Hydrodynamic Behavior of Particles in a 3D Integral Multi-Jet Spout-Fluidized Bed

Chunling Yang, Feng Wu,* Zhiquan Hui, and Xiaoxun Ma

ABSTRACT: The hydrodynamic behavior of particles in a 3D integral multi-jet spout-fluidized bed has been studied experimentally by particle image velocimetry method. In the cross section of the spouted bed, especially in the annulus, it was found that particle movement can be effectively promoted by adding the integral multi-jet, thus enhancing the radial movement of particles in the annulus and effectively eliminating the dead zone of particle flow in the annulus region. With the decrease of particle handling capacity, the fluidization effect of multi-jets was improved. When the static bed depth was 0.165 m, the enhancement effect of multi-jets on the movement of particles in the spouted bed would be optimal. When the particle diameter was overly small, the fluidization effect of the side jet would be relatively low, while excessive particle diameter would weaken the fluidization effect of the side jet due to the rise in the inertia force of particles. The analysis of the average turbulent kinetic energy and radial velocity of the particles revealed that when the particle diameter is equal to 0.72 mm, the strengthening factor of movement of particles (η) reaches the peak, the turbulence fluctuation of particles in the annulus region reaches the highest, and the fluidization effect of side jets on the particles is the best.

1. INTRODUCTION

Because of the prominent heat and mass transfer characteristics in reactors, spouted beds and spouted-fluidized beds are used in a wide range of industrial applications in the chemical, mining, pharmaceutical, energy, and environmental sectors. Numerous experimental and numerical studies on the gas–solid motions in spouted beds have been conducted. Prachayawarakorn et al. conducted a heat transfer experiment in a two-dimensional spouted bed with draft plates. Sari et al. analyzed the flow behavior of heavy particles in conical spouted beds. Qin et al. investigated the effect of static bed height and particle size on spouting pressure drop in oil shale semi-coke cold spouted beds. Nagashima et al. compared the effects of operating parameters on the flow behavior of the spout-fluidized bed (SFB) and SFB with a draft tube (DSFB) using the identical semi-cylindrical column and the identical particles. Mostoufi et al. revealed the hydrodynamic behavior of conical spouted beds by analyzing pressure fluctuation signals in the frequency domain. Yang et al. numerically simulated the dispersion behavior of the solid phase in a three-dimensional spout-fluid bed using coupled computational fluid dynamics and discrete element method (CFD–DEM), in which the fluid and solid phases were solved with the Eulerian and Lagrangian framework, respectively. Furthermore, CFD–DEM was used to simulate the dense gas–solid movement in the spouted fluidized bed. Zhang et al. measured the gas–solid hydrodynamics of coarse particles in a two-dimensional spouted bed using 6 mm glass beads. Kiani et al. analyzed the segregation and mixing processes of particle mixtures of different densities and sizes in a pseudo-2D spouted bed. Beigi et al. experimentally investigated the drying of thorium oxalate using a batch spouted bed dryer containing inert spherical glass particles. Boujia et al. studied the continuous vaporization of biomass in a direct irradiated hybrid solar/combustion spouted bed reactor. Lopez et al. modeled the biomass fast pyrolysis in a conical spouted bed reactor coupling a kinetic model with reactor hydrodynamics. Yang et al. experimentally investigated the fountain height in a shallow rectangular spouted bed using digital image analysis. They also studied the characteristic gas–solid flow under different operating conditions in a 30.2 mm × 101.6 mm rectangular spouted bed using systematic image processing methods.

