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Hydrodynamic characteristics of spout-fluid bed: Pressure drop and minimum spouting/spout-fluidizing velocity

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Abstract

Experimental investigations on the hydrodynamic characteristics were carried out in a two-dimensional spout-fluid bed with cross section of 300 mm × 30 mm and height of 2000 mm. Six kinds of Geldart group D particles were used as bed materials. The effects of static bed height, particle property, spout nozzle width and fluidizing gas velocity on the pressure drop, maximum spouting pressure drop, minimum spouting velocity and minimum spout-fluidizing velocity were systematically studied. The results show that the total bed pressure drop appears a spouted bed characteristic when increasing the spouting gas velocity and keeping the fluidizing gas velocity constant, while it appears a fluidized bed characteristic when increasing the fluidizing gas velocity and keeping the spouting gas velocity constant. The maximum spouting pressure drop required to initiate spouting increases with static bed height and particle density, but decreases with particle diameter, spout nozzle width and fluidizing gas velocity. The minimum spouting and spout-fluidizing velocities both increase with static bed height, particle diameter, spout nozzle width. The minimum spout-fluidizing velocity increases while the minimum spouting velocity decreases with fluidizing gas velocity. Additional, correlations considered all of the above effects were developed to predict the minimum spout-fluidizing and spouting velocities of the spout-fluid bed, which were in satisfied agreement with the present experiments and some published experimental results.

Keywords: Fluidization; Hydrodynamic characteristics; Spout-fluid bed; Pressure drop; Minimum spouting velocity; Minimum spout-fluidizing velocity

1. Introduction

Spout-fluid beds have been of increasing interest in the petrochemical, chemical and metallurgic industries [1–6]. In the past 20's years, many valuable experimental and theoretical studies (e.g. [1–19]) aimed at grasping useful hydrodynamic characteristics of spout-fluid beds have been performed. UBC (University of British Columbia) of Canada have had a very significant role in the effort to understand and apply spout-fluid beds (e.g. [1–3,5,11,12,20]. In SEU (Southeast University) of China, more studies on the complex hydrodynamic characteristics and chemical reactions in spout-fluid beds are being carried out, in order to develop the spout-fluid beds for various applies such as desulfurization, CO_2 capture, combustion and gasification of coal and biomass. For gasification, spout-fluid bed coal gasifiers are adopted for APFBC-CC (advanced pressurized fluidized bed combustion-combined cycle) and PPG-CC (pressurized partial gasification-combined cycle) systems [7].

However, the spout-fluid bed technique has difficulty in being applied in larger-scale industrial process now due to some limitations, in particular the lack of full knowledge on the hydrodynamic characteristics. Since the hydrodynamic characteristics of spout-fluid beds are still not completely unveiled, some hydrodynamic characteristics such as pressure drop, bubble action, particles mixing, gas mixing, flow patterns and transition and even scale-up effect need to be further investigated.

Previous investigations on spouted beds [20,21] had suggested a spouted bed of rectangular cross-section as an alternative to units of circular cross-section to eliminate the scale-up disadvantages of cylindrical–conical columns. Kalwar et al. [20] claimed that the advantages of this configure were seen to be flexibility, simplicity of scale-up by moving the facing vertical walls further apart and the ability to operate in direct-indirect mode for higher thermal efficiency in dying. Another advantage is visual studies of flow patterns. Series of valuable works

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Nomenclature

d_p	particle diameter (m)
D_t	bed width (m)
f	sampling frequency (Hz)
H_0	static bed height (m)
H	bed height (m)
Q_f	fluidizing gas flow rate (m^3/s)
Q_s	spouting gas flow rate (m^3/s)
t	pressure time series sampling time (s)
u_s	spouting gas velocity (m/s)
u_{ms}	minimum spouting velocity (m/s)
$u_{s,msf}$	minimum spouting velocity at minimum spout-fluidizing condition (m/s)
$u_{f,msf}$	fluidizing gas velocity at minimum spout-fluidizing condition (m/s)
u_f	fluidizing gas velocity (m/s)
u_{mf}	minimum fluidizing velocity (m/s)

Greek letters

δ	relative deviation of particle diameter (%)
ε	particles bulk voidage (–)
λ_i	spout nozzle width (mm)
ρ_s	particle density (kg/m^3)
ρ_g	gas density (kg/m^3)

on flow hydrodynamics of rectangular spouted bed have been performed (e.g. [20–24]) attributed to the advantages of such configuration.

In the present work, experiments on the hydrodynamic characteristics of a thin rectangular spout-fluid bed for different operating conditions were carried out. In literatures, some authors (e.g. [22–24]) preferred the term "slot-rectangular" based on the both advantages mentioned above. However, visual study is the main advantage for the present work. Thus, we prefer the term "two-dimensional", since a thin column of this geometry of laboratory scale presents the flow behaviors independent of the transverse dimension.

For spout-fluid beds, in addition to injecting the spouting gas through a central nozzle, the fluidizing gas is also introduced through a perforated distributor surrounding the central nozzle, which can result in more complex hydrodynamic characteristics than either spouted beds or fluidized beds [1–3,5,10–12]. However, there has been lacking of published information on the hydrodynamic characteristics of spout-fluid beds so far. For example, what is the character of the pressure drop in the spout-fluid bed when varying the spouting or fluidizing gas velocity, similar to a spouted bed or fluidized bed? And also, how the fluidizing gas velocity influences the minimum spouting velocity and minimum spout-fluidizing velocity? There is no previous study on the above two interesting questions, the following section mainly focuses on them. Experimental data on pressure drop, maximum spouting pressure drop, minimum spouting velocity and minimum spout-fluidizing velocity are presented.

2. Experiments

The spout-fluid bed experimental system is schematically shown in Fig. 1. This system consists of a spout-fluid bed column, a gas supply system and some sampling instruments. The column has a cross-section of 300 mm × 30 mm and a height of 2000 mm. It was made of 8 mm thick plexiglas. The area of the spout nozzle is 30 mm × 30 mm (can be adjusted). A conical gas distributor with a 60° inclination angle was located at the bottom of the bed. The orifices in the air distributor are 1 mm in diameter, and the total area of all orifices is 1.1% of the gas distributor.

A roots-type blower supplied the spouting gas and the fluidizing gas. A pressure-reducing valve was installed to avoid pressure oscillations and achieve a steady gas flow. The gas flow rates were measured by two flow meters. The spouting gas entered the bed directly through the spout nozzle. The fluidizing gas was divided into two equal fluxes by a flux distributor before flowing into the gas chamber, and then entered the bed via the orifices in the gas distributor.

