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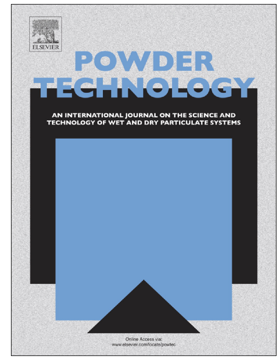

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Detecting Stability of Conical Spouted Beds Based on Information Entropy Theory

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Abstract

Effects of particle size, particle density, gas inlet diameter and static bed height on the stability of operation in conical spouted beds were investigated through analyses of information entropy of pressure fluctuations. In this respect, the maximum information entropy of pressure fluctuations was used as a stability criterion. The results showed that stability of the bed increases with an increase in the maximum entropy. The maximum information entropy of pressure fluctuations increases with increasing particle size and bed height while decreases with increasing gas inlet diameter and particle density. A stability map was also prepared to present the effect of operating parameters on the maximum entropy. Moreover, a correlation for prediction of maximum information entropy was developed to determine the stable operation conditions of conical spouted beds operating with low as well as high density particles.

Keywords: Conical Spouted Bed, Stability, Pressure Fluctuation, Information Entropy

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1. Introduction

Conventional spouted beds have been used in numerous industrial processes as drying, coating, combustion and gasification [1-10]. In spite of several advantages of conventional spouted beds, there are some applications in which their performance is limited (for example in fast reactions, such as ultra-pyrolysis) [11-14]. In these applications, the conical spouted beds are advantageous alternatives due to their short gas residence times with narrow distribution [15]. Operation of conical spouted beds is sensitive to various parameters such as bed geometry, operating conditions as well as gas and solid properties [16-25]. For a combination of these parameters, stable spouting occurs only over a limited range of operating conditions. Therefore, it is necessary to select the operating and design conditions carefully to ensure stable operation needed to improve performance of a conical spouted bed. Various researchers investigated the ranges of geometric parameters of the bed in various spouted bed systems including spout-fluid beds for stable spouting [26-30]. The effect of inlet tube diameter to particle diameter ratio (D_o/d_p) on the stability of conical spouted beds was investigated by Povrennović et al. [29]. Their analyses showed that the criterion $D_o/d_p < 25$ for stable spouting, which was originally proposed for cylindrical beds with conical bottom by Chandnani and Epstein [27] is also valid for conical spouted beds.

Olazar et al. [30] carried out an extensive study on the stability of conical spouted beds and reported the following criteria for the stable operation:

(i) Inlet to cone bottom diameter ratio (D_o/D_i) should be between 1/2 and 5/6. At ratios less than 1/2, dead zones form at the bottom of the bed and ratios greater than 5/6 lead to unstable spout formation because of the rotational movements of the spout.

(ii) The bed is unavoidably unstable for cone angles smaller than 28º and solid circulation is very poor for angles greater than 60º. Therefore, cone angles smaller than 28º and greater than 60º are not recommended to achieve stable spouting.

(iii) Inlet to particle diameter ratio (D_o/d_p) should be between 2 and 60.

Moreover, Olazar et al. [31] reported that in order to maintain a stable spouted bed, there is also an upper limit for the diameter of the bed (D_c), which is another criterion that should be met. They proposed an equation, which includes parameters related to bed geometry, minimum spouting velocity and bed height, for evaluation of the largest possible bed diameter:

$$D_c^3 = [D_o + 2H_b tan(\gamma/2)]^3(1+\psi) - D_o^3\psi \quad (1)$$

where

$$\psi = 2.58 \times 10^4 \left(\frac{U}{U_{ms}}\right)^{3.48} Ar^{-0.52} \left[\frac{D_o + 2H_b tan(\gamma/2)}{D_i}\right]^{-0.53} [tan(\gamma/2)]^{-1.84}\gamma^{1.95} \quad (2)$$

As can be seen from the literature review, studies on the stability of conical spouted beds have mostly focused on the geometric parameters of the contactor. However, parameters such as particle properties (e.g., density and size), bed height and gas velocity are also crucial parameters that affect the flow stability. Moreover, the empirical equations proposed in the literature have been developed based on visual observations through transparent walls. Since visual recognition of the flow structure is not possible in industrial scale equipment, developing non-visual techniques for this purpose is vital. In addition, previous studies on stability criteria focused completely on the beds with moderate density particles (ρ_p < 2500 kg/m^3) and no report can be found on the stability of beds operating with high density particles. Currently, conical spouted bed reactors are widely used for coating of heavy particles in the chemical vapor deposition (CVD) process. To design and scale up these reactors, it is of fundamental importance to have a detailed study on their stability. Since the particle density significantly affects the stability behavior of the beds, further investigations are required to identify the stability of systems operating with relatively high density particles.

