Study of Pressure Drop in the 2D Spouted Bed with Conical Base of Binary Particle Mixtures: Effects of Particle Size and Density

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ABSTRACT: *In this study, the pressure drop for the binary mixtures of particles differing in size and density in a pseudo-2D spouted bed was experimentally studied. A binary mixture of solid particles including sand, Gypsum, and polyurethane was used in the experimental setup. Effects of static bed height, cone angle, particles diameter, and a particles weight fraction on the bed pressure drop were evaluated. The relationship between the peak pressure drops of the binary mixtures to the minimum spouting velocity was discussed. The trend of variation of pressure drop versus superficial gas velocities for binary particle mixtures in the spouted beds was found to be similar with that for the single sized particle system. The particles that sink to the bed bottom are called jetsam, whereas those gathered at the upper section of the bed are called flotsam. At the same air velocity for jetsam and flotsam rich systems, the maximum pressure drop in the jetsam rich system was larger than the flotsam one. The measured values of minimum spouting velocity were compared with some empirical correlations for single sized particles in spouted beds.*

KEYWORDS: *Pressure drop; 2D spouted bed; Minimum spouting velocity; Binary particles; Experiment*.

INTRODUCTION

Spouted beds are efficient air-solid contactors as the particles are thrown up by the high gas velocity in an orifice equipped at the base of a column, and thereby provide effective mixing between the gas and solid phases.

Spouted beds, which provide good mixing and contacting of particles and gas flow for coarse, irregular

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granular materials than the fluidized beds have some problems to hand for, are widely used in various physical and chemical applications such as drying, coating, granulation, combustion, coal gasification, chemical vapor deposition. Compared with the fluidized bed, the spouted bed allows for the treatment of particulate materials which are coarser in size and narrower in particle size distribution [1]. Among different types of spouted beds, the conical spouted beds have an important advantage in terms of short air residence time with narrow distribution compared to the other contacting equipment [2]. In a conical-cylindrical spouted bed, the particles fill the conical and a large portion of the cylindrical section, while in a conical spouted bed the particles are mainly processed in the cone section of the bed. The mixing and flow pattern in these two cases are quite different. Although there are a number of empirical equations for evaluating the minimum spouting velocity, bed pressure drop, and peak pressure drop of conical spouted beds, the geometrical design requirements are more stringent compared to the conventional cylindrical spouted beds [2].

Earlier hydrodynamics experimental studies on the conical spouted beds were mostly focused on measuring minimum spouting velocity, time-averaged bed pressure drop, and pressure fluctuations, and also measuring the velocity and solid volume fraction by optical fiber probes [2–12]. Previously, the pressure fluctuation analysis was utilized to clarify the flow behavior in spouted beds with mono-sized particles [13,14]. *Xu et al.* [7] investigated a statistical and frequency analysis of pressure drop for two sizes of spouted bed. *Mostoufi et al.* [6] studied hydrodynamic behavior of conical spouted beds by using Fourier transform of pressure fluctuation signals for single sized heavy particles. Several spouted beds including three full conical spouted beds with cone angles of 30°, 45° and 60° and two half spouted beds with cone angles of 30° and 45° were used in their work. It should be noted that the half beds were mostly used to visualize the bed content from the flat side of the bed. In this field, *Setarehshenas et al.* [15] found that the half-column cannot describe the hydrodynamics of a full-column, accurately, in the conical spouted beds including single sized heavy zirconia particles.

Kaewklum and *Kuprianov* [16] investigated the hydrodynamics of the air–quartz sand in the conical fluidized beds (CFB). The effects of the static bed height, cone angle, and also particle size on the fluidization pattern and hydrodynamic parameters were investigated by them [16]. They defined the minimum fluidization velocity, u_{mf}, and also the minimum velocity of full fluidization, u_{mff}, by modified *Peng* and *Fan's* [17] models for the CFBs. Their model was confirmed by experimental data for certain operating conditions and the pressure/velocity diagrams were gained with rather a high accuracy for the conical gas/particle beds with 30–45° cone angles, static bed heights in the domain of 20–30 cm and also the sand particles in the range of 300–1180 μm [16].