Pressure fluctuations in the bed were obtained by a multi-channel differential pressure signal sampling system. There were fifteen pressure-measuring holes located on the back wall of the column, some in the spout and some in the annular dense regions, with heights of 160, 245, 400, 600, 700, 800 and 1000 mm above the bottom of the bed. Every differential pressure sensor has two ports, one was connected to the pressure-measuring hole in the column wall, and the other was connected to a fluidizing gas chamber.

There are different locations of pressure tap (pressure benchmark) in the literatures. For spouted beds, the pressure benchmark was located at the spouting gas flow pipe right below the spout nozzle (e.g. [22,23]). For fluidized bed, the pressure benchmark was located at the gas chamber below the distributor. For spout-fluid bed, some [2,11] located the pressure benchmark at the spouting gas flow pipe right below the spout nozzle, while others (e.g. [13]) located that at the fluidizing gas chamber below the distributor. We had also located the pressure benchmark at the spouting gas flow pipe right below the spout nozzle in the previous investigations on the cold units [6,17], however there is somewhat limitation, for example it is hard to judge whether the dense region at a given height is fluidized or not. Thus, we located the pressure benchmark at the fluidizing gas chamber below the distributor in the present work, which is the same to the spout-fluid bed coal gasifiers [7] developed by our lab and the U-gas or Westinghouse jetting fluidized bed coal gasifiers. Location of the pressure benchmark at the fluidizing gas chamber below the distributor is convenient for operating, if the annulus at a certain height is fluidized, the mean value of pressure drop in this region almost keeps constant.

The pressures were measured and then converted into voltage signals by multi-channel differential pressure signal transmitter with a scale of 0–16 kPa. The voltage signals were sent to a computer through an A/D converter. A digital camera (Nikon 5000) and a digital video recorder (Sony DCR-PC330E) were employed to photograph the flow regimes through the transparent wall during the experiments. Two groups of 2000 W

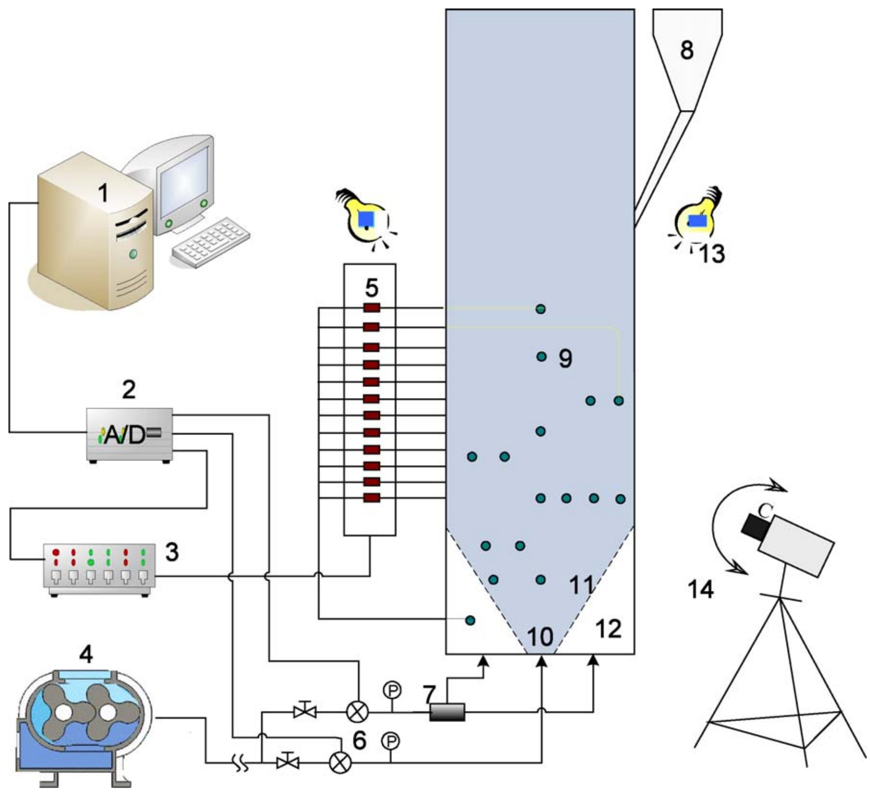

Fig. 1. Schematic diagram of spout-fluid bed experimental system 1: computer; 2: A/D converter; 3: multi-channel differential pressure signal transmitter; 4: roots-type blower; 5: differential pressure sensor; 6: flow meter; 7: fluidization flux distributor; 8: material adding tank; 9: pressure port; 10: spout nozzle; 11: gas distributor; 12: fluidizing gas chamber; 13: floodlight; 14: digital CCD.

Table 1
Experimental and sampling conditions

H_0 (mm)	Q_s (m^3/s)	Q_f (m^3/s)	f (Hz)	t (s)
300–550	0–0.08	0–0.04	100	180

floodlights were used to enhance the photo definition when photographing.

Experimental and sampling conditions and particle properties studied in the present work are summarized in Tables 1 and 2, respectively.

3. Results and discussion

3.1. Pressure drop

The determination of the pressure drops was carried out as follows: obtained the overall pressure drop between a pressure tap in the central spout region (or annular region) at a given height and the gas chamber below the distributor first, then subtracted the distributor pressure drop from the overall pressure drop. The distributor pressure drops at various fluidizing gas velocities were measured with empty bed.

Table 2
Particle properties

Particles	d_p (mm)	δ (%)	ρ_s (kg/m^3)	ε (–)	u_{mf} (m/s)
Mung beans	3.2	10.3	1640	0.42	1.07
Polystyrene	2.8	12.1	1018	0.41	0.82
Millet	1.6	8.4	1330	0.40	0.58
Glass beans (A)	1.3	5.2	2600	0.38	0.62
Glass beans (B)	1.8	5.2	2600	0.39	1.13
Glass beans(C)	2.3	5.2	2600	0.40	1.48

The pressure drops in the spout-fluid bed are significant different at different bed locations and operating conditions. Fig. 2 shows the total pressure drop in the freeboard region with the height of 1000 mm above the bottom of the bed when increasing

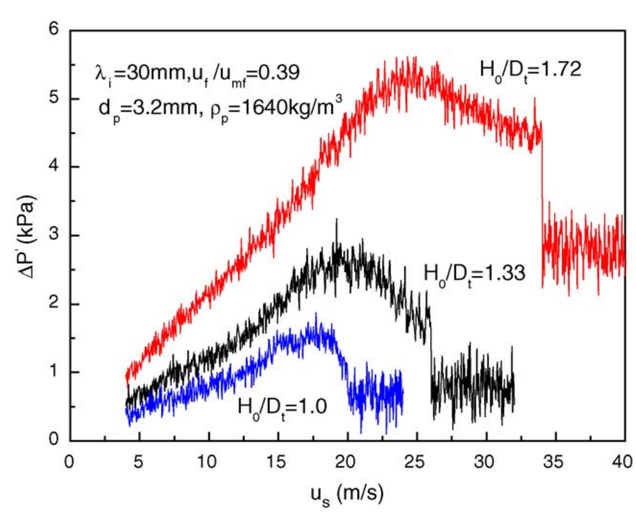

Fig. 2. Total pressure drop at different spouting gas velocities measured at $H/D_t = 3.33$.

