Numerical Study on the Gas—Solid Flow in a Spouted Bed Installed with a Controllable Nozzle and a Swirling Flow Generator

Feng Wu, Xinxin Che, Zhenyu Huang, Haojie Duan, Xiaoxun Ma, and Wenjing Zhou

ABSTRACT: The swirling flow technology is adopted on a nozzle of the spouted bed in order to enhance the radial movement of the particles. The hydrodynamic characteristics in a spouted bed with a swirling flow generator installed on the nozzle are numerically investigated based on the two-fluid model (TFM). The traditional spouted bed and spouted bed with an integral swirling blade nozzle (ISBN) are simulated and analyzed. Numerical results show that the dead zone at the cone region of the annulus can be effectively eliminated by using the ISBN. The maximum decrease in particle concentration near the cone region is 72%, and the ISBN structure can significantly improve the comprehensive fluidization degree of the spouted bed when $\gamma$ equals 86°. The turbulent kinetic energy of gas can be significantly increased by the swirling flow along the radial direction in the spouted bed, especially in the spout region. Also, the swirling flow can promote the radial velocity and granular temperature of the particles in the spouted bed, which is helpful to the radial mixing of particles and gas phase between the central spout and the annulus in the spouted bed. There exists a value of $\xi$ (equals 0.526), which brings the greatest elimination effect of the flow dead zone in the annulus of the limited spouted bed space, and the overall fluidization of the spouted bed has the best performance when $\xi = 0.316$.

1. INTRODUCTION

Spouted bed techniques are highly attractive for drying, mixing, granulation, and coating. Many investigations on hydrodynamics of spouted beds have been reported in the literature. Takeuchi et al.3 has studied the effects of pulse frequency and slot size on the hydrodynamics and particle motion of sawdust with an average diameter of 1.29 mm by an experimental method. Rao et al.4 studied the pressure fluctuations generated by the use of dense zirconia particles in a three-dimensional (3D) spouted bed through a high-intensity microphone. They also studied the influence of gas velocity and static bed height on the hydrodynamics of the spouted bed. Devahastin et al.5 developed a rotary jet annular spouted bed dryer for the drying of particles in the deceleration period. Du et al.6 built a computation fluid dynamics (CFD) model of the spouted bed to evaluate the correlation of drag coefficient. Haghnegahdar et al.7 experimentally investigated the performance of a powder-particle spouted bed for carbon dioxide removal. The hydrodynamic characteristics of spouted beds under a wide range of operating parameters have been investigated by Du et al. Saldarriaga et al.8 carried out an experimental study on the minimum spouting velocity for the spouted beds of plant waste biomaterials. Recently, the flow behavior of ultrfine powders in the spouted bed with coarse particles was numerically studied by Sun et al.9 Zhang et al.10 experimentally studied the gas—solid two-phase flow of silicon particles with a wide scale distribution in a draft tube spouted bed. Wu et al.11—13 studied flow behaviors of gas and particles in three kinds of spouted beds recently: without disturbance units, with a pair of balls and with a pair of longitudinal vortex generators (LVGs). The effect of LVGs' row number on the hydrodynamic behaviors in the spouted bed is also numerically analyzed. Savari et al.14 studied the influence of particle size, particle density, inlet diameter, and static bed height on the operation stability of the conical spouted bed by analyzing the pressure fluctuation information entropy. Estiati et al.15 investigated the effects of the geometry and structure of the restrictor and the guide pipe on the entrainment, operating pressure drop, operating air volume, and maximum cycle time. Also, Golshan et al.16 proposed a new hybrid deterministic—stochastic model and applied it to the simulation of a slot-rectangular spouted bed to reduce the calculation cost.

To overcome the shortcomings of the dead zone at the cone region of the annulus and improve the hydrodynamic behavior in the spouted bed or fluidized beds, the fluidized gas is introduced through bypass air around the central nozzle. A half-column spouted bed with auxiliary flow was experimentally studied by Sutanto et al.17 Four different flow patterns are
Table 1. Governing Equations of Gas—Solid Flow in Spouted Beds

A. Conservation equations

(1) Continuity equations

(a) Fluid phase

\[
\frac{\partial (\rho \varepsilon \rho \nu)}{\partial t} + \nabla \cdot (\rho \varepsilon \rho \nu \mathbf{v}_g) = 0
\]  

(T1-1)