Dogan et al. [18] studied the parameters affecting the minimum spouting velocity and pressure drop for various particles such as bed height and a slot size of the thin rectangular spouted bed. *Jiang et al.* [19] studied the hydrodynamics of a pressurized cylindrical spouted bed with cone base operating at an absolute pressure of 1.0 MPa. They found that with an increase in pressure the minimum spouting velocity (u_{ms}) decreases, while the corresponding gas flow rate indicated an increasing trend. Their result revealed that increasing the pressure results in an increase in fountain height. *Sutkar et al.* [20] showed that the pressure drop in a spout-fluidized bed including the single sized particles increases by increasing the static bed height, nozzle diameter and density of the particles, while this term (pressure drop) is reduced when the gas velocity and the particle diameter increase. In addition, quantification of pressure drop can helpful in the selection of operating parameters and providing sufficient information regarding the generation and bubbles collapse in the bed.

The pressure fluctuations in the binary mixture of particles' systems, however, may be somewhat different than the single sized particle systems. It was shown that these differences are mainly due to the occurrence of particle segregation and mixing in the binary mixture of particle' systems [21]. *Du et al.* [22] evaluated pressure drop and pressure fluctuation signals in a spouted bed containing binary mixtures of particles and studied the flow regime transitions. They found that more irregular and fluctuated signals of pressure drop appear for binary particles spouted bed as the observed peak pressure drop returns to the particles mixing' degree. They also showed that to handle the fine particles in spouted beds, adding the coarse particles is useful to improve the stability of the spout. However, segregation phenomenon may still happen due to inadequate mixing of binary particles, which unfavorably influences on the process performance.

Formisani et al. [23] developed an approach based on the gas velocity for the fluidized bed of bidisperse mixtures of particles varying in size and density. Based on a series of experiments, *Formisani et al.* [23] identified the independent variables of a fluidized bed of bidisperse mixtures of particles affecting the minimum fluidization velocity, and the minimum velocity of full fluidization. They also highlighted the differences of behavior between density and size segregating in the fluidized beds.

More recently, *Kiani et al.* [24] studied the mixing and segregation for bidisperse mixtures of particles varying in size and density in a pseudo-2D spouted bed. They found that the segregation of solid particles and time to equilibrium decrease when the air velocity increases and is much larger than the minimum spouting velocity; the axial segregation also increases with the diameter ratio of the particles.

The above brief review reveals the lack of information about the bed pressure drop and thereby the minimum spouting velocity of pseudo 2D spouted bed for a binary mixture of particles differing in size and density. Moreover, the characterizations of flow regimes are critical for the design and operation of spouted beds with binary mixtures. Therefore, the main target of this experimental research is an investigation of the pressure drop in a spouted bed of binary mixtures of particles including sand, Gypsum, and polyurethane differing in size and density. Effects of static bed height, cone angle, particles diameter, and particles weight fraction on the bed pressure drop are evaluated. As mentioned all experiments were performed in a pseudo-two-dimensional conical spouted bed configuration. Finally, the measured data of minimum spouting velocity for binary mixtures of particles obtained in this study were compared to some famous empirical correlations developed for single sized particles in spouted beds.

EXPERIMENTAL SECTION

Experimental set-up

The experiments were carried out in a pseudo-two-dimensional conical spouted bed. The main advantage of pseudo-2D spouted beds is that they allow observing particle flow behavior and measuring several hydrodynamics parameters. Furthermore, they have a much higher surface per unit volume, and therefore are much more convenient for providing or releasing heat. The bed involves a rectangular column with cross-sectional dimensions of α=15 cm and β=2 cm and a conical section with an inclined angle of θ, which can be changed in order to study the bed cone angle impact. In addition, the cone section height of the bed is l_c =11.5 cm. The physical factors of the bed are listed in Table 1 and a used the setup is schematically shown in Fig. 1.