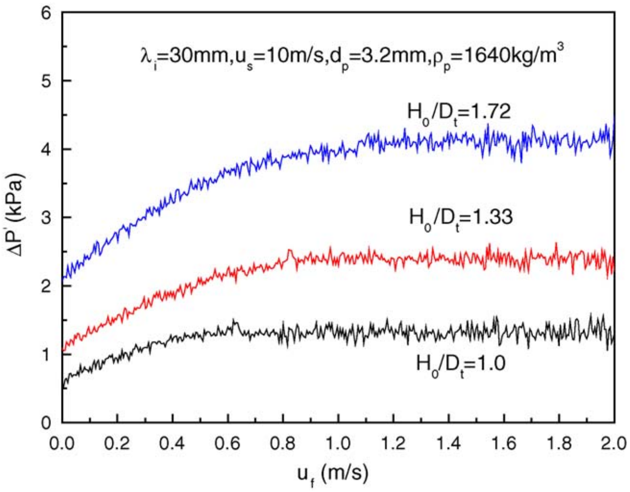

Fig. 3. Total pressure drop at different fluidizing gas superficial velocities measured at $H/D_t = 3.33$.

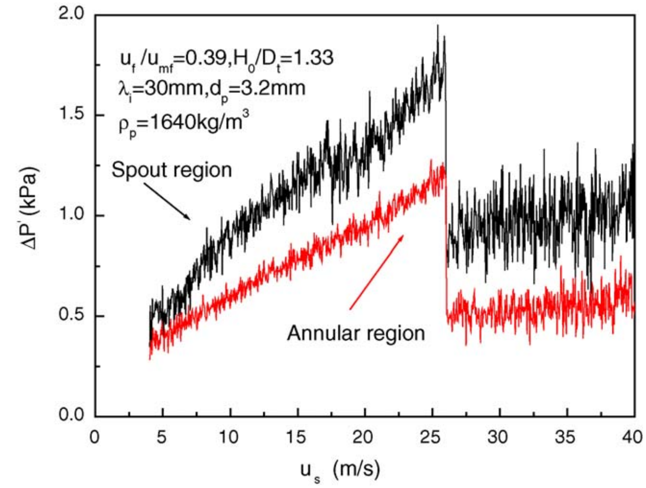

Fig. 4. Pressure drop in the spout and annular region at different spouting gas velocities measured at $H/D_t = 1.33$.

the spouting gas velocity. By increasing the spouting gas velocity, the total pressure drop increases first, and then decreases gradually after it reaches a maximum value. Suddenly the pressure drop declines to a relative low value when the spouting gas velocity continues elevating to a certainly value. When the spouting gas is beyond this value, the mean value of total pressure drop keeps constant but with fluctuations around this value. According to the phenomena observed in the experiments, when the spouting gas penetrates the bed and forms spouting, the total pressure drop suddenly drops. The tendency of the total pressure drop with increasing spouting gas velocity is the same as those observed in spouted beds by Epstein and Grace [27]. This implies that when increasing the spouting gas velocity and keeping the fluidizing gas constant, the total pressure drop of spout-fluid bed shares the characteristics of spouted bed.

Fig. 3 presents the total pressure drop when elevating the fluidizing gas superficial velocity and keeping the spouting gas velocity constant. Compared to the total pressure drop measured by increasing the spouting gas velocity, the total pressure drop profiles obtained with increase in fluidizing gas superficial velocity are remarkably different. The total pressure drop increases gradually with increasing fluidizing gas velocity and then keeps constant. The phenomenon observed in the experiments showed that the particles in the annular region are fluidized when the total pressure drop almost keeps constant, which is similar to the fluidized bed [28]. This indicates that the total pressure drop of the spout-fluid bed shares the same characteristics as the fluidized bed when increasing the fluidizing gas velocity and keeping the spouting gas velocity constant. Besides, it can be seen that the amplitude of the fluctuations of total pressure drop when increasing spouting gas velocity is larger than in the case when increasing the fluidizing gas velocity. This might due to the larger turbulences caused by increasing spouting gas velocity than by increasing fluidizing gas velocity, since most spouting gas is centralized in the central spout region while fluidizing gas is dispersive in the annular dense region. The fluidizing gas momentum is consumedly exhausted when dispersing in the dense phase region.

In the bed, the pressure drops in the spout and annular region are shown different by increasing spouting gas velocity with by increasing fluidizing gas velocity. Fig. 4 shows the pressure drop in the spout region and the annular region when increasing the spouting gas velocity, which was measured at 400 mm height ($H/D_t = 1.33$). By elevating the spouting gas velocity, the pressure drops in both spout region and annular region increase first, and then suddenly drop when the spouting gas velocity increase to a certain value. When the spouting gas is beyond this value, both pressure drops fluctuate around their mean values with slightly increase. Spouting was observed when the pressure drop in both spout region and annular region suddenly drop. It also can be seen from Fig. 4 that the pressure drop in the spout region is higher than that in the annular region. This can be explained that the dynamical pressure of spouting gas converts into static pressure when the spouting gas momentum exhausts due to the resistance of bed materials when the spout jet penetrates and ascends in the bed.

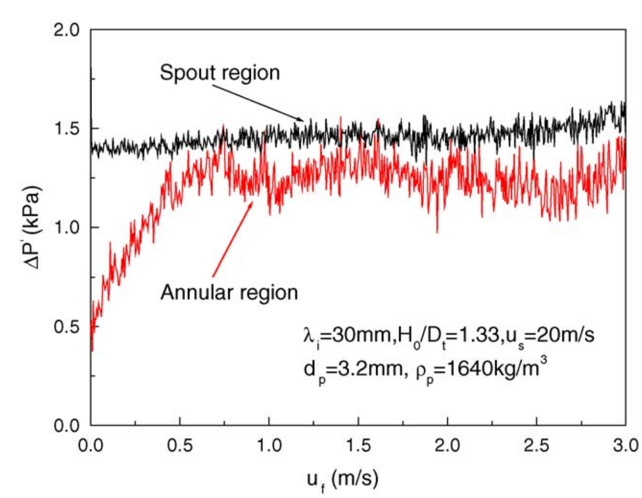

Fig. 5. Pressure drop in the spout and annular region at different fluidizing gas superficial velocities measured at $H/D_t = 1.33$.