(b) Solid phase

\[
\frac{\partial (\rho_s \nu)}{\partial t} + \nabla \cdot (\rho_s \nu \mathbf{v}_s) = 0
\]  

(T1-2)

(2) Momentum equations

(a) Fluid phase

\[
\frac{\partial (\rho \varepsilon \rho \nu \mathbf{v}_g)}{\partial t} + \nabla \cdot (\rho \varepsilon \rho \nu \mathbf{v}_g \mathbf{v}_g) = -\varepsilon \nabla p_g + \varepsilon \rho \nu \mathbf{g} + \beta \rho (\nu - \nu_g) + \nabla \cdot \mathbf{\tau}_g
\]  

(T1-3)

(b) Solid phase

\[
\frac{\partial (\rho_s \nu \mathbf{v}_s)}{\partial t} + \nabla \cdot (\rho_s \nu \mathbf{v}_s \mathbf{v}_s) = -\varepsilon \nabla p_s - \rho \nu \mathbf{g} + \rho \nu \mathbf{g} + \beta \rho (\nu - \nu_g)
\]  

(T1-4)

(3) Granular temperature equation

\[
\frac{3 \partial (\varepsilon \rho \theta)}{2 \partial t} + \nabla \cdot (\varepsilon \rho \mathbf{v}_g \theta) = (\rho \nu - \rho_s \nu_s) \nabla \cdot \mathbf{v}_g + \varepsilon \rho \mathbf{g} - \varepsilon \rho \mathbf{g} - \nabla \cdot \mathbf{\gamma}_g
\]  

(T1-5)

B. Constitutive equations

(a) Solid and gas phase stress tensors

\[
\mathbf{\tau}_g = \varepsilon \rho \nu \mathbf{g} + \beta \rho (\nu - \nu_g)
\]  

(T1-6)

\[
\mathbf{\tau}_s = \varepsilon \rho \nu \mathbf{g} + \beta \rho (\nu - \nu_g)
\]  

(T1-6)

(b) Turbulent kinetic energy equation

\[
\frac{\partial k_g}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho_k u_i k_g \right) = \nu_k \frac{\partial^2 k_g}{\partial x_i \partial x_i} - \nu_k \frac{\partial \mathbf{\tau}_g}{\partial x_i} \cdot \nabla \mathbf{v}_g
\]  

(T1-7)

(c) Specific dissipation rate equation

\[
\frac{\partial \omega}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho \omega u_i \right) = \alpha \left( \frac{\partial \mathbf{\tau}_g}{\partial x_i} \cdot \nabla \mathbf{v}_g \right)
\]  

(T1-8)

(d) Solid phase stress

\[
\tau_s = \varepsilon \rho_s \nu_s \mathbf{g}_s + \beta \rho (\nu - \nu_g)
\]  

(T1-9)

(e) Solid pressure

\[
p_s = \varepsilon \rho_s \nu_s + 2 \mu_s (1 + \varepsilon) \mathbf{g}_s
\]  

(T1-10)

(f) Shear viscosity of solids

\[
\mu_s = \mu_s, 2 \nu_s + (1 - \phi_s) \mu_s + \mu_s
\]  

(T1-11)

(g) Bulk solid viscosity

\[
\psi = \frac{\pi}{\mu_s, 2 \nu_s + 1 - \phi_s} \sqrt{\pi}
\]  

(T1-12)

(h) Frictional viscosity

\[
\mu_f = \frac{p_I \sin \phi_s}{2 \sqrt{\pi}}
\]  

(T1-13)

(i) Collisional energy dissipation

\[
\gamma = \frac{12 (1 - \varepsilon_s) g_0}{d_c \sqrt{\pi}} \mu_s \varepsilon_s^{1/2}
\]  

(T1-14)

(j) Radial distribution function at contact

\[
g_0 = \left[ 1 - (e_s/e_{\text{max}}) \right]^{-1}
\]  

(T1-15)

(k) Diffusion coefficient of granular energy

\[
k_{\text{gh}} = \frac{384 \pi (1 + \varepsilon_s)}{16 \pi g_0 \sqrt{\pi}} \left[ 1 + \frac{6 \varepsilon_s g_0 (1 + \varepsilon_s)}{5} \right]^{1/2}
\]  

(T1-16)

