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Spout characteristics of a cylindrical spout-fluid bed with elevated pressure

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Abstract

Experimental studies on the spout characteristics of a visible pressurized cylindrical spout-fluid bed (I.D. = 0.1 m) with pressure up to 0.4 MPa were carried out. Geldart group D particles of 1.6 and 2.3 mm were used as bed materials. Experimental data of minimum spouting velocity, axial pressure drop and fountain height were obtained. It was found that the minimum spouting velocity increased with increasing initial bed height and particle diameter, while it decreased with increasing fluidizing gas velocity, which is independent of pressure. Elevation of pressure yielded a decrease in minimum spouting velocity. Similar to the spouted bed, the axial pressure drop in spout-fluid bed was found to be insensitive to the change of pressure. The fountain height increased as the spouting gas velocity increased; while it decreased with particle diameter, initial bed height and fluidizing gas velocity. An increase in pressure caused an increase in the fountain height.

Keywords: Spout-fluid bed; Spout; Minimum spouting velocity; Fountain height; Pressure drop

1. Introduction

Spout-fluid beds have been of increasing interest in the petrochemical, chemical and metallurgic industries. For example, Coal Research Establishment (CRE) in Britain had processed a spout-fluid bed coal gasifier at pressure up to 2 MPa to original Pressurized Fluidized bed Combustion Combined Cycle (PFBC–CC) system, combining gasification with combustion, in order to improve the total efficiency to 45–47% [1]. Pressurized spout-fluid bed coal gasifiers at a pressure of 0.5 MPa have been developed for second-generation PFBC–CC system in Southeast University of China [2–4].

The spout characteristics are important for the design, operation and scale-up of both spouted beds and spout-fluid beds. Many valuable experimental and theoretical studies at ambient conditions (e.g. [5–14]) have been carried out in the past 20 years. However, there are very few publications on this subject of elevated pressures especially for spout-fluid beds. A group at University of British Columbia (UBC) of Canada experimentally tested the spouting behavior of a half-cylindrical spouted bed at elevated pressures up to 350 kPa and examined the validity of exiting equations [15]. Xiao et al. [16] investigated the solids circulation flux and gas bypassing in a half-cylindrical pressurized spout-fluid bed with a draft tube. The knowledge about the spout characteristics at elevated pressure is still not completed. Due to the lack of data, the spout-fluid bed technique is currently not widely applied in industrial process.

In the present work, experiments were carried out to determine the spout characteristics in a visible pressurized cylindrical spout-fluid bed with pressures up to 0.4 MPa. It focuses on examining the effect of high pressure on the minimum spouting gas velocity, fountain height and bed pressure drop.

2. Experiments

2.1. Experimental set-up

The visible pressurized cylindrical spout-fluid bed experimental set-up is schematically shown in Fig. 1. This system consists of a visible pressurized cylindrical spout-fluid bed col-

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Nomenclature

d_p	particle diameter (m)
D_t	bed diameter or width (m)
D_i	spout nozzle diameter or width (m)
f	sampling frequency (Hz)
H_0	initial bed height (m)
H	bed height (m)
H_s	fountain height (m)
P	bed pressure (MPa)
P_z	static pressure at height of z (MPa)
P_H	static pressure at height of H (MPa)
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_f	fluidizing gas velocity (m/s)
u_s	spouting gas velocity (m/s)
u_{mf}	minimum fluidizing gas velocity (m/s)
z	axial bed location (m)
ΔP_H	maximum spouting pressure drop (MPa)
ΔP_t	total pressure drop (MPa)

Greek symbols

ε	particles bulk voidage
ρ_p	particle density (kg/m^3)
ρ_g	gas density (kg/m^3)

umn, a gas supply system and some sampling instruments. The column is 0.1 m in diameter and height of 2 m. It was made of 8 mm thick Plexiglas. The spout nozzle is round in shape and 0.01 m in diameter. A conical gas distributor with a 60° inclination angle is located at the bottom of the bed. The orifices on the gas distributor are 1 mm in diameter. They are vertical to the gas distributor and proportional spacing. The total area of all orifices is 1.1% of the gas distributor.