A schematic diagram of the used experimental setup components including the measurement equipment is shown in Fig. 2. The gas (air) was supplied by a compressor and was passed through air filters before entering the spouted bed. The airflow rate was measured by a rotameter. The experiments were performed at the ambient conditions. The pressure drops were measured by pressure transducers. As shown in Fig. 2, the conventional method of using two static pressure taps was used in this setup for measuring the pressure differential. The lower pressure probe was located near the gas distributor, while the upper tap was located at the 50 cm level above the gas distributor. However, in the present study, only the probe close to the distributor was used for measuring bed pressure drop since the pressure at the outlet of the bed is the atmospheric pressure. The openings of both pressure taps were covered with a screen as the particles cannot enter from the probes. All the experiments were conducted following the increasing gas velocity method as it is used in [25]. Although the decreasing air velocity method is preferable, the spout may collapse by decreasing air velocity close to the peak pressure drop condition. This is especially the case for relatively coarse particles similar to those used here, and this criterion was applied. Furthermore, the operating pressure drop is also an essential design parameter and may be obtained from the variation of pressure drop versus gas velocity. Thus, once the spout is open, although air velocity increases the pressure drops remains roughly constant at a value which is the operating pressure.

Materials and conditions

The experiments were conducted with air at room temperature (25°) under atmospheric condition. Sand, Gypsum, and polyurethane were used as the test particle materials in this study.

Table 1: Experimental Condition of the Conical Spouted Bed.

Item	Unit	Values
Column width, α	cm	15
Column thickness, β	cm	2
Overall bed height, δ	cm	90
Slot width, λ	cm	2
conical section height, l_c	cm	11.5
the height of the inlet port, l_p	cm	2

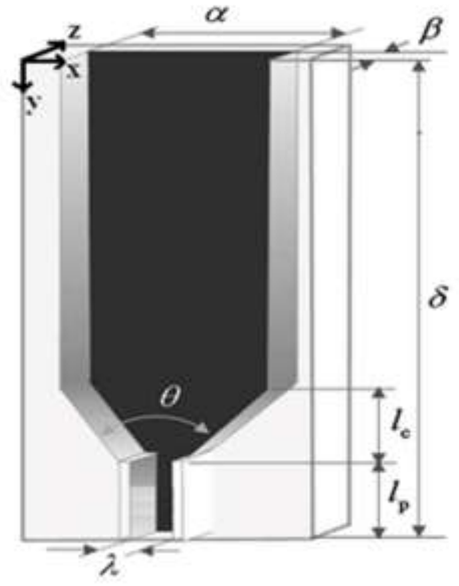

Fig. 1: Schematic of the spouted bed.

Diameters of spherical particles were measured by caliper and the average particle diameter was evaluated. Mean diameters of irregular particles were determined with use of sieve analysis. The particles' physical properties are summarized in Table 2. The density and viscosity of gas inlet are, respectively, 1.185 kg/m^3 and 1.7894×10^{-5} kg/ms. Each experiment is carried out with a binary mixture of particles varying in size or density. The denser or larger particles that sink in the bottom of the bed are stated to "jetsam". The smaller or lighter ones that float to the upper part of the bed are stated to "flotsam". The experiment was performed by Gypsum as the jetsam particles and polyurethane as the flotsam particles. Sand particles with higher diameters were also used as jetsam. Each experiment was carried out with different weight percentages of the particles. The initial particle distribution was fully mixed in each experiment

RESULTS AND DISCUSSION

The pressure drop of the binary particle mixture

Influence of static bed height on pressure drop in bed contain binary particles

Effects of the inlet airflow velocity and static bed height on the pressure drop of the bed with a binary mixture of particles composed of sand (1) and sand (3) are investigated. Accordingly, the experiments were performed for binary mixtures of sand particles with the following components: sand (1) (ρ=2650 kg/m^3; d=1.77 mm), sand (3) (ρ=2650 kg/m^3; d=0.356 mm). These sand particles have the same densities, but different sizes. The binary mixtures are classified based on the jetsam weight fraction, which settles on the bottom of the bed. Fig. 3 shows the pressure drop profile of jetsam particles as a function of air velocity in the jetsam-rich systems (binary mixtures of sand (1) and sand (3) with average weight fractions of 95% and 5%).

Maximum pressure drop and minimum spouting velocity can be clearly identified from the curves shown in Figs. 3−7. At first, as the air velocity increases, the pressure drop increases to its maximum value. Then, by further increase of air velocity, a fountain is created and the pressure drop decreases to a value that remains roughly constant.