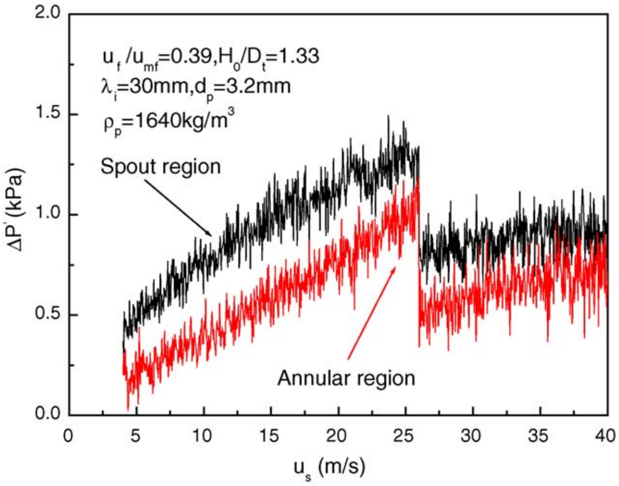

Fig. 6. Pressure drop in the spout and annular region at different spouting gas velocities measured at $H/D_t = 0.53$.

Fig. 5 presents the pressure drop in the spout region and the annular region obtained at $H/D_t = 1.33$ with the increase of fluidizing gas superficial velocity. Compared to the pressure drop measured by increasing spouting gas velocity, the pressure drop obtained by increasing fluidizing gas superficial velocity are completely different. The pressure drop in the spout region changes little with increasing fluidizing gas velocity. While, the pressures drop in the annular region increases first and then keeps constant but with relative larger fluctuations, which presents the typical pressure drop characters of a fluidized bed. Relative larger fluctuations of the pressure drop in the annulus might due to the intensive bubble actions in this region when the fluidizing gas velocity increases.

Figs. 6 and 7 plot the pressure drops in the spout and annular region when increasing the spouting gas velocity and the fluidizing gas velocity, respectively. Within the distributor region ($H/D_t = 0.53$), the pressure drops in both spout region and annular region appear the same tendencies as those at $H/D_t = 1.33$. Besides, it can be seen from Fig. 2 to Fig. 7, the pressure drops increase with bed height, which might due to the increase in the resistance of bed materials.

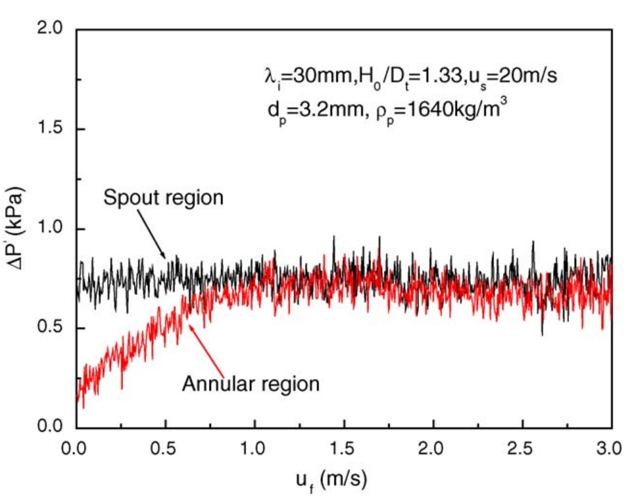

Fig. 7. Pressure drop in the spout and annular region at different fluidizing gas superficial velocities measured at $H/D_t = 0.53$.

It can be seen in Figs. 4–7, there is remarkable difference between the pressure drop in the spout and the annulus. This might due to the strong difference in gas velocity between the spout region and the annular region. While, the radial profiles of pressure drop in the annulus are almost uniform, which is similar to the results reported by He et al. [2]. Besides, the radial point of greater pressure difference is always found at the boundary of the spout region and the annular region. However, the results found that the difference between the pressure drop in the spout and the annulus can be effectively reduced by increasing fluidizing gas flow rate, as shown in Figs. 5 and 7. This can be explained by the horizontal propagation of pressure waves in fluidized particles [18]. This aspect can be used to interpret why the difference in pressure drops between the spout region and the annular region at $H/D_t = 1.33$ are larger than those at $H/D_t = 0.53$ (compare Fig. 4 with Fig. 5 or compare Fig. 6 with Fig. 7). Experiments found that the interaction of spouting gas and fluidizing gas in the distributor region are intensive, and particles in this region are fluidized and many of then are entrained into the spout [6,17–19]. The turbulence movements of gas and particles might contribute to the propagation of pressure waves, which leads to less difference in pressure drops between the spout and annulus.

3.2. Maximum spouting pressure drop

As shown in Fig. 2, at a given fluidizing gas velocity while increasing the spouting gas velocity, the total pressure drop increases first and then decreases gradually after it reaches to a maximum value (see Fig. 2). This value is defined as the maximum spouting pressure drop of a spout-fluid bed. The maximum spouting pressure drop of spout-fluid bed is the data required to initiate spouting, which is an important parameter for spout-fluid bed design and operation.

It should be indicated that the peak pressure drop reproducibility is low. As shown in Figs. 2–7, the pressure drop time serials fluctuate around a certain value at a given operating condition. This value is considered as the pressure drop at this operating condition. However, in order to obtain more reliable data, repetitious experiments must be performed. For the present work, the maximum spouting pressure drop cannot be measured directly from Fig. 2, since the pressure drops are fluctuant and many operating conditions are included in this figure.

The measurement of the maximum spouting pressure drops was carried out as follows: measured the pressure drop time serials when steadily increasing the spouting velocity while keeping the fluidizing gas as constant first, then fitted the dada by least square method. The vale of maximum spouting pressure drop could be obtained in the fitted line. Further, repetitious experiments were performed and three or four vales of maximum spouting pressure drop were obtained. Finally, an algebraic average of these values was determined as the maximum spouting pressure drop. It is sure that the experimental error can be declined to a very low level based on this.

The effect of static bed height on maximum spouting pressure drops for three types of particles is shown in Fig. 8.

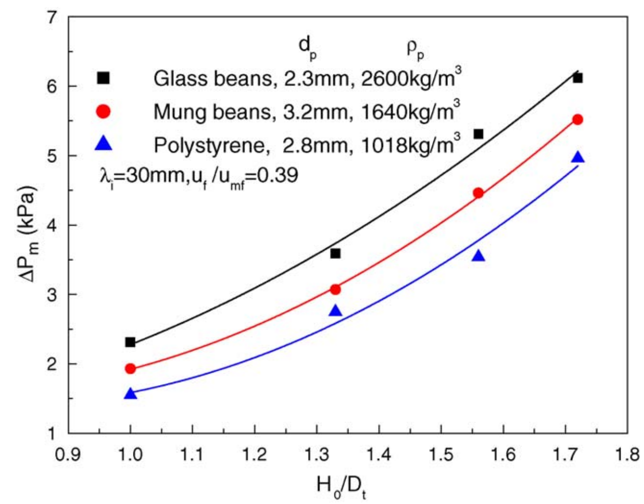

Fig. 8. Maximum spouting pressure drop as a function of static bed height.