An air compressor supplied the spouting gas and the fluidizing gas. 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 injected into the gas chamber and then entered the bed via the orifices on the gas distributor. The bed pressure was controlled by two valves placed on the outlet pipe. One is manual globe valve (equipment 8 in Fig. 1), and the other is automatic pressure control valve (equipment 9 in Fig. 1). The globe valve was used for the coarse adjustment of outlet gas pressure and flux when the inlet gases pressure and flux changed. The automatic pressure control valve was used for the fine adjustment of outlet gas pressure by automatic adjusting outlet gas flux when the inlet gas pressure or flux fluctuated.

Pressure fluctuations in the bed were obtained by a multi-channel differential pressure signals sampling system. Pressure-measuring holes located on the back wall of the column, at heights of 0.14, 0.2, 0.3, 0.4, 0.6, 0.7 and 1.0 m 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. The differential pressures were measured and then converted into voltage signals by multi-channel differential pressure signal transmitter with a scale of 0–100 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 floodlights were used to enhance the photo definition when photographing. The digital camera was used to instantaneously photograph the flow patterns by its high-speed function (three frames per second), and the digital video recorder was used to continuously record the flow patterns.

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

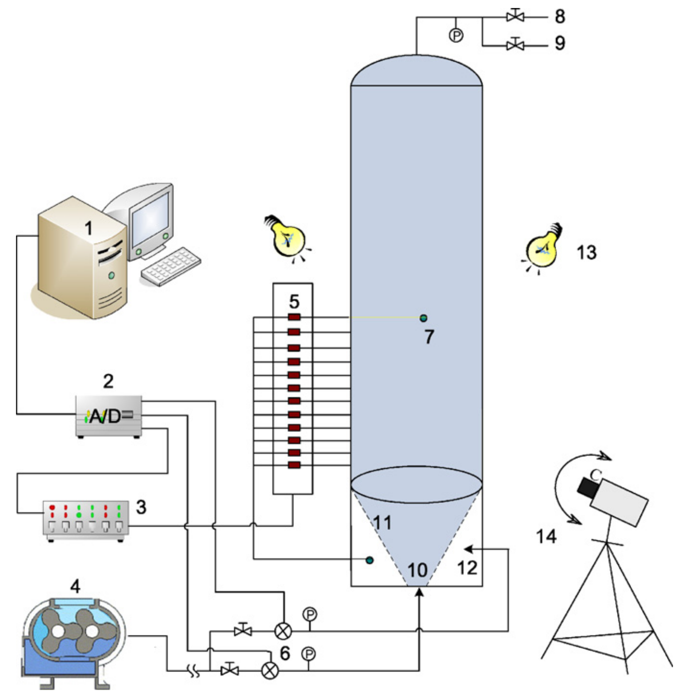

Fig. 1. Schematic diagram of visible pressurized cylindrical spout-fluid bed experimental system. (1) Computer; (2) A/D converter; (3) pressure signal transmitter; (4) air compressor; (5) differential pressure sensor; (6) flow meter; (7) pressure measured port; (8) first bed pressure controlling valve; (9) second bed pressure controlling valve; (10) spout nozzle; (11) gas distributor; (12) fluidizing gas chamber; (13) floodlight; (14) digital CCD.

Table 1
Experimental and sampling conditions

H_0 (m)	Q_s (m^3/s)	Q_f (m^3/s)	f (Hz)	t (s)
0.1–0.3	0–0.08	0–0.04	100	180

Table 2
Particle properties

Particles	d_p (mm)	ρ_p (kg/m^3)	ε	u_{mf} (m/s)
Millet A	1.6	1330	0.40	0.58
Millet B	2.3	1330	0.42	0.81