Fig. 3 shows that the increasing trend of pressure drop with a superficial gas velocity that it reaches a maximum value, after which a sharp decrease occurs. This peak point is the maximum pressure drop and air flow velocity at this point is corresponding to the minimum spouting velocity. This is consistent with the analysis of the Ergun equation that suggests the pressure drop approaches the maximum value, Δp_{max} at $u=u_{mf}$. Then, the pressure drop decreases due to the displacement of sufficient solid particles from the center core that leads to the formation of a steady spouting in the bed. Finally, with further

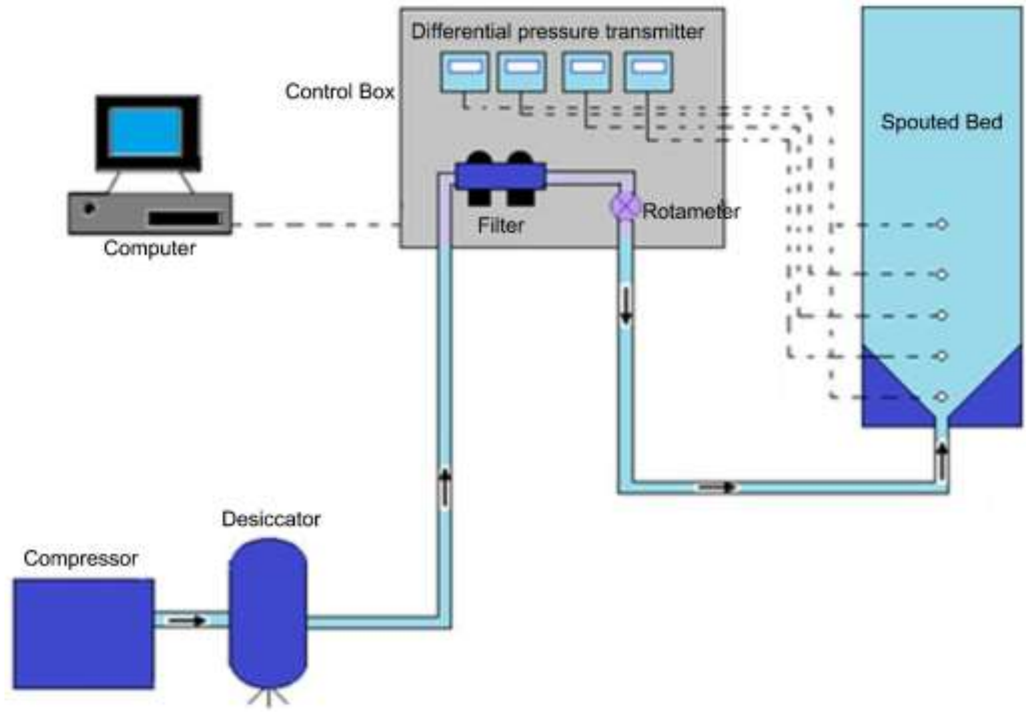

Fig. 2: Schematic of the experiment set-up.

the increase of airflow rate the pressure drop remains roughly constant. Fig. 3 clearly shows that the peak points appeared for different static bed heights are not the same and these points increase by increasing the static bed height. That is, the maximum pressure drop and minimum spouting velocity vary with the static bed height. The trend of the pressure drop against superficial gas velocity seen in Fig. 3 is also consistent with results reported by *Epstein* and *Grace* [1] and *Du et al.* [22]. This observation is consistent with that observed for spouted beds including only single sized coarse particles [22]. *Wang et al.* [4] studied the minimum spout velocity in conical spouted bed. The minimum spout velocity is found to increase with increasing static bed height, as well as the gas inlet diameter to a lesser extent.