Therefore, the main objective of this work is to determine the stability of flow in conical spouted beds with particles of different sizes and densities by analyzing pressure fluctuations based on the information entropy (IE) theory. Effects of the gas inlet diameter, bed height, inlet gas velocity, particle size and particle density on the stability of the system were also investigated. The main novelty of this work is to investigate the stability of conical spouted beds operating with different particles by introducing IE theory as a new method for detecting hydrodynamic stability.

2. Experiments

The experiments were carried out in a circular (γ = 45º) conical spouted bed made of polyoxymethylene with different gas inlet diameters (D_o = 8, 10, 12 and 15 mm). A schematic of the set-up is shown in Fig. 1. A changeable fine wire mesh (300 μm) was placed on the inlet to prevent particles from falling into the inlet air tube. The air was supplied by a screw type compressor at 8 bar with maximum flow rate of 0.05 m^3/s. A pressure regulator and two calming tanks of 30 L in volume were installed in series before the air entry to regulate and smooth the air flow. The air flow rate was measured by a rotameter calibrated with a standard orifice flowmeter.

The bed pressure fluctuations were measured by a differential pressure transducer (Omega PX142-005DV5) connected to the bed internal wall at the base of the conical section. The other line of the transducer was open to atmosphere. The pressure signals were collected by a high speed data acquisition board (National Instruments, Model USB-6351). In each experiment, the pressure fluctuations were recorded at superficial gas velocities ranging from 1 to 1.75U_{ms} for 60 s with a sampling frequency of 500 Hz.

To investigate the sensitivity of the bed stability to different parameters, the experiments were performed with various particles, gas inlet diameters and bed heights. Summary of the experimental conditions is given in Table 1. Visual observation of the bed flow regimes was also done in order to characterize the bed behavior. Each test was repeated three times and the reproducibility of the tests was checked.

In order to investigate the effect of particle density and size on the stability of spouted beds, experiments were conducted using spherical particles with densities ranging from 2470 kg/m^3 to 6050 kg/m^3. Glass beads (GB), alumina (AL) and yttria-stabilized zirconia (YSZ) particles (ZrO_2, also known as zirconia) were used to simulate different particle properties. Properties of the particles are listed in Table 2.

3. Theory

The approach followed in this work was based on a new applicable definition of the information entropy and it was employed to quantify the stability of the bed. The employed information entropy algorithm is extensively described by Nedeltchev et al. [32-37]. In this algorithm, minimum and maximum of each pressure fluctuations time series were determined. Then, the range of each time series was divided into different regions with progressively increasing heights proportional to the division step (e.g., 25, 50, 75, 100 Pa, and so on, Fig. 2). The probability of visit of the signal into each region was defined as follows:

$$P_i = \frac{H_0}{H_i} \frac{N_r H_i}{\sum_{i=1}^{N} N_r H_i} \quad (3)$$

where H_0, H_i and N_r are the height of the smallest region, height of each region and number of visits in each region, respectively. The amount of information I_i in each region is expressed as:

$$I_i = -\log(P_i) \tag{4}$$

The total information entropy, IE_{total}, is a function of both probability and the amount of information and is defined as:

$$IE_{total} = \sum_{i=1}^{N} \frac{H_i}{H_0} P_i I_i \tag{5}$$

The information entropy represents the total information that can be obtained from a signal. The maximum information entropy, IE_{max}, represents the largest value among all local information entropies and is expressed as:

$$IE_{max} = max(IE_i) = max\left(\frac{H_i}{H_0} P_i I_i\right) \tag{6}$$

The maximum information entropy gives the maximum information that can be obtained from a signal which is usually the most frequently visited one.