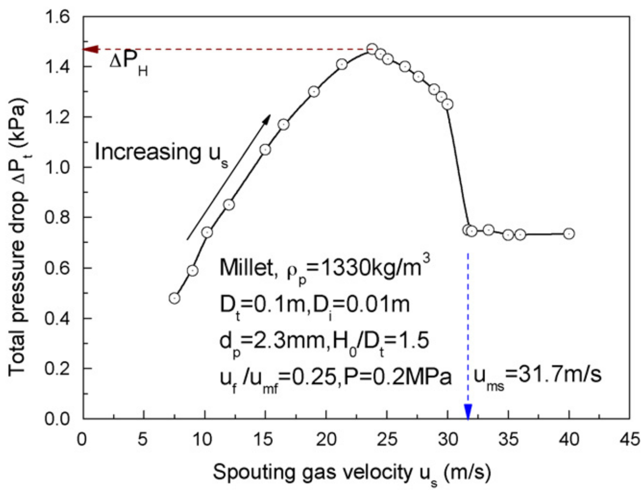

Fig. 2. Determination of the minimum spouting velocity.

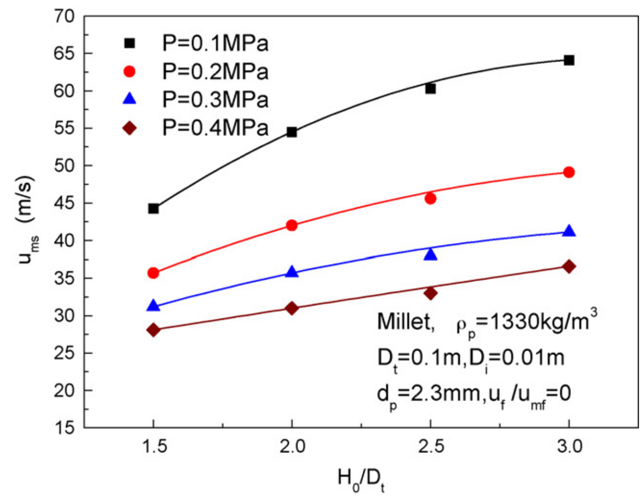

Fig. 4. Effect of initial bed height on the minimum spouting velocity.

3. Results and discussion

3.1. Minimum spouting velocity

The minimum spouting velocity is one of important spout characteristics of both spouted bed and spout-fluid beds. 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. The minimum spouting velocity was measured according to one of the methods proposed by Mathur and Epstein [17]. For a given fluidizing gas velocity, by increasing the spouting gas velocity, the total pressure drop increased first, and then decreased gradually after it reaches a maximum value (maximum spouting pressure drop, ΔP_{H}). Suddenly the pressure drop declined to a relatively lower value when the spouting gas velocity kept on increasing up to a certain value. This value is determined as the minimum spouting velocity u_{ms}, as shown in Fig. 2.

Fig. 3 presents the comparison of minimum spouting velocity for particles in different diameter. It can be seen that the minimum spouting gas velocity increases with increasing particle diameter. This is similar to those reported for conical–cylindrical spouted bed at ambient condition [17–19] and pressurized condition [15]. Particle inertial force and viscosity increase when the particle diameter increases, which dissipates more momentum of spouting gas to overcome the larger resistance of bed materials when the spouting gas penetrates the bed and initiates spouting. Therefore, the minimum spouting velocity increases with increasing particle diameter.

The effect of initial bed height on the minimum spouting velocity is shown in Fig. 4. The minimum spouting velocity increases with increasing initial bed height. This can be explained as follows: increasing initial bed height leads to increase in the weight of bed materials, in this case larger spouting velocity is required to overcome the increased resistance of bed materials and initiate spouting.

The fluidizing gas velocity shows remarkable effect on the minimum spouting velocity, as presented in Fig. 5, the minimum spouting velocity decreases when increasing fluidizing gas velocity. The introduction of fluidizing gas might lead to more intensively exchange of spouting gas and fluidizing gas