Effect of jetsam weight fraction on pressure drop in the bed contains a binary mixture

Fig. 4 illustrates how the jetsam weight fraction of the binary mixtures affect the pressure drop. The experiment was carried out with sand (1) as jetsam particles, and sand (2) as flotsam particles. Fig. 4 shows the pressure drop profile of jetsam particles versus the gas velocity for the two different systems (jetsam rich and flotsam rich). Here, the weight fractions of jetsam particles of 0.05 and 0.95 are used. The static bed height and cone angle are kept fixed at h=20 cm and 30°. Fig. 4 shows that the trend of variation of the bed pressure drop with superficial air velocity in a spouted bed of flotsam rich system is very similar to that observed in a jetsam rich system. With the increase in the jetsam composition, however, the minimum spout velocity and maximum pressure drop increase. It has been shown [26, 27] that the peak pressure drop is proportional to the bed density. In addition, in the case of jetsam rich systems, the bed density is larger than that of flotsam rich systems (the voids between coarse particles are filled with fine particles). Therefore, the peak pressure drop for the jetsam rich system is larger than that for the flotsam rich system for the same condition.

When jetsam weight fraction increases, the number of particles with higher diameter increases, which significantly increases the weight of particles in the fountain region. The increase in jetsam weight fraction effectively increases the weight of bulk content in the column that needs higher pressure drop to support the spouting. For the same superficial air velocity, the maximum pressure drop in the jetsam rich system is larger than that of the flotsam rich system.

Table 2: Physical properties of particles.

Type of particles	Mean particles diameter (mm)	Particles density (kg/m^3)	Geldart type
Gypsum	3.55	2700	D
Poly urethane	3.55	380	D
Sand (1)	1.77	2650	B
Sand (2)	0.575	2650	B
Sand (3)	0.356	2650	B

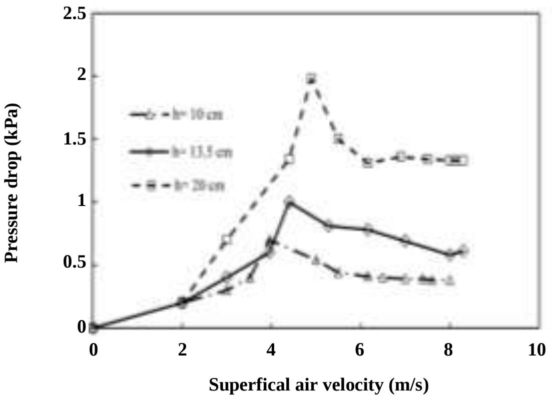

Fig. 3: Effects of static bed height on the pressure drop in binary sand particles. Jetsam rich system, sand (1): 1.77mm, 2650 kg/m^3, 95%; sand (3): 0.356 mm, 2650 kg/m^3, 5%, cone angle=30°.

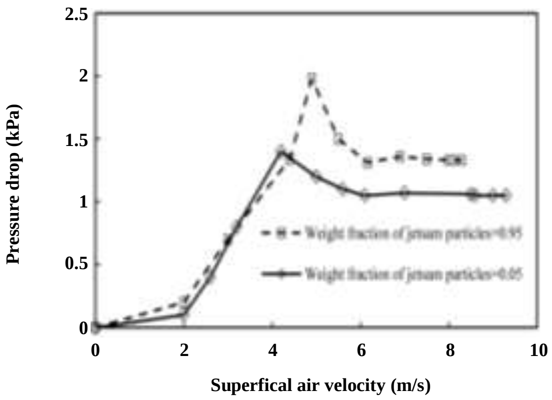

Fig. 4: Pressure drop profile in different binary mixture systems. Jetsam rich systems. (90% jetsam) and flotsam rich systems (5%jetsam). Sand (1): 1.77mm, 2650 kg/m^3; sand (2): 0.575 mm, 2650 kg/m^3. Static bed height, h= 20 cm, cone angle=30°.

Effect of cone angle on pressure drop in the spouted bed containing a binary mixture

To study the pressure drop in mixture with different densities, a set of experiments were performed in the bed with a mixture of Gypsum (ρ=2700 kg/m^3; d_p= 3.55 mm) and polyurethane (ρ=380 kg/m^3; d_p=3.55 mm) particles. Figs. 5 and 6 show the impact of cone angle on pressure drop for the static bed heights of 20 and 40 cm, 30 and 60^o cone angles, and jetsam weight fraction of 0.05.

