main channel. Datta et al. studied fluid flow and heat transfer behavior in microchannel using inclined LVG through the numerical simulation method. Ebrahimi et al. numerically investigated heat transfer and fluid flow for nanofluid flow in a rectangular microchannel heat sink with LVGs. Recently, a preliminary numerical simulation of the longitudinal vortex effect on gas–solid flow behavior in a spouted bed was carried out by Wu et al.. They compared the hydrodynamics in three types of spouted beds: without disturbance units, with a pair of balls and with a pair of LVGs. They also numerically analyzed the effect of the row number of LVGs on gas–solid flow behaviors in a novel spouted bed. However, the structural parameters of LVGs have not been optimized for design, such as the effect of distance between two centers of sphere (L) installed on the LVGS and different shapes of LVGs on hydrodynamics in a spouted bed.

The objective of the present work is to three dimensionally simulate and optimize the effect of L and different shapes of LVGs on gas–solid flow behaviors in a spouted bed and to optimize these structural parameters. Numerical simulation and analysis work have been conducted on four kinds of spouted beds: conventional spouted bed, the spouted bed with a pair of LVGs, and the distance between two centers of spheres installed on LVG (L) equals 30, 35, and 40 mm, respectively. Also, different shapes of LVGs are studied with a constant L (L = 30 mm): with a pair of spherical LVGs, with a pair of cylindrical LVGs, and with a pair of conical LVGs. The radius of sphere on LVG is kept constant as R = 10 mm (Table 1).

### 2. NUMERICAL PROCEDURE

#### 2.1. CFD Model

The Eulerian–Eulerian two-fluid model is adopted to implement the gas–particle flow simulations in a spouted bed, and both the gas and solid phases are assumed to be the interpenetrating continuous phase. Generalized Navier–Stokes equations are employed for the interacting continua. Based on the kinetic theory of granular flows, both the pressure of solid phase and the viscous force can be described as functions of the granular temperature. The Schaeffer model is used to represent the stress of solid phase, which is due to frictional interactions between particles and the diffusion coefficient of granular energy by the Gidaspow model is used. As for the governing equations and constitutive relations for spouted beds, they can be referred to ref. The dispersed turbulence model, in which turbulence predictions for gas phase are obtained by the standard k-ω model supplemented with extra terms including the inter-phase turbulent momentum transfer, has been adopted.

#### 2.2. Model Validation and Simulation Conditions

A spouted bed with LVGs was investigated experimentally, and the physical model and geometry of spouted beds with LVGs are illustrated in Figure 1. Particle image velocimetry was applied to explore effects of longitudinal vortex flow and physical properties of particles on radial velocity of particles in a spouted bed with LVGs. Figure 2 shows the experimental setup and the comparison of radial velocity of particles between experimental data and simulation results. The simulation data of radial velocity of particles are consistent with the experimental results and the maximum deviation is less than 22.5%.

The governing equations presented in Section 2.1 are solved by the CFD code Fluent. For equations related to momentum, turbulence kinetic energy, and turbulence

### Table 1. Parameters and Simulation Settings in the Present Work

| Description                               | Experiment | Computer Run |
|-------------------------------------------|------------|--------------|
| Particle density                          | 2503 kg/m³ | same         |
| Gas density                               | 1.225 kg/m³| same         |
| Particle diameter                         | 1.41 mm    | same         |
| Maximum solid volume fraction             | 0.588      | same         |
| Gas superficial velocity                  | 0.54 m/s   | same         |
| Particle–particle restitution coefficient  | 0.94       |              |
| Diameter of the spout gas inlet           | 19 mm      | same         |
| Diameter of the bed                       | 152 mm     | same         |
| Static bed depth                          | 325 mm     | same         |
| Plate size of LVGs                        | 76 mm × 28 mm |            |
| Installation height of LVGs (Hₗ)          | 150 mm     |              |
| Radius of the sphere (Hₘ)                 | 30 mm, 35 mm, 40 mm | |
| Height of the cylinder                    | 10 mm      |              |
| Diameter of the cone bottom               | 20 mm      |              |
| Height of the cone                        | 10 mm      |              |

