Experimental Study on Gas–Solid Flow in the Spouted Bed under Longitudinal Vortex Effect

Feng Wu,†‡ Xinxin Che, † Haojie Duan, † Lingyi Shang, † Xiaoxun Ma,†‡ Gang Wang,‡ and Zhiquan Hui§
† School of Chemical Engineering, Northwest University, Xi’an 710069, China
‡ School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, China
§ Guangzhou Special Pressure Equipment Inspection and Research Institute, Guangzhou 510663, China

ABSTRACT: To strengthen the particles radial movement and mixing, the longitudinal vortex generator of a sphere was adopted in the spouted bed in this study. To find the influence of the longitudinal vortex and particle properties on axial and radial velocities of particles in a 152 mm-diametered spouted bed, particle image velocimetry (PIV) was employed. The experimental results show that the addition of the longitudinal vortex generator caused the vortex movement of high-speed gas and induced a considerable secondary fine vortex in the cross section of the spouted bed, and the existence of longitudinal vortex significantly improved the radial velocity of particles, compared with that of the conventional spouted bed. Due to the effect of longitudinal vortex on particles, the phenomenon of early dropping of particles was increasingly obvious with the rise in bed height, and the value of axial velocity of particle phase was negative. With the decrease in the particle diameter, the longitudinal vortex effect of gas-driven particle movement would be enhanced. The longitudinal vortex could enhance particle velocity under a wide range of particle diameters, and the enhancement factor η decreased with the rise in the particle diameter and gradually approaches to 1.

1. INTRODUCTION

In the present study, spouted beds were developed as an alternative method to the fluidized beds; it has been extensively employed in industrial applications (e.g., drying, mixing, coating, gasification, and combustion).3–5 Numerous experimental studies of spouted beds have been conducted to obtain the detailed flow behavior of particles.3–9 Devahastin et al.10 studied a rotating jet annular spouted bed drying device to dry particles during the decreasing rate by an experimental method.3,4 Prachayawarakorn et al.11 found the heat transfer behavior of the spouted bed with three agricultural raw materials. Zhong et al.12 experimentally studied the mixing behavior of particles in a large spouted fluidized bed.12 Qin et al.13 proposed and presented a cold spouted bed for oil shale semicoke. The effects of various static bed heights and particle sizes on spouting pressure drops were explored by experiments. Sari et al.14 ascertained the gas–solid flow characteristics in a conical spouted bed with heavy particles. Sutkar et al.15 determined the flow characteristics of a quasi-two-dimensional spouted fluidized bed with a guide plate. Nagashima et al.16 figured out the effects of operating parameters of spouted fluidized bed without and with a draft tube on its hydrodynamic behavior experimentally. Mostofi et al.17,18 adopted pressure fluctuation signals to study the flow structure characteristics in a conical spouted bed. Sutkar et al.19 experimentally studied the gas–solid flow of a spout fluidized bed with draft plates to identify the flow behavior by constructing a flow regime map by image analysis. Wang et al.20 developed a rectangular spouted bed with double column grooves to facilitate solid exchange between adjacent chambers.

Recently, Zhang et al.21 experimentally investigated gas–solid hydrodynamics of coarse particles in a two-dimensional spouted bed. Kiani et al.22 experimentally probed into the mixing and separation of binary mixtures with different particle sizes and densities on a pseudo-two-dimensional spouted bed. Parise et al.23 characterized the flow behavior of a narrow rectangular spouted bed with biomass particles under the simultaneous injection of a jet and pulsating airflow. By experiments, Breault et al.19,20 determined the gas–solid flow behavior in a rectangular spouted bed with three initial bed heights at two different jet sizes. Moreover, the minimum spouting velocity of a flat spouted fluidized bed was also studied. Rao et al.21 characterized the pressure fluctuation in a 3D spouted bed at a density of zirconia particles. Estiati et al.22 studied the effects of the geometry and structure of a restraint pipe on entrainment, pressure drop, air flow rate, as well as maximum cycle time.

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It is well known that the longitudinal vortex technique has been extensively used to enhance the efficiency of heat exchangers.\textsuperscript{23−29} Ahmed et al.\textsuperscript{23} reviewed the use of longitudinal vortex generators and nano fluids to facilitate heat transfer. Hsiao et al.\textsuperscript{25} analyzed the T-channel micromixer installed at the bottom of the major channel of the longitudinal vortex generator. Datta et al.\textsuperscript{26} studied the heat transfer behavior in microchannels using an inclined longitudinal vortex generator by a numerical method. Ebrahimi et al.\textsuperscript{27,28} numerically researched the conjugate heat transfer and hydrodynamics of nano fluid flow in a rectangular microchannel radiator using a longitudinal vortex generator (LVG). Recently, Wu et al.\textsuperscript{30−32} numerically characterized the mixing behavior of gas and particles in a spouted bed with the longitudinal vortex effect. They also investigated the effects of LVG with different rows on hydrodynamics in a spouted bed.