These figures show that increasing the bed cone angle leads to an increase in the maximum pressure drop and minimum spouting velocity. This is because of an increase in cone angle, the number of particles in the bed increases and hence the minimum spouting velocity and maximum pressure drop increase. As seen in Fig. 5, the maximum pressure drop across the bed in the case of 60^o cone angle is noticeably larger than that observed for 30^o cone angle. The difference between the maximum pressure drops of those cone angles is 0.13 kPa for static bed height of 20 cm, while Fig 6 shows that the maximum pressure drops of those cone angles for static bed height of 40 cm is 0.66 kPa. The experimental data presented in Figs. 5 and 6 shows that the maximum pressure drop, which is greatly affected by static bed height, is also a function of the cone angle, and this effect was more important for beds with high static bed heights. For the static bed height of 20 cm, the effect of the cone angle on the maximum pressure drop is quite small. This is in agreement with most literature data [4,28,29]. As the cone angle increases, the minimum spout velocity becomes higher and the slope of the line becomes also steeper. When static bed height is smaller than about 100 mm, the cone angle seems to have less effect on minimum spout velocity.

Effect of particles diameter on pressure drop in spouted bed contain binary mixtures

To study the effect of particle diameter, experiments were conducted for a binary mixture of sand particles (sand (1): 1.77mm, 2650 kg/m^3, 5%; sand (2): 0.575 mm, 2650 kg/m^3, 95%; sand (3): 0.356 mm, 2650 kg/m^3, 95%).

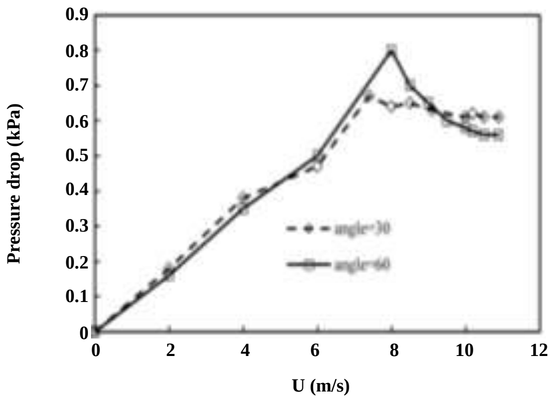

Fig. 5: Effects of cone angle on the variation of pressure drop against superficial gas velocity. Flotsam rich systems. Polyurethane: 380 kg/m³, 3.55 mm, 95%. Gypsum: 2700 kg/m³, 3.55 mm, 5%. Static bed height is h= 20 cm.

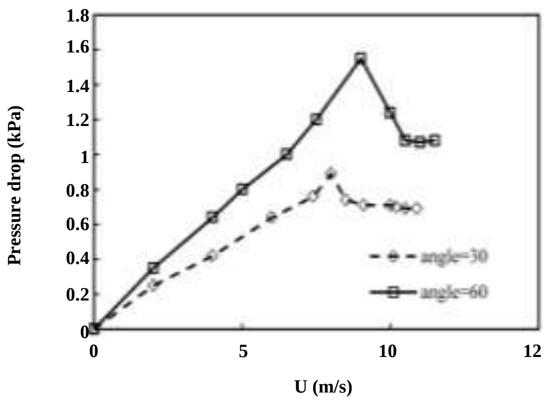

Fig. 6: Impact of cone angle on the pressure drop in the case of flotsam rich systems. Polyurethane: 380 kg/m³, 3.55 mm, 95%. Gypsum: 2700 kg/m³, 3.55 mm, 5%. Static bed height is h= 40 cm.

Fig 7 shows the impact of particle diameter on minimum spouting velocity and also pressure drop for the bed with a column cone angle of 30°, and a static bed height of 20 cm. It is seen that the minimum spouting velocity and maximum pressure drop are significantly affected by the particle size. For sands mixture of (1)/(3), the maximum pressure drop and minimum spouting velocity are, respectively, 1kPa and 4 m/s. For sands mixture of (1)/ (2), the maximum pressure drop and the minimum spouting velocity are 1.4 kPa and 6 m/s. The maximum pressure drop for a mixture of sand (1) and (2) particles appears at a higher air velocity compared to that for a mixture of sand (1) and (3) particles. That is, with increasing particles diameter, the maximum pressure drop and minimum spouting velocity increase. This result is in agreement with empirical equations reported in [1, 30-32].