### Figure 1. Physical model and geometry of the spouted bed with LVGs. (a) Physical model (case A), (b) spouted bed with LVGs, and (c) geometry of a spouted bed.
dissipation rate, a second-order upwind discretization scheme is adopted, while for the volume fraction term, a first-order upwind scheme is chosen. The time step in unsteady simulations was set to $1 \times 10^{-5}$ s. When the scaled residuals were less than $1 \times 10^{-5}$ for all variables, the solution was considered converged. A grid independence analysis has been made in Wu et al., in which 452 452, 608 515, 620 682, and 608 774 grid cells have been adopted for four cases of spouted beds, namely, without disturbance units (case A), with LVGs and the distance between two centers of spheres installed on LVG ($L$) equaling 20 mm (case B), 25 mm (case C), and 30 mm (case D), respectively. The total number of grid cells are 611595 and 613823 for spouted beds: with a pair of cylindrical LVGs (case E) and with a pair of conical LVGs (case F).

3. RESULTS AND DISCUSSION

3.1. Influence of $L$ on Particle Concentrations. In order to consider the effect of distance between centers of two spheres ($L$) on gas–solid flow behavior in spouted beds, the radius of sphere located on LVG is kept constant as $R = 10$ mm (Figure 3). The comparison of particle concentrations is illustrated in Figure 4 for case A–case F with a velocity of 0.864 m/s for the inlet gas jet at stable state ($U = 1.6U_{ms}$). It can be seen from this figure that the fountain height increases with the increase of $L$ in a spouted bed with LVGs because the cross-sectional area of the flow channel in a spout zone increases with the increase of $L$. Compared with other cases, the height of the fountain in case E is the lowest, which indicates that case E has the maximum axial flow resistance at the same design size of LVGs.

Figure 5 shows the comparison of velocity vectors of gas and solid particles in the longitudinal cross section of spouted beds for case A–case F. The existence of LVGs leads to the radial velocity distribution and secondary vortex flow of gas and particle phases, which strengthens the radial mixing of particles in spout and annulus, thus strengthening the momentum exchange between particles and gas. The resistance of axial movement of particles increases when LVGs are adopted, which consumes the kinetic energy of particles, and the velocity direction of particles changes after collision between particles and LVGs. Also, it can be seen from Figure 5 that the secondary vortex flow generated by gas and particles is the most significant when the shape of LVGs is cylindrical (case E).

Figure 6 displays particle concentration distributions along the radial direction in case A–case D at different spouted bed levels for $U = 1.6U_{ms}$. It can be seen from Figure 6 that, compared with the simulation results in conventional spouted bed (case A), the profiles of particle concentration along the radial direction become more smooth in spouted bed under the effect of a longitudinal vortex. The value of concentration of particles near spout decreases first and then increases with the increase of $L$. The particle volume fraction is close to a constant value in the annulus and the longitudinal vortex has little effect on that because the particle concentration in annulus is too large.

In order to analyze the improved quality of the spouted bed structure, the coefficient of variation (CV) of particle concentration is used to analyze the uniformity of particles’ distribution

$$CV = \left(\frac{S}{\bar{\varepsilon}}\right) \times 100\%$$

$$S = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (\varepsilon_{ij} - \bar{\varepsilon})^2}$$

where $S$ is the standard deviation, $\varepsilon_{ij}$ is the particle volume fraction of sampling point, $\bar{\varepsilon}$ is the average particle volume fraction of all sampling points, and $n$ is the number of samples, which equals the total number of grid cells in the spouted bed. The comparison of CV of particles’ concentration in spouted beds is shown in Figure 7 for different values of $L$. It can be observed that, compared to a conventional spouted bed (case A), the magnitude of CV has been significantly reduced by the longitudinal vortex produced in spouted beds. When $L$ equals

Figure 2. Experimental setup and model validation. (a) Schematic diagram of cross section selected in the spouted bed and (b) comparison of numerical simulation and experimental results

Figure 3. Geometry, grids, and values of design parameter ($L$) of LVGs. (a) Geometry of LVGs, (b) grids of LVGs, (c) design size of LVGs, (d) $L = 30$ mm (case B), (e) $L = 35$ mm (case C), and (f) $L = 40$ mm (case D).
30 mm, CV reaches its minimum value and then increases with the increase of \( N \), finally it reaches a stable value.