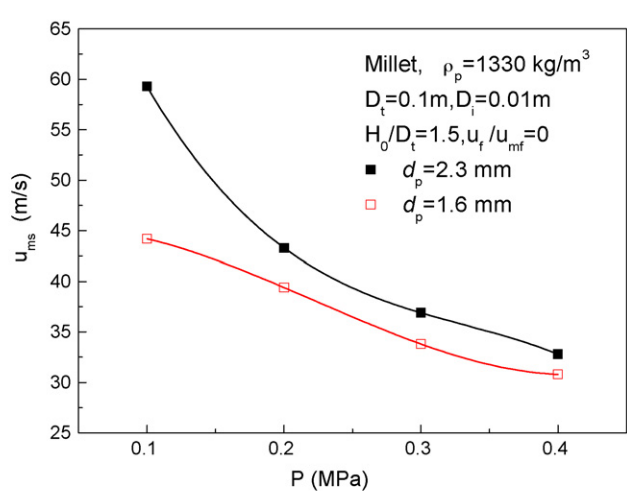

Fig. 3. Effect of particle diameter on the minimum spouting velocity.

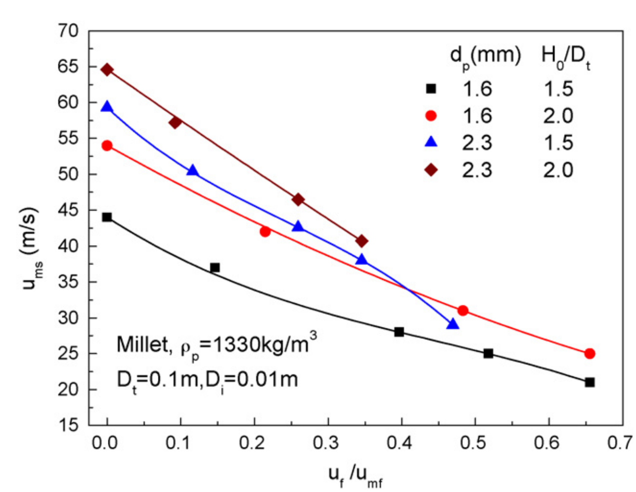

Fig. 5. Effect of fluidizing gas velocity on the minimum spouting velocity.

[6,9]. In the case when the fluidizing gas is added into the bed, the bed voidage increases which leads to the central spout gas diffusing to annular dense region, which is adverse to the initiation of spouting. On the other hand, the fluidizing gas transfers from the annular region into spout region, which contributes to initiating spouting. However, the present results show that the minimum spouting velocity decreases with increasing fluidizing gas velocity. This implies that more fluidizing gas enters into the spout region than spouting gas enters into the annular region when increasing fluidizing gas velocity and keeping the spouting gas constant.

It can be seen that the minimum spouting velocities increase with increasing particle diameter and initial bed height, while they decrease with increasing fluidizing gas velocity under ambient and pressurized conditions. This implies that the effects of particle diameter, initial bed height and fluidizing gas velocity on the minimum spouting velocities are independent of pressure.

However, the minimum spouting velocity was found to decrease with increasing pressure, as shown in Figs. 3, 4 and 6. Fig. 6 presents the experimental data of minimum spouting velocities under different pressures. This can be explained as follows: increasing pressure causes an increase in gas density, which results in increasing gas drag and promoting the particles in the central spout region upwards above the surface of the bed; in the meanwhile, the penetration ability increases due to the increase in spouting gas density. Thus, smaller spouting gas velocity is required to initiate spouting in this case. The trend that u_{ms} decreases with increasing pressure can also be found from the well-known Mathur and Gishler (1955) correlation [17] for spouted bed and Zhong et al. (2006) correlation [20] derived from spout-fluid beds. The correlations are presented as follows.

Mathur and Gishler correlation [17]:

$$u_{ms}=\left(\frac{d_p}{D_t}\right)\left(\frac{D_i}{D_t}\right)^{1/3}\left(\frac{2gH_0(\rho_p-\rho_g)}{\rho_g}\right)^{0.5} \quad (1)$$