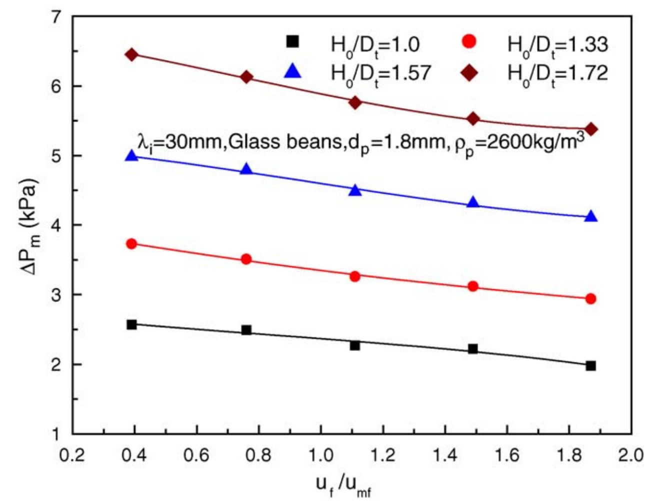

Fig. 10. Maximum spouting pressure drop as a function of fluidizing gas superficial velocity.

The maximum spouting pressure drop increases with static bed height. Because much lower particle density, the bed packed with polyethylene particles requires much lower maximum spouting pressure drop than packed with glass beans. These trends are similar to those reported for conical–cylindrical spouted beds [1–3,25–27] and rectangular spouted beds [22–24]. Fig. 9 shows the maximum spout pressure drops as a function of particle diameter for four static bed heights. As shown by Fig. 9, the maximum spouting pressure drop decreases with particle diameter. The well-known Ergun equation [28] shows that the resistance of particles decreases with particle diameter. When the spouting gas penetrates the bed to initiate spouting, lower maximum spouting pressure drop is required due to the less resistance of bed materials.

Fig. 10 illustrates the maximum spouting pressure drops as a function of fluidizing gas superficial velocity for four static bed heights. As shown in Fig. 10, the maximum spouting pressure drops decrease with increasing fluidizing gas superficial velocity. It is known that large start-up pressure drop is one of the disadvantages of pouted beds, however the present results show that spout-fluid bed can somewhat lighten this disadvantage by introducing an auxiliary gas (fluidizing gas) into the bed.

The effect of spout nozzle width on the maximum spout pressure drops for three types of particles is presented in Fig. 10. Previous investigation on rectangular spouted bed [22,23] showed that there is little or no influence of spout nozzle width. However, the present experiments showed that the maximum spouting pressure drop somewhat increases with spout nozzle width when both spouting and fluidizing gas velocities are kept constant. This might due to the following reasons: for a given spout nozzle based spouting gas velocity, the entrainment ability of central spout jet increases with spout nozzle width due to the larger spouting gas momentum flow rate in this case. More particles are entrained into the spout from annulus. This might exhaust more spouting gas momentum, leading to the increase in maximum spouting pressure drop (Fig. 11).

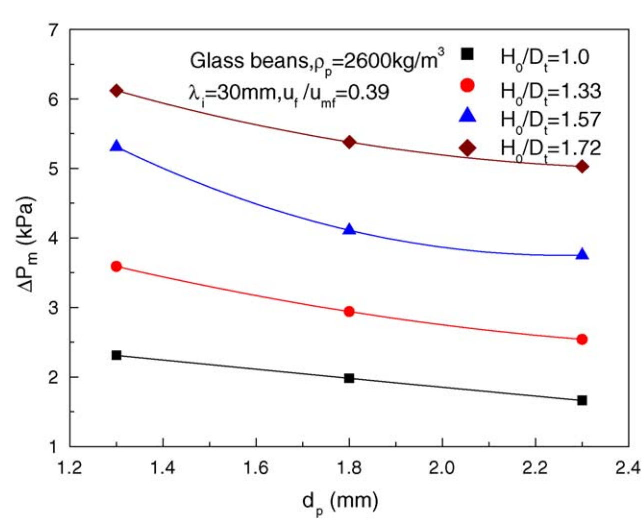

Fig. 9. Maximum spouting pressure drop as a function of particle diameter.

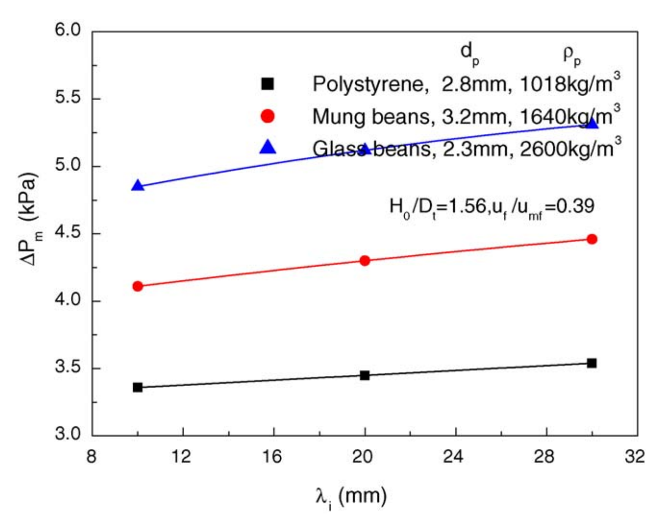

Fig. 11. Maximum spouting pressure drop as a function of spout nozzle width.

3.3. Minimum spouting/spout-fluidizing velocity

The minimum spout-fluidizing velocity and the minimum spouting velocity are two important parameters for the design and operation of spout-fluid beds. The minimum spout-fluidizing velocity u_{msf} is the minimum superficial gas velocity when the spouting initiates in the central spout region and the annulus is fluidized. The determination of minimum spout-fluidizing velocity in the present work was based on the method proposed by Littman et al. [8]. The minimum spouting velocity u_{ms} in spout-fluid bed is defined as the spout nozzle based spouting gas velocity required to initiate spouting but not considering whether the annulus is fluidized or not. For a given fluidizing gas velocity, the minimum spouting velocity was measured according to the method proposed by Mathur and Epstein [26].