### 3.2. Influence of \( L \) on Flow of Gas and Particle Phases

Figure 8 displays the profile of magnitude of particles’ velocities along the radial direction in a spouted bed at different heights of case A—case D. It can be obviously seen that the magnitude velocity of particles in a spouted bed can be enhanced significantly by a longitudinal vortex, especially in the annular region. The strengthening degree of particles’ velocity by LVGs increases with the increase of the spouted bed height (\( z \)), which indicates that the strength and influence range of the longitudinal vortex gradually increase with the...
increase of the bed height \((z)\). The value of velocity of particles in spout increases first and then decreases with the increase of \(L\).

Figure 9 shows the radial distribution of turbulent kinetic energy of gas phase along the radial direction in four kinds of spouted beds for different values of \(L\). It can be seen from Figure 9 that the value of turbulent kinetic energy of gas phase along the radial direction in a spouted bed can be significantly promoted by a longitudinal vortex; especially near the spout region, the turbulent kinetic energy of the gas phase profile is symmetric about the central axis of the spouted bed. Because of the boundary effect of LVGs, a minimum value of gas turbulent kinetic energy can be found in the center of the spout zone. With the increase of \(L\), the turbulent kinetic energy of particles in spout decreases first and then increases, and the turbulent kinetic energy of gas phase along axial direction can be significantly intensified by a longitudinal vortex simultaneously.

3.3. Influence of Shapes of LVGs. To consider the effect of LVG shape on gas–solid flow behavior in a spouted bed, the distance between two sphere centers is kept constant as \(L = 30\) mm (Figure 10). Figure 11 shows the radial distribution of particle concentration at different heights for \(U = 1.6U_{ms}\) in four types of spouted beds. It can be observed that compared with other cases, the value of particle concentration in the central spout region of case E is the highest, the second highest is case B, and then case F, which indicates that with the increase of LVGs’ volume, the effect of a longitudinal vortex on the enhancement of particles’ movement increases, and the intensity of a longitudinal vortex increases with the increase of the LVGs’ volume. When the shape of LVGs is cylindrical, the strengthening effect on particles’ horizontal movement achieves the best, and then for the particle volume fraction, a maximum increase of 188% is achieved near the spout region of the spouted bed. Figure 12 compares the value of CV of particle concentration in spouted beds with LVGs of different shapes. As shown in Figure 12, there exists a lowest value of CV in a spouted bed for LVGs of different shapes. The value of CV in a spouted bed reaches its maximum value in case A, while it reaches its minimum value with a pair of cylindrical LVGs (case E), which indicates that the cylindrical shape for LVGs can make the particle concentration distribution the most uniform in the spouted bed, and under the influence of...
the cylindrical shape of LVGs, the particles in the spouted bed can be fully mixed between spout and annulus. Also, the influence of shapes of LVGs on magnitude velocity and granular temperature of particle phase in a spouted bed is reflected in Figures 13 and 14. It can be seen from Figure 13 that when the shape of the LVGs is cylindrical (case E), the strengthening effect of particles velocity achieves the best in annulus of the spouted bed, revealing that the increase of LVGs’ volume is helpful to the rise of longitudinal eddy strengthening effect on particles’ transversal mixing in a spouted bed, and the optimum shape for LVG is cylindrical under a certain fluid mechanics condition. As observed in Figure 14a,b, compared with the conventional spouted bed (case A), the value of granular temperature in annulus can be

![Figure 10. Physical model and meshes of spouted beds with different shapes of LVGs (L = 30 mm): (a) case B, (b) case E, and (c) case F](image)

![Figure 11. Particle concentrations profile along the radial direction in four types of spouted beds for different shapes of LVGs. (a) z = 0.17 m and (b) z = 0.2 m.](image)

![Figure 12. Comparison of CV of particles’ concentration in spouted beds for different shapes of LVGs.](image)

![Figure 13. Velocity profile of particle phase along the radial direction in spouted beds for different shapes of LVGs. (a) z = 0.17 m and (b) z = 0.2 m.](image)
increased by LVGs. Also, the increase of granular temperature reaches its maximum value in case E under the influence of the longitudinal vortex. The decrease of granular temperature in the spout region reveals that under the effect of the longitudinal vortex, the radial motion of the particles is enhanced and the radial momentum exchange in particle swarm is strengthened. The collision frequency between particles can be increased by the increase of radial motion and turbulent kinetic energy of the gas phase. As the pulsating kinetic energy of particles’ random motion is reflected by the granular temperature, the loss of kinetic energy of the particle pulsation is caused, and the granular temperature decreases to a certain extent.