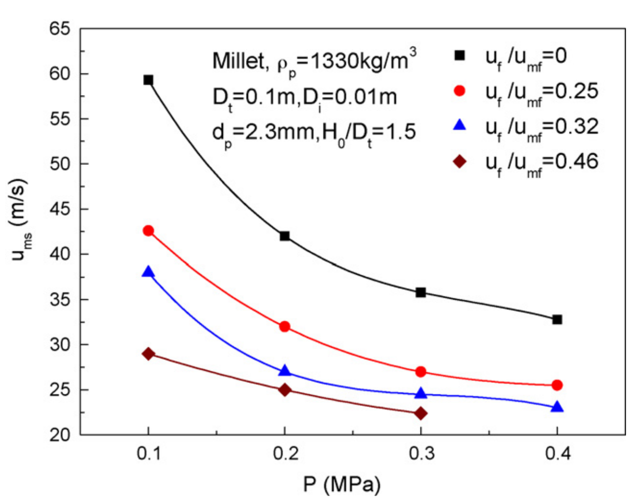

Fig. 6. Effect of pressure on the minimum spouting velocity.

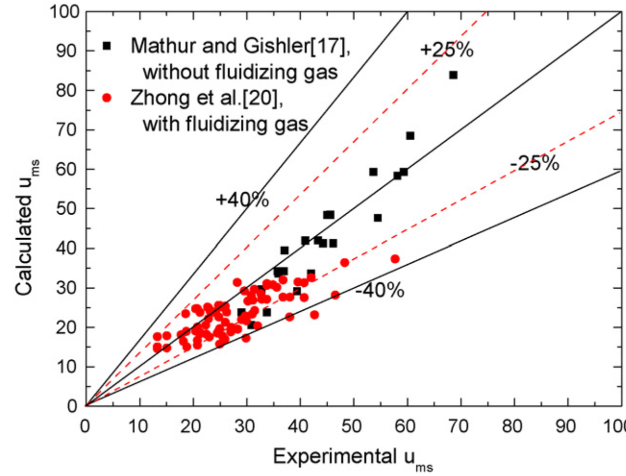

Fig. 7. Comparisons of present experimental data with calculated data by existing correlations in literatures.

Zhong et al. correlation [20]:

$$u_{ms}=24.5(2gH_0)^{0.5}\left(\frac{d_p}{D_t}\right)^{0.472}\left(\frac{D_i}{D_t}\right)^{0.183}\left(\frac{H_0}{D_t}\right)^{0.208}\times\left(1+\frac{u_f}{u_{mf}}\right)^{-0.284}\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{0.225},\quad u_f\geq 0 \quad (2)$$

Fig. 7 shows the comparisons of present experimental data with calculated data by these two correlations. It is seen that experimental data are in well agreement with the calculated data by Mathur and Gishler correlation without fluidizing gas. The deviations of most experimental data with calculated data are within 25%, the mean deviation is only 13.4%. This deviation is mainly due to the under-prediction of u_{ms}. This deviation is less than the previous study [17] on a half-cylindrical spouted bed ranged from 26 to 50% for different particles. However, the deviations of some experimental data with calculated data by Zhong et al. correlation with fluidizing gas are larger than 25% but within 40%, the mean deviation is 19.2%. Some of the calculated data underpredicts u_{ms}. These findings indicate that the existing correlation [17,20] obtained at ambient condition (20 °C, 101325 Pa) could predict reasonable trend of u_{ms} within certain deviation except that some of the predictions are less than experimental value.

3.2. Fountain height

The fountain heights at different operating conditions were measured from digital photographs obtained in the experiments. The fountain height is defined as the vertical distance between the top of the spout and the dense bed surface. The determination of the fountain height is shown in Fig. 8.

The fountain heights at different spouting gas velocities and initial bed heights under the pressure of 0.2 MPa are presented in Fig. 9. The fountain height increases with increasing spouting gas velocity while it decreases with initial bed height. Increasing spouting gas velocity results in increasing spouting gas momen-