(l) Interface momentum transfer coefficient

\[
k_{\text{gh}} = \frac{150 \pi d_c ^{1/2} \sqrt{\pi}}{384 (1 + \varepsilon_s) g_0} \left[ 1 + \frac{6 \varepsilon_s g_0 (1 + \varepsilon_s)}{5} \right]^{1/2}
\]  

(T1-17)
Table 1. continued

\[ \beta_0 = 150 \frac{\epsilon_f^2 h_g}{\epsilon_d d_s} + 1.75 \frac{\epsilon_f^2 h_g - u_j}{d_s} \epsilon_g < 0.8 \]

\[ \beta_0 = \frac{3}{4} C_d \frac{\epsilon_f^2 h_g - u_j}{d_s} \epsilon_g^{-2.65} \epsilon_g \geq 0.8 \]

\[ C_d = \begin{cases} \frac{24}{\epsilon_g R_e} (1 + 0.15(\epsilon_g R_e)^{0.87}) & (R_e < 1000) \\ 0.44 & (R_e \geq 1000) \end{cases} \]

\[ R_e = \frac{\rho d_s u_j - u_j}{\mu_g} \]

method. They found that, with an increase in fluidization rate, the dead zones diminished.

All of the previous studies have shown that the hydrodynamic behavior in the auxiliary gas spouted fluidized bed with cone base still needs to be studied. Moreover, at present, there have been no research reports about the swirling flow effect on the enhancement of the gas—solid flow in the spouted bed. The focus of the current work is to design and develop an efficient, integral, and controllable nozzle installed with a swirling flow generator to enhance and optimize the gas—solid flow process in the spouted bed. In order to utilize cylindrical spouted beds more effectively in industrial application, such as drying of granular material and heat transfer of fluidized bed, a swirling flow generator installed on the nozzle is adopted to improve the radial contact between gas and solid phases in the spout and annulus of the spouted bed. In the work reported herein, three-dimensional hydrodynamic behaviors of a spouted bed under the action of swirling flow were numerically studied, the Gidaspow drag model is selected to describe the momentum exchange of the interface, and the two-fluid model is used. The physical models and mathematical formulations of the gas and particle two phase in the spouted bed are given. The hydrodynamic characteristic of gas and particles in a conventional spouted bed was compared to that in a spouted bed with the ISBN, and detailed analyses were carried out. In addition, the effects of the inclination angle of swirl blade (\(\phi\)) and the internal/external radius ratio of the ISBN (\(\xi\)) on the hydrodynamic behavior in the spouted bed are studied.

2. COMPUTATIONAL MODELS

2.1. CFD Model. Simulation of hydrodynamic behaviors in the spouted bed by the Euler—Eulerian two-fluid model and both the gas and particles are regarded as an interpenetrating continuous phase. Flow behavior is described by generalized Navier—Stokes (N—S) equations, and the viscous forces and solid phase pressure are described by a function of particle temperature. The Schaeffer model is used to represent the stress of solid phase, and the Gidaspow model is used to describe the diffusion coefficient of the particle energy. The governing equation and constitutive relation of the spouted bed are shown in ref 11.

The Eulerian approach is adopted for both gas and solid phases in spouted beds. The dispersed turbulence model has been used, in which turbulence predictions for gas are gained by the standard \(k-\omega\) model. The equations of \(k-\omega\) turbulence model are shown in ref 11. The velocity of the particle phase between numerical simulation results (through
Therefore, the standard \( k-\omega \) turbulence model is used for simulations of this work. The numerical model of the conventional spouted bed was verified by the experimental results of the cone base cylindrical spouted bed of He et al.\(^{42,43} \) The numerical model of spouted beds with an ISBN are displayed in Figures 1 and 2. The structural parameters of spouted beds for the present calculation are listed in Table 2, and the boundary conditions are shown in Table 3.