In general, conventional spray beds are divided into three distinct zones: a central spout, a fountain zone, and an annulus region between the spout and the column wall. The radial mixing of gas and particles between the spout and annulus zone is inadequate. The particles in the annulus region flow slowly and stick to the wall of the bed, resulting in poor mass and heat transfer in the bed. Many optimizations have been implemented to reduce the dead zone at the bottom of the annulus and to fluidize particles in the annulus of the spouted bed to address the limitations of conventional spouted beds. Zhong et al. experimentally delved into the hydrodynamic behavior in a two-dimensional spout-fluid bed with a cross-
section of 300 mm × 30 mm and a height of 2000 mm. They also studied the spout behavior of a visible pressurized cylindrical spout-fluid bed (I.D. = 0.1 m) under the pressure of 0.4 MPa. Sutkar et al.25 delved into the flow behavior at different gas velocities in a pseudo-2D spout fluidized bed with draft plates. Wang et al.26 explored the exchange of solids between two adjacent chambers in a two-column trough rectangular spouted bed with suspended partitions. Bieberle and Barthel27 measured both the phase distribution and particle velocity in spout-fluidized beds by ultrafast X-ray computed tomography. In a numerical simulation work conducted by Saidi et al.,28 the hydrodynamics of gas–solid flow in rectangular spout-fluid bed was numerically simulated by CFD−DEM modeling. Estiati et al.29 studied the capacity of the fountain confiner to avoid fine particle entrainment, and its effect on hydrodynamics has been assessed for systems without draft tubes and with open-sided and nonporous draft tubes. Wu et al.30,31 numerically simulated the effects of side jet number and side jet width on gas–solid two-phase flow in the integral multi-jet spout-fluidized

Figure 1. Schematic diagram of the experiment setup.

Table 1. Particle Properties and Operating Conditions

| Property                          | Value     |
|----------------------------------|-----------|
| particle density ($\rho$)         | 2200 kg/m³|
| particle diameter ($d_p$)         | 0.57, 0.72, 1.13, 1.42 mm |
| vessel height ($H$)               | 0.7 m     |
| height of cross section of data acquisition ($H_a$) | 0.23 m |
| static bed depth ($H_s$)          | 0.165, 0.180, 0.195, 0.225 m |
| spouting gas volume flow rate ($Q$) | $6.33 \times 10^{-3}$ m³/s |
| main jet inlet gas velocity       | 0.2186 m/s |
| diameter of the spout gas inlet ($D_s$) | 0.019, 0.024 m |
| diameter of the bed ($D_t$)        | 0.152 m   |
| diameter of side jet ($d$)         | 4 mm      |

Table 2. Experimental Measurement Error

| $Q$ (m³/s) | $S$   | rms  |
|------------|-------|------|
| $6.33 \times 10^{-3}$ | 0.0582 | 0.09954 |
| $6.667 \times 10^{-3}$ | 0.1198 | 0.07276 |

Figure 2. Geometry and size of integral IMJSFB (unit: m).

Figure 3. Position of the three lines of particle radial velocity in the cross section of spouted bed.
bed (IMJSFB) and preliminary experimental analysis of gas–solid two-phase flow in a 3D IMJSFB. Moreover, they delved into the radial mixing behavior in a spouted bed with longitudinal vortex effects by experimental and numerical methods.\textsuperscript{32-36}

Different from the spouted-fluidized bed studied in the previous literature, the three-dimensional integral multi-nozzle spouted-fluidized bed is proposed without the need to increase the air intake, enhancing the transfer process between phases in the spouted bed and enhancing the circulating flow of particles in the annulus region of the spouted bed. The two-dimensional multi-nozzle model\textsuperscript{30} cannot truly reflect the influence of the rich spatial structure and distribution characteristics of side nozzles on the gas–solid two-phase flow. Therefore, it is necessary to extend the two-dimensional model to three-dimensional, which can more realistically study and analyze the gas–solid two-phase flow characteristics in IMJSFB. Moreover, other operational parameters of IMJSFB were not considered for analysis in our previous work.\textsuperscript{31} The aim of the present study was to analyze the mechanism behind the enhancement effect on the radial movement of particles in the IMJSFB. Particle image velocimetry (PIV)\textsuperscript{37} was employed to analyze the effects of multi-jet

Figure 4. Vector diagram of particle velocity on cross section of two different spouted beds with $d_p = 0.72$ mm, $H_0 = 0.180$ m.

Figure 5. Average radial velocity of particles in two spouted beds with $d_p = 0.72$ mm, $H_0 = 0.180$ m.

Figure 6. Average TKE of two spouted bed cross sections with $d_p = 0.72$ mm, $H_0 = 0.180$ m.
structure, depths of static bed, and particle diameter on the radial velocity and turbulence fluctuation of particles in the IMJSFB.