4. CONCLUSIONS

In this paper, 3D gas–solid two phase flow characteristics in a novel spouted bed structure under the longitudinal vortex effects were numerically studied. The effect of distance between a pair of spherical (L) and shapes of LVGs on hydrodynamics in spouted beds is discussed. The main conclusions of the present paper are as follows:

1. The longitudinal vortex has a significant effect on the radial distribution of the particle concentration in the spouted bed and the secondary vortex flow emerges for gas and particle phases. The value of particle concentration near the spout decreases first and then increases with the increase of L. The particle volume fraction in the annulus approaches a constant value and the longitudinal vortex has little effect on particle volume fraction in the annulus region.

2. The value of velocity of particles in spout increases first and then decreases with the increase of Lg and the value of turbulent kinetic energy of gas phase along radial and axial directions in a spouted bed can be significantly promoted by a longitudinal vortex near the spout region.

3. The increase of LVGs’ volume is beneficial for the rise of the longitudinal eddy strengthening effect on particles transverse mixing in a spouted bed, and the optimum shape of LVG is cylindrical under a certain fluid mechanics condition.

■ AUTHOR INFORMATION

Corresponding Author
*E-mail: wufeng@nwu.edu.cn. Phone: +86-15309202861.
ORCID
Feng Wu: 0000-0002-8943-4926

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (grant nos. 21878245, 21476181), Natural Science Foundation of Shaanxi province (grant no.2019JM-039) and Cyrus Tang Foundation.

■ NOMENCLATURE

\( C_D \) [–] drag coefficient, dimensionless
\( d_i \) [mm] particle diameter
\( CV \) [–] coefficient of variation
\( D_i \) [mm] diameter of the spouted gas inlet
\( D_r \) [mm] diameter of the bed
\( e_r \) [–] coefficient of restitution of particle
\( \theta^0 \) [rad] radial distribution coefficient
\( H \) [mm] vessel height
\( H_0 \) [mm] static bed depth
\( H_L \) [mm] installation height of LVGs
\( k \) \([m^2/s^2]\) turbulent kinetic energy
\( L \) [mm] distance between two centers of sphere
\( \bar{T} \) [–] stress tensor
\( P \) [–] pressure
\( P_s \) [–] solid pressure
\( R \) [mm] radius of sphere install on LVGs
\( Re \) [–] Reynolds number
\( t \) [s] time
\( U \) [m/s] superficial gas velocity
\( U_{ins} \) [m/s] minimum spouting velocity
\( x, y \) [m] Cartesian coordinates

Greek symbols
\( \beta_h \) [kg/(m3s)] fluid-particle friction coefficient
\( \varepsilon \) [–] volume fraction of par
\( \theta \) \([m^2/s^2]\) granular temperature
\( \gamma_e \) [kg/(m3s)] energy dissipation
\( \mu_s \) [Pa s] gas viscosity
\( \mu_p \) [Pa s] particle viscosity
\( \rho \) [kg/m3] density
\( \mu \) [kg/(ms)] shear viscosity
\( \tau \) [Pa] stress tensor
\( \phi \) [deg] angle of internal friction
\( w \) [1/s] specific dissipation rate

Subscripts
\( g \) [–] gas
\( q \) [–] phase type (solid or gas)
\( s \) [–] solids

Figure 14. Profile of granular temperature along the radial direction in four types of spouted beds for different shapes of LVGs (z = 0.17 m). (a) Granular temperature and (b) granular temperature in annulus.
REFERENCES

(1) Epstein, N.; Grace, J. R. Spouting of Particulate Solids, Handbook of Powder Science and Technology, 2nd ed.; Chapman & Hall: New York, 1997.

(2) Takeuchi, H.; Wang, Z.; Lim, C. J.; Grace, J. R. Hydrodynamic characteristics of sawdust in a pulsed slot-rectangular spouted bed. Powder Technol. 2018, 339, 995–1004.

(3) Devahastin, S.; Mujumdar, A. S.; Raghavan, G. S. V. Hydrodynamic characteristics of a rotating jet annular spouted bed. Powder Technol. 1999, 103, 169–174.

(4) Parise, M. R.; Wang, Z.; Lim, C. J.; Grace, J. R. Hydrodynamics of a slot-rectangular spouted bed of biomass particles with simultaneous injection of spouting and pulsating air streams. Chem. Eng. J. 2017, 330, 82–91.