Mostoufi et al. [6] studied the impact of particle diameter on the Power Spectral Density Fluctuations (PSDF) in the full conical spouted bed with 60° cone angle for different gas velocities. They showed that the bulk of particles is more mobile in a bed including 0.5 mm particles compared to that filled with 1mm particles, at the low air velocity near the minimum spouting velocity. These differences, however, practically vanishes at the higher gas velocities. In all previous experimental studies the pressure time series were measured for spouted beds containing monosized particles. In a bed with a bidisperse mixture of particles, more complex dynamic behaviors are anticipated due to interactions between the particles varying in size and density. *Du et al.* [22] showed that at the same bed height, by increasing particles diameter, the U_{ms} of the binary mixture only slightly increases. They found that in spouted beds including the fine particles the stability of spout can be improved with coarse particle mixing.

Evaluation of different empirical correlations for U_{ms}

The corresponding Root-Mean-Square-Error (RMSE) was evaluated and reported. The RMSE quantifies the differences between the values predicted by a model and the experimentally measured values. In order to evaluate the values of Ums predicted by the famous empirical correlations, they should be compared with the present experimental data and the root-mean-square error (RMSE) used as a fitting index RMSE is an extent of the differences between the values predicted by a model and the values actually extracted experimentally [30]. This term is calculated as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(U_{ms}^{Exp.} - U_{ms}^{Calc.})^2}{n}} \quad (1)$$

Where $U_{ms}^{Exp.}$ is the experimental value and $U_{ms}^{Calc.}$ is the value predicted by the empirical equation, and n is the number of data points.

Almost all previous researches show that the minimum spouting velocity is greatly affected by the bed diameter (Dc), nozzle diameter (Di), static bed height (H_0), gas density(ρ_g) and viscosity (μ), particle diameter (d_p), particle density(ρ_p), and bed cone angle (Θ) [33].

Table 3: Empirical expressions used to predict the minimum spouting velocity and relevant RMSEs.

author	correlation	RMSE
Mathur and Gishler [31]	$U_{ms} = \left(\frac{d_p}{D_c}\right)\left(\frac{D_i}{D_c}\right)^{1/3}\sqrt{2gH_0\left(\frac{\rho_p-\rho_g}{\rho_g}\right)}$	0.1828
Anabtawi [32]	$U_{ms} = 0.25\left(\frac{d_p}{D_c}\right)^{0.65}\left(\frac{D_i}{D_c}\right)^{0.312}\left(\frac{H_0}{D_c}\right)^{0.254}\sqrt{2gH_0\left(\frac{\rho_p-\rho_g}{\rho_g}\right)}$	0.2175
Choi and Maisen [34]	$U_{ms} = 13.5\left(2gH_0\right)^{0.5}\left(\frac{d_p}{D_c}\right)^{1.17}\left(\frac{D_i}{D_c}\right)^{0.372}\left(\frac{H_0}{D_c}\right)^{-0.148}\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{0.289}$	0.1341
Hosseini et al. [33]	$U_{ms} = \sqrt{2H_0 g}\left[\left(\frac{D_i}{D_c}\right)^{0.8}+\left(\frac{d_p}{D_c}+\left(\frac{D_i}{D_c}\right)\right)^{0.8}A\right]\left(A-B\right)$ $A = \left(\frac{d_p}{D_c}\right)\log_2\left(\frac{d_p}{D_c}\right)\Big/\left(\frac{H_0}{D_c}\right)+\sqrt{\frac{d_p}{D_c}}\left(\frac{\rho_p-\rho_g}{\rho_g}\right)$ $B = \left(\frac{d_p}{D_c}+\sqrt{\frac{d_p}{D_c}}+\left(\frac{D_i}{D_c}\right)^{0.8}\right)\frac{H_0}{D_c}$	0.1258