2. EXPERIMENTAL SETUP AND ANALYSIS METHOD

2.1. Setup and Process of PIV

The experimental study was carried out in a small, spouted bed at the PIV Fluid Mechanics Laboratory of Northwest University Engineering Center. The spouted beds used in the experiment were made of organic glass. The schematic diagram of laser chip light source, CCD camera, and laser location in the experiment is shown in Figure 1. The laser uses New wave’s Mini YAG double pulse laser. The CCD camera is the flow sense 4M-MKII camera produced by Dantec. The full pixel resolution is $2048 \times 2048$, and the maximum frame rate is 21 pairs/s. The data acquisition system is Dynamic Studio software. The geometry and size of the IMJSFB are presented in Figure 2. Two types of spouted bed were used during the experimental process, which are the conventional spouted bed (Figure 2a) and the IMJSFB (Figure 2b). Details of multi-jet are provided in Figure 2c,d, and the diameter of the side jet ($\delta$) is 4 mm. The operating conditions of spouted beds are listed in Table 1.

The specific experimental process is as follows: an air compressor is used to feed gas into the spouted bed from the bottom of the bed. The gas flow is adjusted to move the particles, and the spouting condition in the bed is observed. The movement of the particles is recorded by a laser beam illuminating the cross section of the spouted bed and a high-speed camera on the top of the bed. Finally, Dynamic Studio software is used to analyze the captured image and the radial velocity distribution of the cross section of the spouted bed is obtained. In order to study the effect of the multi-jet structure on the particle movement in different bed heights ($H_a$) of the spouted bed, measurements are made at the constant height of $H_a = 0.23$ m. The velocities on the three parallel lines close to the spout and the annulus in the cross section are the data collected for the experiments.

2.2. Assessment of rms and $k$ from PIV Measurement

The experimental measurement error is listed in Table 2. To determine the accuracy of the experimental data, standard deviation ($S$) and uncertainty analysis methods are used in most experimental verification. PIV system, as an advanced measuring instrument, can also be represented by this method. The root mean square (rms) of the random uncertainty should match the standard deviation of the measurement speed and be expressed as

$$S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (u_i - \bar{u})^2}$$

(1)

$$\text{rms}(U) = \frac{\sum_{i=1}^{N} (u_i - \bar{u})^2}{N} = \sigma$$

(2)

where $u_i$ stands for the instantaneous velocity, $\bar{u}$ represents the time-averaged velocity of the particles, and $N$ indicates the number of samples. From Table 2, the uncertainty error analysis of the experimental data results is 7.276–9.954%, corresponding to the spouting gas volume flow rates $6.667 \times 10^{-3}$ and $6.333 \times 10^{-3} \text{m}^3/\text{s}$, which is similar to those reported in the paper, so the measured experimental data has a certain degree of authenticity and reliability.

The particle motion is analyzed by taking the average value of radial velocity of cross section on three lines, the average radial velocity $V_a$ is expressed as:

$$V_a = \frac{u_{\text{Line1}} + u_{\text{Line2}} + u_{\text{Line3}}}{3}$$

(3)
where $u_{line 1}^r$, $u_{line 2}^r$, and $u_{line 3}^r$ depict radial velocity on each cross section. Figure 3 shows the position of the three radial velocity lines on the spouted bed cross section.

Turbulence kinetic energy is an important index to measure the turbulence degree of a fluid; the fluctuating velocities for the turbulent kinetic energy (TKE$^{39}$ or $k$) were calculated by considering $u' = u^*$, that is, considering the processed fluctuations free from the influence of the periodic motion. TKE is expressed as

$$K = \frac{1}{4} (U^2 + V^2)$$
where $\overline{U^2}$ and $\overline{V^2}$ are the average values of the square of the axial and radial pulsation velocities, respectively, and $K_v$ represents the average of TKE over the three cross sections.

3. RESULTS AND DISCUSSION

3.1. Effect of Multi-Jet on the Movement of Particles. In order to study the influence of multi-jet on hydrodynamic behavior of spout bed, the experiment was carried out under the conditions of static bed depth of 0.180 m, particle density of 2200 kg/m$^3$, particle size of 0.72 mm, and volume flow of gas of 6.333 $\times$ 10$^{-3}$ m$^3$/s.

Figure 4 shows a comparison of the two types of spouted bed particle velocity vectors. It is suggested that the radial velocity distribution of particles was axisymmetric on the cross section of a conventional spouted bed. In the cross section of the spouted bed, especially in the annulus, the particle movement can be effectively promoted by adding the integral multi-jet, thus enhancing the radial movement of particles in the annulus and effectively eliminating the dead zone of particle flow in the annulus region. Also, the radial mixing of gas and particles and between particles in the annular and spouted regions was enhanced, which effectively improves the utilization efficiency of laminar particles in the annulus.