2.2. Solution Method of Equations. The set of governing equations given in section 2.1 are solved by CFD code Fluent 15. The phase-coupled PC-SIMPLE algorithm was adopted for the pressure–velocity coupling. The second-order upwind scheme is used for other equations. The transient simulation is carried out with a constant time step of \( 1 \times 10^{-5} \)
Table 2. Parameters and Simulation Settings

| description                       | experiment | computer run |
|-----------------------------------|------------|--------------|
| gas density                        | 1.225 kg/m³ | same         |
| particle density                   | 2503 kg/m³  | same         |
| particle diameter                  | 1.41 mm     | same         |
| maximum solid volume fraction      | 0.588       | same         |
| static bed depth                   | 325 mm      | same         |
| gas superficial velocity           | 0.54 m/s    | same         |
| diameter of the spout gas inlet    | 19 mm       | same         |
| diameter of the bed                | 152 mm      | same         |
| length of swirl nozzle (L)         | 50 mm       | same         |
| outer diameter of swirl nozzle (D₂) | 19 mm     | same         |
| inner diameter of swirl nozzle (D₁) | 6 mm, 8 mm, 10 mm, 12 mm, 14 mm |
| number of swirling blades          | 8           |              |
| width of swirling blades (L₁)      | 6.4 mm      |              |
| thickness of swirling blades (L₂)  | 0.5 mm      |              |
| inlet angle of swirl blade (β)     | 45°         |              |
| inclination angle of swirl blade (γ)| 76°, 80°, 86°|

Table 3. Boundary and Initial Conditions for Numerical Simulation

| initial and boundary conditions   | parameter |
|-----------------------------------|-----------|
| inlet of gas                      | The turbulent velocity distribution, spouting inlet gas velocity U (m/s), turbulence kinetic intensity is 2%. |
| outlet of gas                     | Uniform velocity distribution for the fluid phase |
| wall                              | No particle exists for the solid phase. |
| initial condition                 | The particle concentration in the spouted bed was specified, and the gas velocity inside the spouted bed was set to 0. |

Figure 3. Grid size independency test.

Figure 4. Comparison of the particle concentration in the spouted bed with different values of γ. (a) Case A. (b) Case B. (c) Case C. (d) Case D.

3. RESULTS AND DISCUSSION

3.1. Particle Volume Fraction. In order to investigate the influence of swirling flow of the inlet gas and the inclination angle of the swirl blade (γ) on the hydrodynamic behavior in the spouted bed, the ratio of the internal radius to external radius of the ISBN, and the number of swirling blades are all kept constant as β = 45° (Figure 2) and ξ = 0.526 and 8 (Table 1), respectively. Meanwhile, the inclination angles of the swirl blade (γ) in the spouted bed with an ISBN for case B, case C, and case D are 86°, 80°, and 76°, respectively. Figure 4 illustrates the comparison of particle volume fractions in case A–case D with an inlet gas velocity of 0.864 m/s in a stable state (U = 1.6U₀). It can be observed from the figure that when the ISBN is used in the spouted bed, the energy dissipation increases due to the swirling flow of gases, resulting in the decrease in fountain height; when the particle volume fraction redistributes in spouted beds, the particles’ fountain region becomes flat. Close to the fountain area, aggregation and bubbling of gas occurred in the spouted bed due to the gas swirling diversion of the cone and convergence near the spout. Also, the range of particle fountain in spouted beds with an ISBN has been expanded. It can be seen in Figure 3 that a stable three-zone spouting structure can still be maintained in the spouted bed with the ISBN equipment, whereas the ISBN can only destroy the flow dead zone in column cones in the spouted bed.

Figure 5 compares the particle concentrations on different cross sections of the spouted bed in case A and case B for U = 1.6U₀. It can be observed in Figure 4 that the value of particle concentration near the annulus region can be reduced by the ISBN at a low height of the spouted bed (column cones). Compared to the conventional spouted bed (case A), the scope of particle aggregation in the cone region for case B significantly decreases under ISBN effects (Figure 4b).
However, at high levels of the spouted bed in the annulus, the swirling influence of gas on the particle distribution is not obvious, revealing that the ISBN has an obvious impact on the radial distribution of the particles and the value of particle concentrations near the cone region in the spouted bed can be most effectively reduced. Therefore, the dead zone at the cone region of the annulus of the spouted bed can be eliminated effectively.

The particle volume fraction profile along the radial direction in case A–case D for $U = 1.6U_{\text{rms}}$ is shown in Figure 6. Due to the emergence of the radial swirling flow of the gas phase in the spouted bed, the particle concentration near the annulus, especially near the cone region, decreases obviously. The maximum decrease in particle concentration near the cone region is 72%, and the largest reduction of particle concentration in the annulus is found in case B ($\gamma = 86^\circ$) among four kinds of spouted beds. Figure 7 shows the particle volume fraction profile along the central axial direction in case A–case D. It can be observed that the distribution of particle concentration along the axis of the spouted bed has been...
adjusted. The ISBN along the axial direction can obviously intensify the value of particle volume fraction near the spout of the spouted bed, and the maximum increase in particle concentration near the spout is 195% in the spouted bed with the effect of swirling flow when $\gamma = 76^\circ$ (case D). Overall, because of the swirling flow effect of the gas phase, the axial particle aggregation area in the spouted bed moves toward the fountain area.