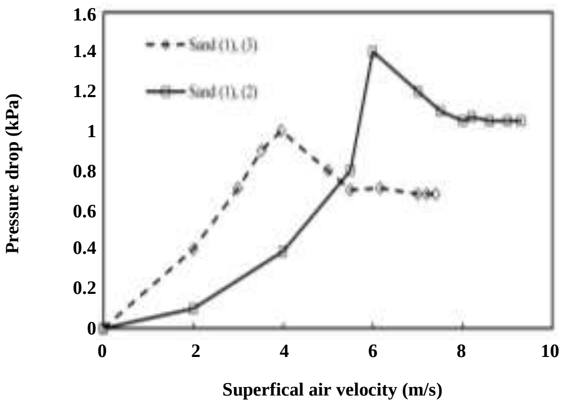

Fig. 7: Effect of particles diameter on pressure drop in spouted bed containing binary mixture for static bed height, h= 20 cm, and cone angle=30°. (Flotsam rich: sand (1): 1.77mm, 2650 kg/m³, 5%; sand (2): 0.575 mm, 2650 kg/m³, 95%; sand (3): 0.356 mm, 2650 kg/m³, 95%).

The first step in the process for estimating U_{ms} lies in finding the effective dimensionless groups. Afterward, by using the experimental data which have been obtained from different material types and operating conditions, a mathematical model can be developed to predict minimum velocity in binary mixture systems. Notice that when a distribution of particle sizes exists, the well-known expression for calculating the mean diameter can be used:

$$d_p = \frac{1}{\sum \frac{f_i}{d_{pi}}} \tag{2}$$

Where *fi* is the fraction of particles with diameter *dpi*. To evaluate the applicability of some available relations of U_{ms} obtained for monosized particles, the minimum spouting velocity obtained from the 150 experimental data points extracted here is compared with the obtained empirical correlation summarized in Table 3.

As can be seen in Table 3, four empirical expressions that are mostly used to estimate the minimum spouting velocity are evaluated by 150 data points and the corresponding RMSE are also listed in this table. It is observed that predictions by the empirical equation of *Hosseini et al.* [33] obtained by genetic programming are in a close agreement with the present experimental data leads to the lowest RMSE of 0.1258 m/s. It should be pointed out that none of the empirical equations shown in Table 3 contains the base angle of the bed and particles fraction relevant parameters, while Fig 6 clearly shows that with an increase in the bed cone angle, the minimum spouting velocity also increases.

CONCLUSIONS

A series of experiments in a conical spouted bed were performed, in which the binary particle mixtures with different densities and sizes were used. The effects of operating variables on the pressure drop and minimum spouting velocity were recognized to be significant. Based on the presented findings, the following conclusions can be drawn:

● For spouted beds with particle mixtures, the variation of pressure drop versus the superficial gas velocity is similar to that for the monosized particle beds. Maximum pressure drop and minimum spouting velocity vary with the static bed height, considerably.

● Pressure drop variation against the gas velocity in a spouted bed of flotsam rich system is similar to that observed in a jetsam rich bed. With an increase in the jetsam composition, the minimum spouting velocity and the maximum pressure drop increase. The increase in jetsam weight fraction effectively increases the bulk density in the column, which requires higher pressure drop to create the spout region.

● For both the jetsam and flotsam rich systems, the maximum pressure drop (peak point) in the case of jetsam rich system is considerably larger than that obtained for flotsam rich system under the same air velocity.

● By an increase in cone angle, the maximum pressure drop and also the minimum spouting velocity increase due to an increase of the effective solid density with cone angle.

● The peak of pressure drop (maximum) is a function of the bed cone angle and the dependence is more apparent for high static bed heights. On the other hand, for the static bed height of 20 cm (low), the effect of the bed cone angle on the maximum pressure drop is quite weak.

● The present experiments are evaluated by comparison of the experimentally measure U_{ms} with the empirical equations for hydrodynamics of shallow spouted beds, where the Root-Mean-Square-Error (RMSE) analysis is performed.

● Among the empirical expressions for the minimum spouting velocity used for comparison with the measured data; the expression of *Hosseini et al.* [33] showed a good agreement with the data and provided the lowest RMSE of 0.1258 m/s.

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