Figure 5 shows a comparison of the radially averaged particle velocities in the two types of spouted beds. The average velocity of particles along the radial direction is significantly strengthened in the IMJSFB compared to that in the conventional spouted bed. The average radial velocity of particles in IMJSFB was significantly greater than that in the spout region, representing that the side jet can completely strengthen the radial movement of particles and the particles are redistributed in the bed.

Figure 6 shows the average TKE in the cross section of two types of spouted beds. With the increase of radial distance, the value of turbulence fluctuation of conventional spouted bed decreases gradually, while that of IMJSFB presents fluctuation distribution and reaches the maximum near $R = 0.4r$. It is found that the IMJSFB can effectively strengthen the friction and collision of particles close to the wall, destroy the accumulation of particles, and intensify the disturbance on particles near the wall.

Figure 7 exhibits vortex cloud diagram of two spouted bed cross sections. The absolute value of the vorticity reflects the intensity of particles’ rotation. Compared to a conventional spouted bed, the vorticity value in IMJSFB has a higher level. Moreover, the rotation of particles is more likely to cause airflow disturbances, which enhances the momentum exchange between two phases in the bed. At the same time, particles will generate a lift force to antagonize gravity and reduce the porosity in the annulus region due to the Magnus effect. The particle phase will have a more even distribution in IMJSFB. Figure 8 shows the circulation of vortex in the cross section of two kinds of spouted beds. The circulation of vortex is the integral of vorticity in a closed interval, which can indicate the overall magnitude of vorticity. As can be noticed, the circulation of vortex in cross section of IMJSFB is higher than that of CSB. Therefore, integral multi-jet can improve processing efficiency.

3.2. Effect of the Depth of Static Bed on the Movement of Particles. To analyze the fluidization effect of multi-jet at different heights of static bed, the effect of different static bed heights ($H_s = 0.165$, 0.195, and 0.225 m) on the movement of particles in spouted bed was studied.

When the particle size was kept at 0.72 mm, the particle density remained unchanged, which was $\rho = 2200$ kg/m$^3$. Figures 9 and 10 present the vector diagram and the average radial velocity of particles in the cross section for different depths of static bed in IMJSFB. These figures suggest that the fluidization effect of multi-jets was enhanced when the particle handling capacity was reduced. When the static bed depth was 0.165 m, the enhancement effect of multi-jets on the movement of particles in the spouted bed was optimal, and excessive material handling would down-regulate the fluidization effect of multiple jets on particles, implying that the gas flow rate of side jet is more suitable for the condition of low depth of static bed in the spouted bed. Nevertheless, when the static bed depth was too large, the energy of side jet gas was insufficient to significantly drive the radial circulation of a large number of particles, reducing the local fluidization quality of particles in the annulus region by side jets.

Figure 11 shows the average TKE for different depths of static bed in IMJSFB. According to the data analysis, the smaller the processing volume of the particles, the higher the turbulent pulsation of the particles is than the processing capacity of the particles under other conditions. The turbulence kinetic energy is the most prominent when the filling height is 0.195 m, and the best particle-handling capacity makes the turbulence fluctuation range of particles in the fountain area reach the maximum.

3.3. Effect of the Diameter of Particles on Their Movement. The diameter of particles plays an important role in deciding the hydrodynamic behavior of particles in a spouted bed. To analyze the effect of the diameter of particles on their movement with the integral multi-jet effect, Figure 12 presents the vector diagram of particles in the cross section for different diameters of particles ($d_p = 0.57, 0.72, 1.13,$ and 1.41 mm) in IMJSFB, while the density of particles is kept as 2200 kg/m$^3$. 

$$K_v = \frac{K_{v\text{line1}} + K_{v\text{line2}} + K_{v\text{line3}}}{3}$$

(5)
It is clear that, with the rise in particle diameter, the particle mass increases gradually, which results in the weakening of the fluidization effect of side jets on the radial movement of particles in the annulus region, which is reflected in the gradual increase of the concentration of particles in the fountain region of the spouted bed.
The quantitative distribution of the radial velocity of particles along the radial direction of IMJSFB for different diameters of particles is illustrated in Figure 13. It is suggested that the variation of diameter of particles significantly affected the local fluidization of particles. When the diameter of particles was too small, the fluidization effect of the side jet was relatively low because of the rise in the specific surface area of the particles and the adhesion force of the particles, while excessive particle diameter will reduce the fluidization effect of side jet due to the rise in inertia force of particles. Therefore, there exists an optimum diameter for particles, that is, $d_p = 0.72$ mm, at which the local fluidization effect of the side jet is optimal.