Fig. 12(a) presents the effect of static bed height on the minimum spout-fluidizing velocity u_{msf} at four fluidizing gas velocity. It can be seen that the minimum spout-fluidizing velocity increases with increasing static bed height. Fig. 13(a) shows the minimum spout-fluidizing velocity as a function of particle diameter. As shown in Fig. 13(a), the minimum spout-fluidizing velocity increases with particle diameter. The effect of spout nozzle width on minimum spout-fluidizing velocity is presented in Fig. 14(a), which shows that the minimum spout-fluidizing velocity increases with spout nozzle width. These trends are similar to those reported for conical–cylindrical spout-fluid bed [1–3,5,10,11]. Besides, Figs. 12(a), 13(a) and 14(a) also show the effect of fluidizing gas velocity on the minimum spout-fluidizing velocity. The minimum spout-fluidizing velocity increases with fluidizing gas velocity.

Figs. 12(b), 13(b) and 14(b) present the contributions of spouting gas velocity $u_{s,msf}$ and fluidizing gas velocity $u_{f,msf}$ at the minimum spout-fluidizing condition. The contribution of spouting gas velocity $u_{s,msf}$ can be consider as the minimum spouting velocity when the annular region is fluidized. As shown in these figures, the minimum spouting velocities increase with static bed height, particle diameter and spout nozzle width at minimum spout-fluidizing condition. However, the minimum spouting velocity at minimum spout-fluidizing condition decreases with fluidizing gas velocity. This implies that the fluidizing gas transfer from the annular region into spout region, which contributes to initiating the spouting. Our previous study on the gas mixing in the same experimental equipment [19] can confirm this.

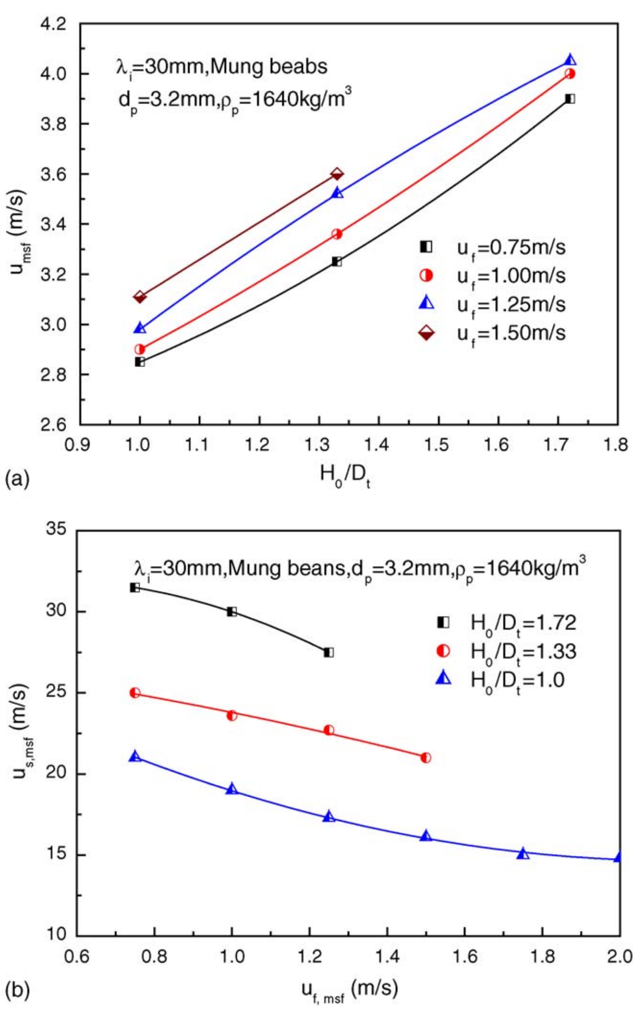

Fig. 12. Minimum spout-fluidizing velocity as a function of static bed height.

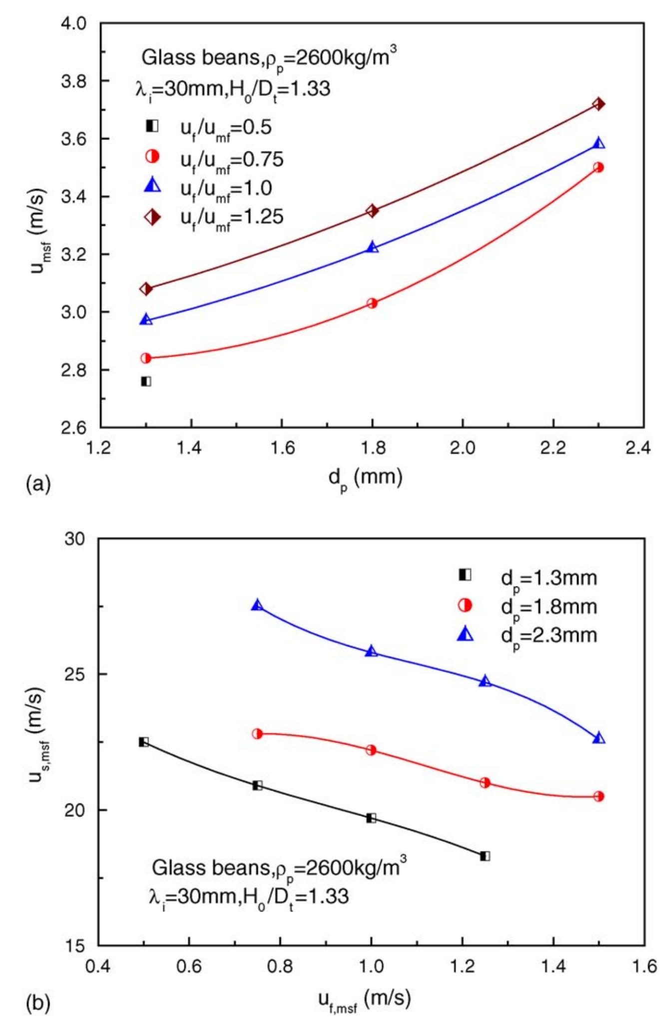

Fig. 13. Minimum spout-fluidizing velocity as a function of particle diameter.