The above reviews revealed that there has been rare experimental analysis on hydrodynamics in the spouted bed with longitudinal vortex effects. The present study aimed to experimental analysis on hydrodynamics in a spouted bed with LVGs. For the study of the effects of the longitudinal vortex and particle properties on the axial and radial velocities of the particle phase in a spouted bed, particle image velocimetry (PIV)\textsuperscript{33} was employed. The effect of LVGs, diameters and densities of particles on the flow behavior of particles were studied.

2. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the experimental device applied in this investigation. The experimental instruments primarily include a compressor of the type GX4FF-10, a flowmeter of the type D07-60B. The PIV system primarily consisted of laser emitters, CCD cameras, synchronizers, as well as image acquisition and processing software. Figure 2 presents the size and structure of the spouted beds. As displayed in Figure 2, two types of spouted beds were adopted in the experimental study: the conventional spouted bed (Figure 2a) and the spouted bed with one row of LVG (Figure 2b). Figure 3 displays the structure and size of one row of LVG in a spouted bed, and the LVG is spherical in shape. The main dimensions of the spouted bed and the characteristics of the particles used in the experiments are shown in Table 1.

| Operating Conditions and Properties of the Particles Used in Experiments |
|-------------------------------------------------------------|
| particle density ($\rho$) | 2200 kg/m$^3$ |
| particle diameter ($d_p$) | 0.72 mm, 1.13 mm, 1.42 mm |
| bed height ($H$) | 700 mm |
| height of cross section of data acquisition ($H_a$) | 210 mm, 230 mm, 250 mm |
| static bed depth ($H_0$) | 180 mm |
| spouting gas volume flow rate | 400 L/min |
| diameter of the spout gas inlet ($D_s$) | 19 mm |
| diameter of the bed ($D_t$) | 152 mm |
| radius of spheres ($R$) | 10 mm |
| thickness of deflector ($\delta$) | 2 mm |
| distance between two centers of sphere ($L$) | 35 mm |
| width of deflector ($\delta$) | 80 mm |

The gas generated by the air compressor entered the spouted bed from the bottom of the bed during the experiment. Subsequently, by driving the gas to make the particles move, the spouting situation in the spouted bed was observed. The laser beam was illuminated parallel to the cross section of the nozzle at the entrance of the spouted bed (the height of the data acquisition cross section was set to 230 mm from the entrance nozzle). Next, the camera is placed on the top of the spouted bed to capture the flow behavior of particles. Finally, the collected image is analyzed by dynamic studio software; the radial velocity vector and the radial velocity distribution of the section are obtained. Figure 4 illustrates the schematic diagram of data acquisition process in the experiment.
3. RESULTS AND DISCUSSION

3.1. Effect of Longitudinal Vortex. The radial velocity of the particle phase in the spouted bed was ascertained and analyzed using a longitudinal vortex generator. The movement of particles in the cross section of the spouted bed under the action of the longitudinal vortex was primarily investigated. Figure 5 draws the comparison of particle vector diagrams in the cross section of two types of spouted beds. The comparison suggests that in the absence of LVG, the radial velocity of the particles was axisymmetrically distributed across the cross section of the bed. The addition of LVG caused the vortex movement of the high-speed gas flow passing through the affected region and made the particle phase to generate a

Figure 4. Schematic diagram of selected cross section in spouted bed.

Figure 5. Comparison of particle vector diagrams in cross sections of two kinds of spouted beds:

(a)

(b)

Figure 6. Location of selected particle velocity in cross section of spouted bed.
considerable secondary fine vortex flow, the longitudinal vortex, thereby improving the radial motion ability of the gas and the particle phase. Furthermore, the radial mixing between gas and particle phase, particles and particles in the spouted bed was enhanced, effectively destroying the layered flow and flow dead zone of particles in the annulus.

To enhance the comprehensiveness of data acquisition results, three parallel lines (Figure 6) were taken close to the baffle in the cross section and the annulus area as the data acquisition point during the experiment; the radial velocity values of the three lines were taken for comparative analysis.

Figure 7 reveals that the radial velocity of the particle phase shifted opposite in the spouted bed, and the absolute value of radial velocity of the particles was upregulated due to the existence of the longitudinal vortex in a spouted bed. The radial velocity of the particle phase in the annulus was noticeably higher than that in the spouting zone, suggesting that the longitudinal vortex could effectively promote the radial movement and mixing of the particle phase. Also, Figure 8 draws the comparison of particle axial velocities in two types of spouted beds. The experimental results suggested that compared with the conventional spouted bed, with the rise in the bed height, the phenomenon of particles falling back to the bottom of the bed earlier was increasingly significant in a
spouted bed because of the effect of the longitudinal vortex on particles, and the axial velocity of particles turned negative, implying that most of the energy of the inlet gas was exploited to strengthen the radial movement and mixing under the effect of the longitudinal vortex, which led to the downregulation in the height of the particulate fountain.