3.2. Hydrodynamic Behaviors. Figure 8 displays the radial velocity profile of particles along the radial direction at different heights of the spouted bed for case A–case D. It can be clearly seen that the radial velocity of particles is significantly enhanced by the ISBN in the cone region, and this effect increases with increasing the inclination angle of swirl blade $\gamma$. When $\gamma = 86^\circ$ (case B), the radial velocity of the particle phase is increased in both the cone and the spout region. Also, the degree of enhancement for particles’ radial velocity by the ISBN decreases with increasing the height of spouted bed ($z$), which reveals that the swirling effect of gas on the particles in the spouted bed cone region leads to a large energy dissipation of the gas phase flow at the low bed level of the spouted bed, thus resulting in a sharp decrease in the swirling effect of gas on particles in the high bed region. The effect of the ISBN on the magnitude of velocities of particles along the axial direction at different heights of the spouted bed for case A–case D is shown in Figure 9. Compared with case A, the velocity of the particle phase along the axial direction in the spouted bed decreases because of the swirling influence of imported gas. Due to the existence of the ISBN, the inlet gas has a flow diversion effect in the annular of the spouted bed, which reduces both the gas flow flux in the spout and the magnitude of particles’ velocities along the axis direction of the spouted bed. Also, the velocities of particles increase with the increase in $\gamma$ for the spouted bed with an ISBN. When $\gamma = 86^\circ$, the velocities of particles along the axial direction of the spouted bed reach the highest value.

Figures 10 and 11 show the comparison of turbulent kinetic energy of gas for different values of $\gamma$. Compared with the conventional spouted bed, the ISBN can significantly enhance both the magnitude and range of turbulent kinetic energy of gas, especially in the column cone region, which is helpful to promote the radial movement between the particle and gas phases in the spouted bed. As a result, the flow dead zone in the annulus of the spouted bed can be eliminated effectively by
The pressure drop in spouted beds is displayed in Figure 12 for different values of $\gamma$. It can be seen that the pressure drop in spouted beds increases because of the inner device of the ISBN. Compared with case A, the maximum increase in pressure drop in spouted beds is 40.7% for case D, which reveals that the dissipation of gas swirling flow can increase the pressure drop of the spouted bed to a certain extent.

The uniformity of particles’ distribution is analyzed by the coefficient of variation (CV) of particle concentration as follows

$$\text{CV} = \left( \frac{S}{\bar{c}_s} \right) \times 100\%$$  \hspace{1cm} (1)
where \( S \) is the standard deviation, \( \bar{e}_v \) 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 definition of the dimensionless particle flow factor \( \eta \) is as follows

\[
\eta = \frac{C V \Delta P / \Delta P_{N=0}}{}
\]

where \( \Delta P \) is the pressure drop in the spouted bed with an ISBN, and \( \Delta P_{N=0} \) is the pressure drop in the conventional spouted bed.

Figure 13 shows the comparison of \( \eta \) in spouted beds for different values of \( \gamma \). It is seen that \( \eta \) fluctuates with the increase in \( \gamma \). When \( \gamma \) equals 86° (case B), \( \eta \) has a minimum value. It can be revealed that, compared with the conventional spouted bed, the ISBN structure can significantly improve the comprehensive fluidization quality for the spouted bed with a slight increase in the pressure drop. When the swirling of the gas phase angle is set properly, the inlet gas can make the best fluidization influence on the particle flow in the spouted bed.