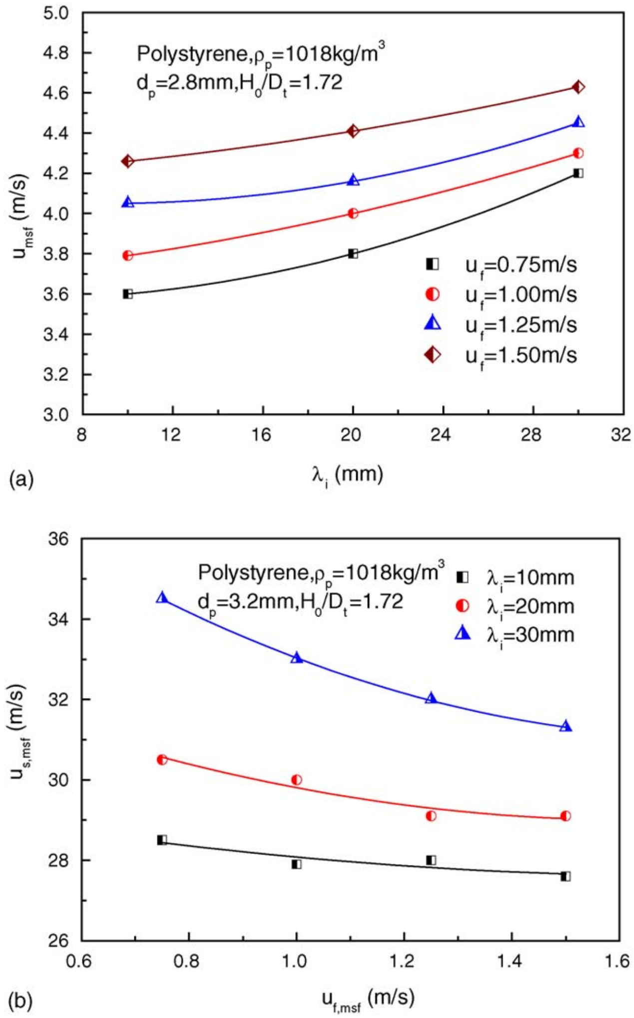

Fig. 14. Minimum spout-fluidizing velocity as a function of spout nozzle width.

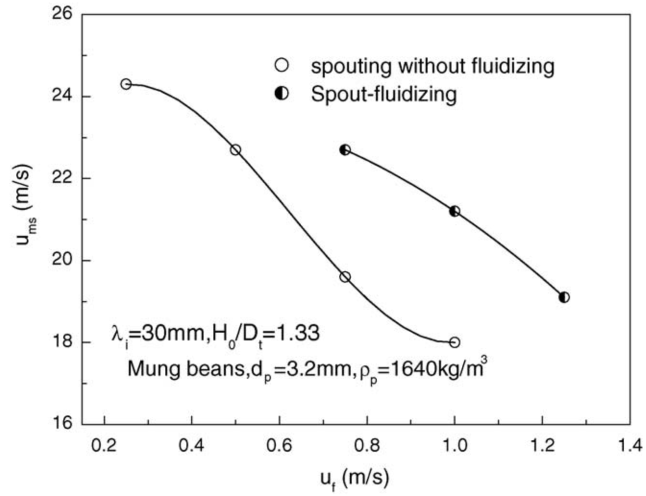

Fig. 15. Comparison of minimum spouting velocity with annular region fluidized to without annular region fluidized.

The above discussion on minimum spouting velocity is under the condition that the annular region is fluidized. However, the spout-fluid bed is always operated under the condition that the annular region is not fluidized. Fig. 15 shows the comparison of minimum spouting velocity when the annular region is fluidized with the annular region is not fluidized. The annular region is hard to get fluidized without fluidizing gas (this case turns to be a spouted bed), though there is gas transfer from the spout jet into the annular region. It can be seen that the minimum spouting velocity when the annular dense region is fluidized is larger than in the case when the annular region is not fluidized. Similar to the case when the annulus is fluidized, the minimum spouting velocity when the annulus is not fluidized decreases with fluidizing gas velocity.

3.4. Correlation of minimum spouting/spout-fluidizing velocity

Though the minimum spout-fluidizing velocity and minimum spouting velocity are two important parameters for spout-fluid bed design and operation, there has been lacking of study on correlation of these two parameters in publications so far. Thus, investigations on the corrections of minimum spout-fluidizing velocity and minimum spouting velocity of spout-fluid bed are expected. In literatures, many corrections of minimum spouting velocity for spouted beds, for example well-known Mathur-Gishler (1955) [25] correlation and some others (e.g. [29–34]). Bi (2004) [35] performed a detailed discussion on these correlations. However, these correlations did not consider the effect of fluidizing gas velocity on the minimum spouting velocity since they are based the experiments on spouted beds (Fig. 16). The present work has performed a preliminary effort, to develop a correlation of minimum spouting velocity for the spout-fluid bed.

According to the analysis above, static bed height, spout nozzle diameter, particle density, particle diameter and fluidizing gas flow rate take effect on the minimum spout-fluidizing velocity and minimum spouting velocity. Based on correlation of Choi and Meisen (1992) [33] for the spouted bed and added the term $(1+(u_f/u_{mf}))$ to consider the effect of fluidizing gas on the minimum spouting velocity, the correlation of minimum spouting

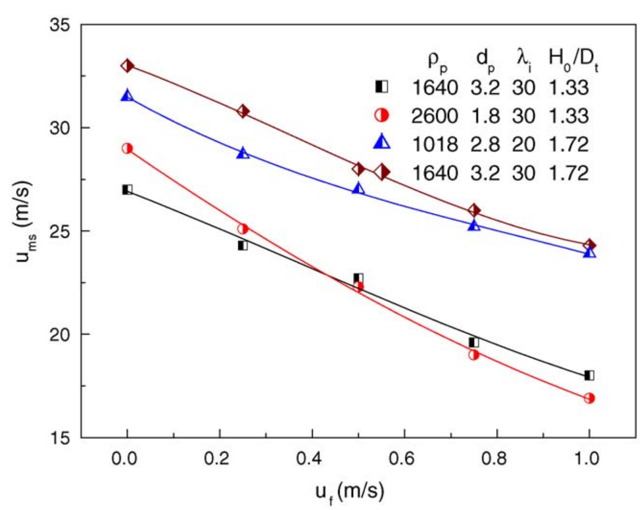

Fig. 16. Minimum spouting velocity as a function of fluidizing gas velocity.

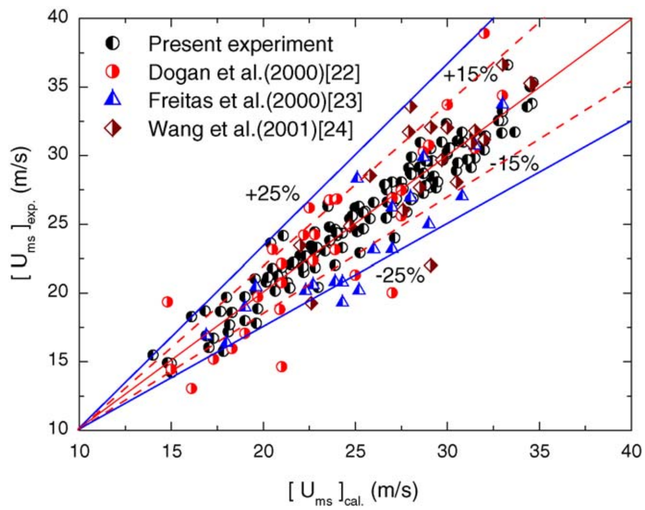

Fig. 17. Comparisons of minimum spouting velocity experimental data with calculated data from the present correlation.