Figure 9 compares the pressure drop of two types of spouted beds. It is suggested that compared with the conventional spouted bed, the pressure drop at the inlet and outlet of the spouted bed with LVGs was upregulated significantly, and the pressure drop increased by 38.6%, revealing that the LVGs in a spouted bed not only eliminated the accumulation of particles in the annulus of the spouted bed but also facilitated the energy dissipation of gas and particles in the spouted bed under the radial movement of particles caused by LVGs, thereby accelerating the pressure drop of the spouted bed.

Figure 10 compares the particle radial velocities of two types of spouted beds at different values of $H_a$. It is suggested that with the rise in the bed height, the enhancement of the radial velocity of particles by side jets was gradually decelerated, indicating that the enhancement of particles by side jets was largely concentrated in the low bed region, and the energy consumption of side jets for particle velocity enhancement was primarily concentrated in the low bed (Figure 9a).

3.2. Effect of Particle Diameter. Figures 11−13 draw the comparison of the particle vector diagrams as well as radial and axial velocities in the cross section under different particle diameters. It is suggested that when the particle diameter was 0.72 mm, the enhancement influence of the longitudinal vortex on particle radial motion was considered the best. The smaller the particle diameter, the more significant influence of the longitudinal vortex on the particle radial velocity would be, and the larger the effect of the driving particle motion by the longitudinal vortex would be. This finding implied that with the decrease in the particle size, the specific surface area of particles increased, while the gas force on each particle increased at the same gas velocity; besides, the mass and inertia force of each particle weredownregulated with the decrease in the particle diameter. Based on the noted factors, the decrease in the particle diameter would lead to the enhancement of the longitudinal vortex effect of gas-driven particle movement.

To study the effect of the particle diameter on particle movement enhancement under longitudinal vortex conditions in depth, a dimensionless enhancement factor of the particle velocity was defined below:

$$\eta = \frac{\overline{|V_{L}|}}{\overline{|V_{N}|}}$$  \hspace{1cm} (1)

where $\overline{|V_{L}|}$ denotes the average value of absolute particle velocity with the effect of the longitudinal vortex. $\overline{|V_{N}|}$ represents the average value of absolute particle velocity without the effect of the longitudinal vortex.
Figure 11. Particle vector diagrams in cross sections under different particle diameters: (a) $d_p = 1.42$ mm, (b) $d_p = 1.13$ mm, and (c) $d_p = 0.72$ mm.

Figure 14 gives the variation of $\eta$ under different particle diameters. This figure shows that the enhancement factor of the longitudinal vortex on particle movement under different particle diameters was larger than 1; the enhancement factor $\eta$ decreased with the rise in the particle diameter and gradually approached to 1. This finding implied that the longitudinal vortex could enhance particle velocity under a wide range of particle diameters, the smaller the particle diameter, the smaller the inertia force of the particle would be, and the stronger enhancement of the longitudinal vortex would be.
4. CONCLUSIONS

(1) The addition of LVG caused the vortex movement of the high-speed gas passing through the affected area and made the particle phase to generate a considerable secondary fine vortex flow in the cross section of a spouted bed.

(2) The radial velocity of the particle phase was significantly promoted by the longitudinal vortex compared with that of the conventional spouted bed. The radial velocity of the particle phase in the annulus was significantly higher than that of the spout region. Due to the effect of longitudinal vortex on particles, the phenomenon of early dropping of particles was increasingly obvious with the rise in the bed height, and the value of axial velocity of particles was negative.

(3) The decrease in the particle diameter would lead to the enhancement of the longitudinal vortex effect of gas-driven particle movement. The longitudinal vortex could enhance particle velocity under a wide range of particle diameters, and...
the enhancement factor $\eta$ decreased with the rise in particle diameter and gradually approached to 1.

■ AUTHOR INFORMATION

Corresponding Authors
*E-mail: wufeng@nwu.edu.cn (F.W.).
*E-mail: maxym@nwu.edu.cn (X.M.)

ORCID
Feng Wu: 0000-0002-8943-4926

Notes
The authors declare no competing financial interest.

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■ NOMENCLATURE

- $d_n$ [mm]: particle diameter
- $D_n$ [mm]: diameter of the spouted gas inlet
- $D_b$ [mm]: diameter of the bed
- $H$ [mm]: vessel height
- $H_s$ [mm]: height of cross section of data acquisition
- $H_0$ [mm]: static bed depth
- $L$ [mm]: distance between two centers of sphere
- $R$ [mm]: radius of spheres
- $S$ [mm]: width of deflector
- $x, y, z$ [m]: Cartesian coordinates

Greek Symbols

- $\rho$ [kg/m$^3$]: density
- $\delta$ [mm]: thickness of deflector
- $\eta$ [—]: dimensionless enhancement factor of particle velocity

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