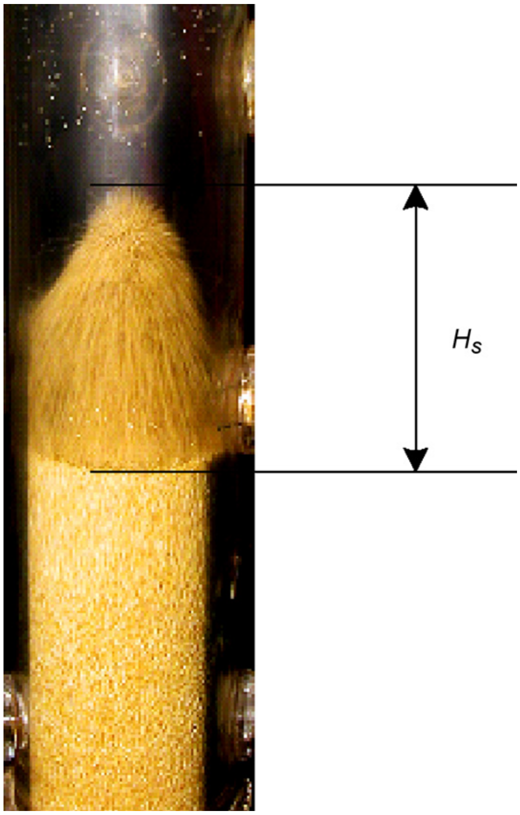

Fig. 8. Determination of the fountain height.

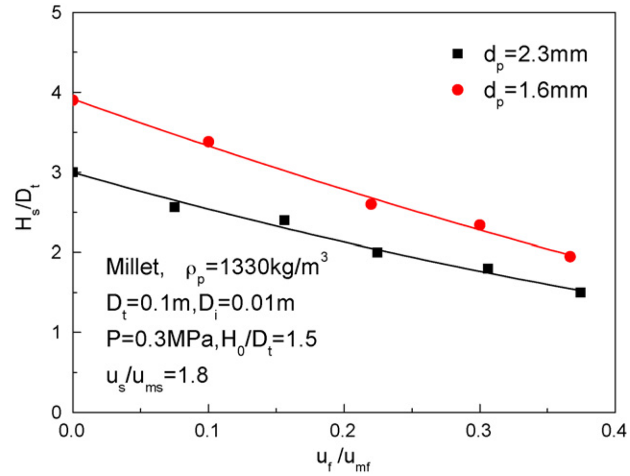

Fig. 10. Effect of fluidizing gas velocity and particle diameter on the fountain height.

tum, which leads to a larger fountain height since the particles in the central spout region can be spouted much higher. However, more spouting gas momentum would be exhausted when the spout jet penetrates the bed because the resistance of bed materials increases in the case that the initial bed height increases. As a result, the fountain height decreases.

By increasing the fluidizing gas velocity and particle diameter, the fountain height decreases, as shown in Fig. 10. Increasing fluidizing gas velocity might lead to more intensively exchange of spouting gas and fluidizing gas. Though there is more fluidizing gas transfer from annular region to the central spout region leading to decreasing minimum spouting gas velocity, the exchange and interaction of spouting with fluidizing gas exhaust the spouting gas momentum, the rigidity and penetration ability of spout jet decrease. As a result, the particles are spouted to less higher place. Thus, the fountain height decreases with increasing fluidizing gas velocity. For particles with larger diameter, larger particle inertial force and viscosity will lead to larger resistance that requires the spouting gas to overcome when penetrating the bed. Therefore, the fountain height decreases with increasing particle diameter.

Fig. 11 shows the influence of pressure on the fountain height. Increase in pressure would lead to the increase in fountain height. This can be explained as follows: increasing pressure causes an increase in gas density, which results in increasing gas drag and promoting the particles in the central spout region upwards above the surface of the bed; on the other hand, the penetration ability of spouting gas increases due to increasing spouting gas density. Therefore, the fountain height increases with increasing pressure.

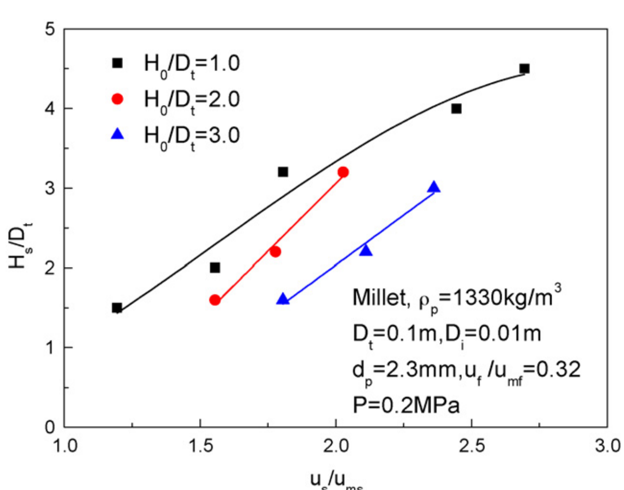

Fig. 9. Effect of spouting gas velocity and initial bed height on the fountain height.