3.3. Influence of the Internal/External Radius Ratio of the ISBN. In order to investigate the effect of the ratio of the internal radius to external radius of the ISBN (\( \xi = D_2/D_1 \)) on hydrodynamic behaviors in the spouted bed, the inclination angle of the swirl blade and the external radius of the ISBN are kept constant as \( \gamma = 86^\circ \) and \( D_1 = 19 \text{ mm} \). Five nozzles with different internal radii (\( D_2 \)) of 6 mm (\( \xi = 0.316 \)), 8 mm (\( \xi = 0.521 \)), 10 mm (\( \xi = 0.526 \)), 12 mm (\( \xi = 0.632 \)), and 14 mm (\( \xi = 0.737 \)) are studied for the spouted bed with an ISBN. Figure 14 shows the effect of \( \xi \) on the particle concentration profile along the radial direction in four kinds of spouted beds at different heights for \( U = 1.6 U_{ms} \). It can be seen that, when \( \xi = 0.526 \), the particle concentration near the annulus region is the lowest, which indicates that there exists a value of \( \xi \) (0.526), which can best eliminate the flow dead zone of the annular region in the limited spouted bed space. Accordingly, the pressure drop in spouted beds increases when adding the swirl blade in the nozzle, and it reaches the maximum value when \( \xi \) equals 0.526 (Figure 15), which reveals that the greater the
degree of damage to the flow dead zone in the annulus region, the larger the energy consumption of gas in spouted beds.

To determine the comprehensive fluidization effect of the spouted bed with an ISBN, the comparison of $\eta$ in spouted beds for different values of $\xi$ was analyzed. As shown in Figure 16, it is noteworthy that the optimal overall fluidization quality of the spouted bed occurs when $\xi$ equals 0.316 rather than 0.526, although the fluidization effect of the gas swirl flow on the particles’ dead zone in the spouted bed is the best when $\xi$ equals 0.526. Therefore, an appropriate increase in the cross-sectional area of the swirling channel is beneficial to the enhancement of the overall fluidization quality of the spouted bed with an ISBN.

4. CONCLUSIONS

In this paper, three-dimensional gas–particle flow in a novel spouted bed structure with the swirling flow effects was numerically investigated. The effect of the inclination angle of the swirl blade ($\gamma$) and the internal/external radius ratio of the ISBN ($\xi$) on hydrodynamic characteristics in spouted beds has been discussed. The main conclusions are presented as follows:

1. When the ISBN is used in the spouted bed, an increasing energy dissipation due to swirling flow of gas causes the height of the fountain to decrease, and the value of particle concentration near the annulus can be reduced by the ISBN at low heights of the spouted bed (column cones). Compared with the conventional spouted bed, the maximum decrease in particle concentration near the cone is 72%, and the ISBN structure can significantly improve the comprehensive fluidization quality of the spouted bed when $\gamma$ equals 86°.

2. The radial velocity of particles can be enhanced significantly by the ISBN in the cone region, and the improvement effect of the ISBN on the radial velocity of particles increases with the increase in inclination angle of the swirl blade $\gamma$. The turbulent kinetic energy of gas in the spouted bed can be enhanced significantly by the ISBN, especially in the column cone region, which is helpful in improving the radial movement of particles in the spouted bed.

3. There exists a value of $\xi$ (0.526), which makes the elimination of the flow dead zone in the annular region reach the best effect in the limited spouted bed space. Accordingly, the pressure drop in spouted beds increases when adding the swirl blade in the nozzle, and it reaches the maximum value when $\xi$ equals 0.526. The optimal overall fluidization quality of the spouted bed occurs when $\xi = 0.316$.

In addition, it is of great significance to study the influence of the number of swirling blades and the inlet angle of the swirl blade ($\beta$) on gas–solid two-phase flow behaviors in spouted beds. This will be the subject of future studies.

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■ NOMENCLATURE

C_D drag coefficient, dimensionless
$d_i$ particle diameter (mm)
$D_s$ diameter of the spouted gas inlet (mm)
$D_b$ diameter of the bed (mm)
$e_s$ coefficient of restitution of particle
$\delta_b$ radial distribution coefficient
$H$ vessel height (mm)
$H_0$ static bed depth (mm)
$k$ turbulent kinetic energy (m²/s²)
$I$ stress tensor
$P$ pressure
$P_s$ solid pressure
$D_o$ diameter of the outer tube of the ISBN (mm)
$D_i$ diameter of the inner tube of the ISBN (mm)
$Re$ Reynolds number
$t$ time (s)
$U$ superficial gas velocity (m/s)
$U_{ms}$ minimum spouting velocity (m/s)
$x, y, z$ Cartesian coordinates (m)