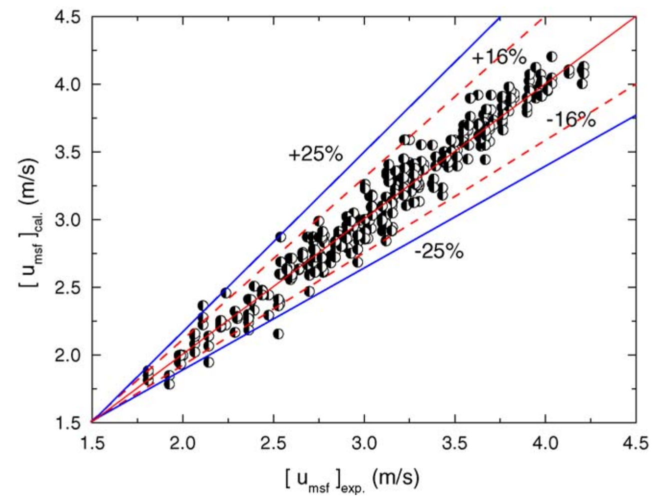

Fig. 18. Comparisons of minimum spout-fluidizing velocity experimental data with calculated data from the present correlation.

velocity for the spout-fluid bed is given as

$$u_{\mathrm{ms}} = f\left(\frac{d_{\mathrm{p}}}{D_{\mathrm{t}}}, \frac{\lambda_i}{D_{\mathrm{t}}}, (1+\frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}), \frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}, \frac{H_0}{D_{\mathrm{t}}}\right) = a(2gH_0)^{0.5}\left(\frac{d_{\mathrm{p}}}{D_{\mathrm{t}}}\right)^b\left(\frac{\lambda_i}{D_{\mathrm{t}}}\right)^c\left(\frac{H_0}{D_{\mathrm{t}}}\right)^d \times\left(1+\frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}\right)^e\left(\frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}\right)^f \quad (1)$$

The correlation of the minimum spouting velocity was also determined by regressing 314 groups of present experimental data by using a commercial PEMS (Package of Encyclopedias of Medical Statistic) program [17], it is

$$u_{\mathrm{ms}} = 24.5(2gH_0)^{0.5}\left(\frac{d_{\mathrm{p}}}{D_t}\right)^{0.472}\left(\frac{\lambda_i}{D_t}\right)^{0.183}\left(\frac{H_0}{D_{\mathrm{t}}}\right)^{0.208} \times\left(1+\frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}\right)^{-0.284}\left(\frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}\right)^{0.225} \quad u_{\mathrm{f}} \geq 0 \quad (2)$$

The correlation was used to predict the minimum spouting velocity at various operation conditions. Typical comparisons of present experimental data and some publications with calculated data from present correlation are presented in Fig. 17. In which, the experimental data from publications [22–24] were obtained from rectangular spouted beds. The results show that the present correlation is in satisfied agreement with the present experiments and some published experimental results.

The correlation of minimum spout-fluidizing velocity can be expressed as

$$u_{\mathrm{msf}} = f\left(\frac{d_{\mathrm{p}}}{D_{\mathrm{t}}}, \frac{\lambda_i}{D_{\mathrm{t}}}, \frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}, \frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}, \frac{H_0}{D_{\mathrm{t}}}\right) = a(2gH_0)^{0.5}\left(\frac{d_{\mathrm{p}}}{D_{\mathrm{t}}}\right)^b \times\left(\frac{\lambda_i}{D_t}\right)^c\left(\frac{H_0}{D_{\mathrm{t}}}\right)^d\left(\frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}\right)^e\left(\frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}\right)^f \quad (3)$$

This format is very similar to the correlation of minimum spouting velocity, only to replace the term $(1+(u_{\mathrm{f}}/u_{\mathrm{mf}}))$ by $(u_{\mathrm{f}}/u_{\mathrm{mf}})$. Because the present experiments show that spouting can achieve without reference to fluidizing gas, while spout-fluidizing can not achieve if the fluidizing gas is zero.

By regressing 426 groups of present experimental data by using the same commercial PEMS, the correlation of the minimum spout-fluidizing velocity was determined as

$$u_{\mathrm{msf}} = 1.65(2gH_0)^{0.5}\left(\frac{d_{\mathrm{p}}}{D_t}\right)^{0.465}\left(\frac{\lambda_i}{D_{\mathrm{t}}}\right)^{0.264}\left(\frac{H_0}{D_{\mathrm{t}}}\right)^{0.178} \times\left(\frac{u_{\mathrm{f}}}{u_{\mathrm{mf}}}\right)^{0.172}\left(\frac{\rho_{\mathrm{p}}-\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}}\right)^{0.273} \quad u_{\mathrm{f}} > 0 \quad (4)$$

The correlation was put forward to predict the minimum spout-fluidizing velocity at various operation conditions. Typical comparisons of present experimental data with calculated data from present correlation are presented in Fig. 18. The present correlation agrees with experimental results qualitatively. However, It is pity that detailed comparisons of the present calculations to any measurement in publications is not available due to the lack of experimental data.

4. Conclusions

Experimental investigations on the hydrodynamic characteristics were carried out in a rectangular spout-fluid bed with cross section of 300 mm × 30 mm and height of 2000 mm. Six kinds of Geldart group D particles were used as bed materials. The effects of static bed height, particle property, spout nozzle width and fluidizing gas velocity on the pressure drop, maximum spouting pressure drop, minimum spouting and spout-fluidizing velocities were systematically studied.

The results show that the total bed pressure drop appears a spouted bed characteristic when increasing the spouting gas velocity and keeping the fluidizing gas velocity constant, while it appears a fluidized bed characteristic when increasing the fluidizing gas velocity and keeping the spouting gas velocity constant. The maximum spouting pressure drop required initiating spouting increases with static bed height, spout nozzle width and particle density, while it decreases with particle diameter and fluidizing gas velocity.

The minimum spouting and spout-fluidizing velocities both increase with static bed height, particle diameter, particles diameter, spout nozzle width. The minimum spout-fluidizing velocity increases while the minimum spouting velocity decreases with fluidizing gas velocity. Besides, correlations considered all of the above effects were developed to predict the minimum spouting and spout-fluidizing velocities, which were in satisfied agreement with the present experiments and some publications.

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