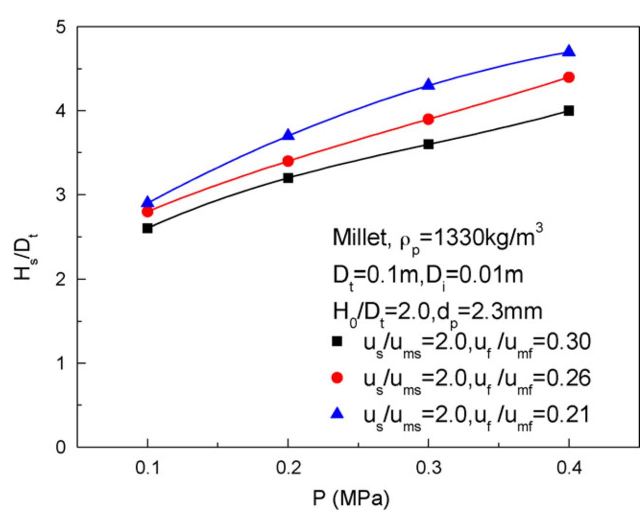

Fig. 11. Effect of pressure on the fountain height.

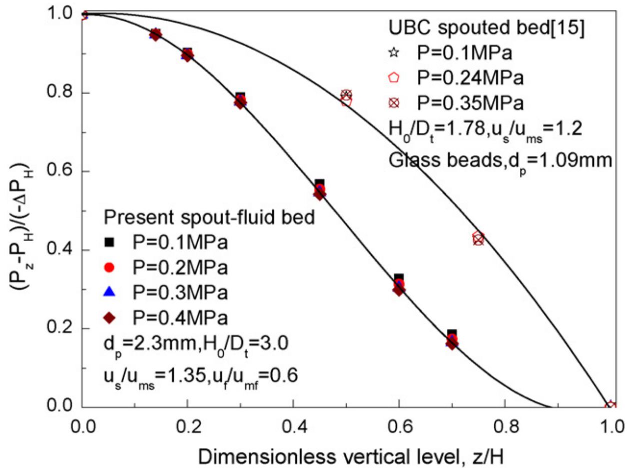

Fig. 12. Effect of pressure on the axial dimensionless pressure drop.

3.3. Pressure drop

The effect of pressure on the axial dimensionless pressure drop of present spout-fluid bed and UBC spouted bed [15] is presented in Fig. 12. It can be seen that the axial dimensionless pressure drop is independent of pressure. The explanation of insensitivity of the axial pressure gradient to pressure is that when the pressure is increased, the gas density increases and the voidage and gas velocity in the annular region decreases, which in turn produces constant or offsetting values of viscosity item and kinetic energy item in well-known Ergun equation [15]. However, the axial dimensionless pressure drop of present spout-fluid bed is less than spouted bed due to the introduction of fluidizing gas. The fluidizing gas will increase the voidage in spout-fluid bed [6], which lead to decrease in pressure drop according to Ergun equation.

4. Conclusion

The spout characteristics of a visible pressurized cylindrical spout-fluid bed (I.D. = 0.1 m) with pressure up to 0.4 MPa were experimentally studied. Experimental data of minimum spouting velocity, axial pressure drop and fountain height were obtained. The results show that the minimum spouting velocity increases with increasing initial bed height and particle diameter, while it decreased with increasing fluidizing gas velocity, which is independent of pressure. Elevating pressure leads to decrease in minimum spouting velocity. The axial pressure drop is insensitive to the pressure. The fountain height increases with increasing spouting gas velocity but decreases with particle diameter, initial bed height and fluidizing gas velocity. Increase in pressure results in increasing fountain height.

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