Greek Symbols
$\beta_p$ fluid-particle friction coefficient (kg/(m³s))
$\nu$ volume fraction of particles
$\theta$ granular temperature (m²/s²)
$\gamma_s$ energy dissipation (kg/(m³s))
$\mu_s$ gas viscosity (Pa·s)
$\mu_p$ particle viscosity (Pa·s)
$\rho$ density (kg/m³)
$\mu_s$ shear viscosity (kg/(m·s))
$\tau$ stress tensor (Pa)
$\phi$ angle of internal friction (°)
$\omega$ specific dissipation rate (1/s)
$\gamma$ inclination angle of the swirl blade (°)
$\beta$ inlet angle of the swirl blade (°)
$\xi$ internal/external radius ratio of the ISBN

Subscripts
g gas
$q$ phase type (solid or gas)
s solids

■ REFERENCES

(1) Epstein, N.; Grace, J. R. Spouted and spout-fluid beds: fundamental and applications. Cambridge University Press: 2011.
(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) Rao, P. T.; Babu, M. V. J.; Ravikanth, K. V.; Dasgupta, K.; Krishnan, M. Deciphering conical spouted bed hydrodynamics using high intensity microphone. *Nucl. Eng. Des.* 2018, 340, 54–61.

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

(5) Du, W.; Bao, X.; Xu, J.; Wei, W. Computational fluid dynamics (CFD) modeling of spouted bed: Assessment of drag coefficient correlations. *Powder Technol.* 2006, 61, 1401–1420.

(6) Haghnejadfar, M. R.; Hatamipour, M. S.; Rahimi, A. Removal of carbon dioxide in an experimental powder-particle spouted bed reactor. *Sep. Purif. Technol.* 2010, 72, 288–293.

(7) Du, W.; Zhang, L.; Zhang, B.; Bao, S.; Xu, J.; Wei, W.; Bao, X. Flow regime transition and hydrodynamics of spouted beds with binary mixtures. *Powder Technol.* 2015, 281, 138–150.

(8) Saldarriaga, J. F.; Aguado, R.; Altzibar, H.; Atxutegi, A.; Bilbao, J.; Olazar, M. Minimum spouting velocity for conical spouted beds of vegetable waste biomasses. *J. Taiwan Inst. Chem. Eng.* 2016, 60, 509–519.

(9) 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.

(10) Zhang, Y.; Huang, G.; Su, G. Hydrodynamic behavior of silicon particles with a wide size distribution in a draft tube spout-fluid bed. *Chem. Eng. J.* 2017, 328, 645–653.

(11) 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.

(12) 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.

(13) Wu, F.; Huang, Z.; Zhang, J.; Zhou, W.; Ma, X. Influence of longitudinal vortex generator configuration on the hydrodynamics in a novel spouted bed. *Chem. Eng. Technol.* 2018, 41, 1716–1726.

(14) Wu, F.; Bai, J.; Zhang, J.; Zhou, W.; Ma, X. CFD Simulation and Optimization of Mixing Behaviors in a Spouted Bed with a Longitudinal Vortex. *ACS Omega* 2019, 4, 8214–8221.

(15) Savari, C.; Sotudeh-Gharebagh, R.; Kulah, G.; Koksal, M.; Mostoufi, N. Detecting stability of conical spouted beds based on information entropy theory. *Powder Technol.* 2019, 343, 185–193.

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

(17) Golshan, S.; Zarghami, R.; Mostoufi, N. A hybrid deterministic–stochastic model for spouted beds. *Particuology* 2019, 42, 104–113.

(18) Sutanto, W.; Epstein, N.; Grace, J. R. Hydrodynamics of spout-fluid beds. *Powder Technol.* 1985, 44, 205–212.

(19) Zhao, J.; Lim, C. J.; Grace, J. R. Flow regimes and combustion behavior in coal-burning spouted and spouted-fluid beds. *Chem. Eng. Sci.* 1987, 42, 2865–2875.

(20) Arnold, M. S. T. J.; Gale, J. J.; Laughlin, M. K. The British coal spouted fluidised bed gasification process. *Can. J. Chem. Eng.* 1992, 70, 991–997.

(21) Pianarosa, D. L.; Freitas, L. A. P.; Lim, C. J.; Grace, J. R.; Dogan, O. M. Voidage and particle velocity profiles in a spout-fluid bed. *Can. J. Chem. Eng.* 2000, 78, 132–142.