Figure 14 displays the average TKE for different diameters of particles in IMJSFB. It can be seen from the figure that the maximum turbulent kinetic energy exists in the particle diameter range of 0.72–1.13 mm, which makes the particle fluidization effect reach the best in the fountain region. Among them, the impact fluidization effect of particles with a particle diameter of 0.72 mm is the best. The fluidization of the side-jet gas is that the particles in the annulus area of the spouted bed are fully mixed with the gas in the spout region, which enhances the turbulence of the particles and gas in the bed.

To characterize the strengthening effect of multi-jet on the radial movement of particles, a dimensionless strengthening factor of the movement of particles is defined as

$$
\eta = \frac{\bar{V}_r}{\bar{V}_N}
$$

(6)

where $\bar{V}_r$ denotes the average value of the absolute radial velocity of particles in the IMJSFB. $\bar{V}_N$ refers to the average value of absolute particle radial velocity in the conventional spouted bed. The variations of $\eta$ with the varying diameter of particles in IMJSFB are shown in Figure 15. Obviously, the radial velocity of particles in the IMJSFB could be significantly increased by side jets ($\eta > 1$) by comparing with the conventional spouted bed. The strengthening factor rose first and then decreased with increasing particle diameter. When the diameter was 0.72 mm, the strengthening factor of the movement of particles ($\eta$) reaches its peak, which indicates that larger the particle diameter is, larger the inertia force of particle motion is and lesser the fluidization effect of the multi-jet structure of the spouted bed is. On the contrary, smaller the particle diameter is, greater the interaction force between particles is and the same is not conducive to the fluidization effect of the multi-jet structure of the spouted bed. As a result, there exists an optimal range of particle diameter to optimize the fluidization effect of multi-jet structure on particles.

4. CONCLUSIONS

(1) The addition of the integral multi-jet can stimulate the particles to generate considerable secondary eddy currents and can be effective in promoting particle movement of spouted bed, thereby effectively narrowing the dead zone of particle flow.

(2) The fluidization effect of multi-jets is enhanced when the particle handling capacity is reduced. At the depth of static bed of 0.165 m, the enhancement effect of multi-jets on the movement of particles in the spouted bed is optimal. When the diameter of particles is overly small, the fluidization effect of the side jet is relatively less, while excessive particle diameter will down-regulate the fluidization effect of side jet due to the rise in inertia force of particles.

(3) The radial velocity of particles in the IMJSFB could be significantly increased by side jets ($\eta > 1$) when compared with the conventional spouted bed. When the particle diameter equals 0.72 mm, the strengthening factor ($\eta$) of particle motion reaches the peak value. There exists an optimal range of particle diameter to optimize the fluidization effect of multi-jet structure on particles.

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NOMENCLATURE

- \( d_p \) [mm] particle diameter
- \( D_a \) [m] diameter of the spouted gas inlet
- \( D_t \) [m] diameter of the bed
- \( H \) [m] vessel height
- \( H_s \) [m] height of cross section of data acquisition
- \( H_0 \) [m] static bed depth
- \( Q \) [m\(^3\)/s] spouting gas volume flow rate
- \( S \) [---] standard deviation
- \( \text{rms} \) [---] uncertainty analysis
- \( V_a \) [m/s] average radial velocity
- \( K \) [m\(^2\)/s\(^2\)] turbulence kinetic energy
- \( K_s \) [m\(^2\)/s\(^2\)] average turbulence kinetic energy
- \( x, y, z \) [m] Cartesian coordinates

GREEK SYMBOLS

- \( \eta \) [---] dimensionless strengthening factor of particle movement
- \( \rho \) [kg/m\(^3\)] density
- \( \delta \) [mm] diameter of side jet

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