(5) Kiani, M.; Rahimi, M. R.; Hosseini, S. H.; Ahmadi, G. Mixing and segregation of solid particles in a conical spouted bed: Effect of particle size and density. Particuology 2017, 32, 132–140.

(6) Yang, J.; Breault, R. W.; Weber, J. M.; Rowan, S. L. Determination of flow patterns by a novel image analysis technique in a rectangular spouted bed. Powder Technol. 2018, 334, 151–162.

(7) Monazam, E. R.; Breault, R. W.; Weber, J.; Layfield, K. Minimum spouting velocity of flat-base spouted fluid bed. Particuology 2018, 36, 27–36.

(8) Rao, P. T.; Babu, M. V. J.; Ravikanth, K. V.; Dasgupta, K.; Krishnan, M. Deciphering conical spouted bed hydrodynamics using high intensity microphone. Nucl. Engr. Des. 2018, 340, 54–61.

(9) Estiati, I.; Tellabide, M.; Saldariaga, J. F.; Alizbar, H.; Olazar, M. Fine particle entrainment in fountain confined conical spouted beds. Powder Technol. 2019, 344, 278–285.

(10) Szafrański, R. G.; Kmiec, A. CFD modeling of heat and mass transfer in a spouted bed dryer. Ind. Eng. Chem. Res. 2004, 43, 1113–1124.

(11) Lan, X.; Xu, C.; Gao, J.; Al-Dahan, M. Influence of solid-phase wall boundary condition on CFD simulation of spouted beds. Chem. Eng. Sci. 2012, 69, 419–430.

(12) Wang, S.; Shao, B.; Liu, R.; Zhao, J.; Liu, Y.; Liu, Y.; Yang, S. Comparison of numerical simulations and experiments in conical gas-solid spouted bed. Chin. J. Chem. Eng. 2015, 23, 1579–1586.

(13) Jiang, X.; Zhong, W.; Liu, X.; Jin, B. Study on gas-solid flow behaviors in a spouted bed at elevated pressure: Numerical simulation aspect. Powder Technol. 2014, 264, 22–30.

(14) Hosseini, S. H.; Fattahi, M.; Ahmadi, G. CFD Study of hydrodynamic and heat transfer in a 2D spouted bed: Assessment of radial distribution function. J. Taiwan Inst. Chem. Eng. 2016, 58, 107–116.

(15) Du, W.; Zhang, J.; Bao, S.; Xu, J.; Zhang, L. Numerical investigation of particle mixing and segregation in spouted beds with binary mixtures of particles. Powder Technol. 2016, 301, 1159–1171.

(16) Ludwig, W.; Zającz, D. Modeling of particle velocities in an apparatus with a draft tube operating in a fast circulating dilute spout-fluid bed regime. Powder Technol. 2017, 319, 332–345.

(17) Sun, L.; Luo, K.; Fan, J. Numerical study on flow behavior of ultrafine powders in conical spouted bed with coarse particles. Chem. Eng. Res. Des. 2017, 125, 461–470.

(18) Wu, F.; Zhang, X.; Zhou, W.; Ma, X. X. Numerical simulation and optimization of hydrodynamics in a novel integral multi-jet spout-fluidized bed. Powder Technol. 2018, 336, 112–121.

(19) Zhang, Y.; Jin, B.; Zhong, W.; Ren, B.; Xiao, R. DEM simulation of particle mixing in flat-bottom spout-fluid bed. Chem. Eng. Res. Des. 2010, 88, 757–771.

(20) Sutkar, V. S.; Deen, N. G.; Patil, A. V.; Sălîkov, V.; Antonyuk, S.; Heinrich, S.; Kuipers, J. A. M. CFD-DEM model for coupled heat and mass transfer in a spout fluidized bed with liquid injection. Chem. Eng. J. 2016, 288, 185–197.

(21) Pietk, S.; Heinrich, S.; Karpinski, K.; Müller, M.; Schönherr, M.; Kleine Jäger, F. CFD-DEM modeling of a three-dimensional prismatic spouted bed. Powder Technol. 2017, 316, 245–255.

(22) Xu, H.; Zhong, W.; Yuan, Z.; Yu, A. B. CFD-DEM study on cohesive particles in a spouted bed. Powder Technol. 2017, 314, 377–386.

(23) Ebrahimi, M.; Siegmann, E.; Prieling, D.; Glasser, B. J.; Khinast, J. G. An investigation of the hydrodynamic similarity of single-spout fluidized beds using CFD-DEM simulations. Adv. Powder Technol. 2017, 28, 2465–2481.