(22) Zhong, W.; Zhang, M. Characterization of dynamic behavior of a spout-fluid bed with Shannon entropy analysis. *Powder Technol.* 2005, 159, 121–126.

(23) Zhong, W.; Zhang, M. Jet penetration depth in a two-dimensional spout-fluid bed. *Chem. Eng. Sci.* 2005, 60, 315–327.

(24) Zhong, W.; Zhang, M. Pressure fluctuation frequency characteristics in a spout-fluid bed by modern ARM power spectrum analysis. *Powder Technol.* 2005, 152, 52–61.

(25) Wang, S.; Zhao, L.; Wang, C.; Liu, Y.; Gao, J.; Liu, Y.; Cheng, Q. Numerical simulation of gas–solid flow with two fluid model in a spouted-fluid bed. *Particuology* 2014, 14, 109–116.

(26) Nagashima, H.; Kawashiri, Y.; Suzukawa, K.; Ishikura, T. Effects of operating parameters on hydrodynamic behavior of spout-fluid beds without and with a draft tube. *Proc. Eng.* 2015, 102, 952–958.

(27) Sutkar, V. S.; Deen, N. G.; Patil, A. V.; Sulikov, 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.

(28) Kieckhefen, P.; Lichtenegger, T.; Pietsch, S.; Pirker, S.; Heinrich, S. Simulation of spray coating in a spouted bed using recurrency CFD. *Particuology* 2019, 42, 92–103.

(29) Monazam, E. R.; Breault, R. W.; Weber, J. Analysis of maximum pressure drop for a flat-base spouted fluid bed. *Chem. Eng. Res. Des.* 2017, 122, 43–51.

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

(31) Devalashist, S.; Mujumdar, A. S. Some hydrodynamic and mixing characteristics of a pulsed spouted bed dryer. *Powder Technol.* 2001, 117, 189–197.

(32) Bizhaem, H. K.; Tabrizi, H. B. Investigating effect of pulsed flow on hydrodynamics of gas-solid fluidized bed using two-fluid model simulation and experiment. *Powder Technol.* 2017, 311, 328–340.

(33) Saidi, M.; Tabrizi, H. B. Influences of the fluidizing and spouting pulsation on particle motion in spout-fluid beds. *Particuology* 2018, 36, 139–148.

(34) Sousa, R. C.; Ferreira, M. C.; Altzibar, H.; Freire, F. B.; Freire, J. T. Drying of pastry and granular materials in mechanically and conventional spouted beds. *Particuology* 2019, 42, 176–183.

(35) Chuwattanakul, V.; Eiamsaard, S. Hydrodynamics Investigation of Pepper Drying in a Swirling Fluidized Bed Dryer with Multiple-Group Twisted Tape Swirl Generators. *Case Studies in Thermal Engineering* 2019, 13, 100389.

(36) Tawilk, M. H. M.; Diab, M. R.; Abdelmotali, H. M. An experimental investigation of wall-bed heat transfer and flow characteristics in a swirling fluidized bed reactor. *Appl. Therm. Eng.* 2019, 155, 501–507.

(37) Gidaspow, D.; Bezburiua, R.; Ding, J. Hydrodynamics of circulating fluidized beds. Kinetic Theory Approach. Fluidization VII. *In Proceedings of the Seventh Engineering Foundation Conference on Fluidization 1992* 75–82.

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

(39) Lun, C. K.; Savage, S. B.; Jeffrey, D. J.; Chepurniy, N. Kinetic theories for granular flow: inelastic particles in Couette flow and slightly inelastic particles in general flow field. *J. Fluid Mech.* 1984, 140, 223–256.

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

(41) Wilcox, D. C. Reassessment of the scale-determining equation for advanced turbulence model. *Aiaa Journal* 1988, 26, 1299–1310.

(42) He, Y.-L.; Lim, C. J.; Grace, J. R.; Zhu, J.-X.; Qzn, S.-Z. Measurements of voidage profiles in spouted beds. *Can. J. Chem. Eng.* 1994, 72, 229–234.

(43) He, Y. L.; Qin, S. Z.; Lim, C. J.; Grace, J. R. Particle velocity profiles and solid flow patterns in spouted beds. *Can. J. Chem. Eng.* 1994, 72, 561–568.

(44) Johnson, P. C.; Jackson, R. Frictional-collisional constitutive relations for granular materials with application to plane shearing. *J. Fluid Mech.* 1987, 176, 67–93.