(24) Golshan, S.; Zarghami, R.; Mostoufi, N. Hydrodynamics of slot-rectangular spouted beds: Process intensification. Chem. Eng. Res. Des. 2017, 121, 315–328.

(25) Golshan, S.; Zarghami, R.; Mostouf, N. Hydrodynamics of slot-rectangular spouted beds: Process intensification. Chem. Eng. Res. Des. 2017, 121, 315–328.

(26) Takabatake, K.; Morii, Y.; Khinast, J. G.; Sakai, M. Numerical investigation of a coarse-grain discrete element method in solid mixing in a spouted bed. Chem. Eng. J. 2018, 346, 416–426.

(27) Gui, N.; Yang, X.; Tu, J.; Jiang, S. A fine LES-DEM coupled simulation of gas-lag particle motion in spouted bed using a conservative virtual volume fraction method. Powder Technol. 2018, 330, 174–189.

(28) Ludwig, W.; Pluszka, P. Euler-Lagrange model of particle circulation in a spout-fluid bed apparatus for dry coating. Powder Technol. 2018, 328, 375–388.

(29) Breuninger, P.; Weis, D.; Behrendt, I.; Grohn, P.; Krull, F.; Antonysu, S. CFD-DEM simulation of fine particles in a spouted bed apparatus with a Wurster tube. Particuology 2019, 42, 114–125.

(30) Fiebig, M. Vortex generators for compact heat exchangers. J. Enhanced Heat Transfer 1995, 2, 43–61.

(31) Ahmed, H. E.; Mohammed, H. A.; Yusoff, M. Z. An overview on heat transfer augmentation using vortex generators and nanofluids: Approaches and applications. Renewable Sustainable Energy Rev. 2012, 16, 5951–5993.

(32) Hsiao, K.-Y.; Wu, C.-Y.; Huang, Y.-T. Fluid mixing in a microchannel with longitudinal vortex generators. Chem. Eng. J. 2014, 235, 27–36.

(33) Datta, A.; Sanyal, D.; Das, A. K. Numerical investigation of heat transfer in microchannel using inclined longitudinal vortex generator. Appl. Therm. Eng. 2016, 108, 1008–1019.

(34) Ebrahimi, A.; Rikhtegar, F.; Sabaghan, A.; Roobi, E. Heat transfer and entropy generation in a microchannel with longitudinal vortex generators using nanofluids. Energy 2016, 101, 190–201.

(35) Ebrahimi, A.; Naranjani, B.; Milan, S.; Dadras Javan, F. Laminar convective heat transfer of shear-thinning liquids in rectangular channels with longitudinal vortex generators. Chem. Eng. Sci. 2017, 173, 264–274.

(36) Wu, F.; Gao, W.; Zhang, J.; Ma, X.; Zhou, W. Numerical analysis of gas-solid flow in a novel spouted bed structure under the longitudinal vortex effects. Chem. Eng. J. 2018, 334, 2105–2114.

(37) Wu, F.; Zhang, J.; Ma, X.; Zhou, W. Numerical simulation of gas-solid flow in a novel spouted bed: Influence of row number of longitudinal vortex generators. Adv. Powder Technol. 2018, 29, 1848–1858.

(38) Gidaspaw, D.; Bemburaah, R.; Ding, J. Hydrodynamics of circulating fluidized beds. Kinetic Theory Approach, Fluidization VII. Proceedings of the Seventh Engineering Foundation Conference on Fluidization, 1992; pp 75–82.

(39) Ding, J.; Gidaspaw, D. A bubbling fluidization model using kinetic theory of granular flow. AIChE J. 1990, 36, 523–538.

(40) Lü, C. K. K.; Savage, S. B.; Jeffrey, D. J.; Chepurnyi, N. Kinetic theories for granular flow: inelastic particles in Couette flow and slightly inelastic particles in a general flowfield. J. Fluid Mech. 1984, 140, 223–256.

(41) Schaeffer, D. G. Instability in the evolution equations describing incompressible granular flow. J. Differ. Equ. 1987, 66, 19–50.

(42) Li, F.-C.; Hishida, K. Chapter 3 Particle Image Velocimetry Techniques and its Applications in Multiphase Systems. Adv. Chem. Eng. 2009, 37, 87–147.