4. Results and discussion

4.1. Flow regimes

The flow regimes encountered in spouted beds have been described in various studies [17, 30, 31]. At very low gas flow rates, the particles form a fixed bed through which the gas percolates. By increasing the gas velocity, the internal jet regime is reached in which a submerged cavity or jet is formed at the inlet orifice, while the rest of the particles remain at the fixed bed regime. After the formation of the internal jet, increasing the gas flow rate leads to appearance of the conventional spouted bed. In this regime, particles are transported individually by the upward flow of gas in the center of the bed. The gas velocity decreases in the fountain region, and then particles disengage from the gas and move downward in the annulus. The downward moving particles re-enter the spout, mainly at the bottom, and this cycle of particles movement repeats again. The movement of particles is smooth and non-pulsating when the spout is stable and the fountain is also stable and well defined. At high gas flow rates, the jet (or dilute-phase) spouting regime is reached for which the main characteristics are (*i*) high gas velocity, (*ii*) high bed voidage and (*iii*) cyclic movement of particles. The hydrodynamic behavior of the jet spouting regime is different from that of a conventional spouting regime.

As pointed out earlier, stable operation in the spouting regime is quite sensitive to design and operating parameters. By changing the geometry and operating conditions, instabilities can be observed and these instabilities can be divided into two main groups: asymmetric and axisymmetric instabilities, similar to those described by Dogan et al. [38] and Freitas et al. [39]. The axisymmetric instability refers to the pulsatory behavior of the spout. In this type of instability, the fountain height fluctuates vigorously and this can be attributed to the air flow distribution in the spout. The intensity of axisymmetric instability can lead to slugging in which large slugs are formed at the top of the annulus. The asymmetric instability is the oscillatory behavior of the spout in which the fountain swings from side to side. In this type of instability, the spout cavity is diverted to the bed wall, creating totally different recirculation trajectories of particles. Both axisymmetric and asymmetric instabilities initiate at the bottom of the bed and the gradual growth of the instability causes spout termination.

In this work, bed pressure fluctuations were monitored in the presence and absence of these instabilities in order to study the hydrodynamic stability of the bed. Fig. 3 illustrates a typical time series of pressure fluctuations in a conical spouted bed containing glass beads operated at various bed heights and gas inlet diameters and at inlet gas velocity of $1.3U_{ms}$. In this figure, irregular random-like oscillations are clearly seen in signals measured at smaller inlet diameters. By enlarging the gas inlet diameter, amplitude of the fluctuations increases and, unlike the pressure fluctuations at smaller inlet diameters, a more periodic behavior in the signal is observed. This trend implies a rapid decrease in the complexity of the gas-solid dynamics (hence, an increase in instability) with increasing the gas inlet diameter. In other words, in beds with smaller gas inlet diameters, a stable spouting regime, which is free of intermittent spout formation/collapse and fountain height fluctuations, is established more readily. In the case of stable spouting, irregular and random pressure fluctuations originate mainly from inter-particle and gas-particle interactions. On the other hand, once the bed is in the unstable regime due to either axisymmetric or asymmetric instability, the associated pulsatile behavior or slugs lead to more periodic pressure fluctuations. A similar trend was also observed in pressure signals with a decrease in the bed height. However, the periodic motion in the signal was not as clear as the periodic behavior observed in the signals measured at higher gas inlet diameters. This behavior implies that the effect of bed height on the hydrodynamic stability is less noticeable than the effect of gas inlet diameter.

Based on the above discussion, it can be concluded that overall patterns in the pressure time series can provide some useful insights about the dynamics of the bed. However, detection of the changes in finer patterns in the signals needs a quantitative analysis. Therefore, in this study, the signals are further quantified by utilizing the information entropy theory. For this purpose, the change of maximum information entropy ($IE_{\max}$) with gas velocity obtained with different gas inlet diameters, bed heights and with various particles were explored and are presented in Figs. 4-7 and discussed below.

4.2. Effect of gas inlet diameter

As reported in the literature [30, 31], selection of the gas inlet diameter deserves a special attention in spouted beds, as it greatly affects the stability of the bed. Therefore, the effect of gas inlet diameter on the bed stability was carefully monitored in this study by visual observations as well as analyses of the pressure fluctuations. The effect of gas inlet diameter on the maximum information entropy of pressure signals obtained in the spouted bed operating with 1 mm glass beads is illustrated in Fig. 4. For the case where the inlet diameter was 10 mm, the spouting regime was quite stable at all gas velocities where the spout was well defined without any rotation and the bed was uniform and free from bubbles and slugs. In this stable spouting regime, particle-particle and gas-particle interactions are the leading phenomena in the bed and the pressure signals originate from the movement of single or multiple particles simultaneously. All the pressure fluctuations measured in this stable operation exhibit a random-like oscillation with a narrow band of amplitude which leads to an increase in the information entropy. As can be seen in Fig. 4, the maximum information entropy increases with a decrease in the gas inlet diameter, reflecting the fact that gas-solid interaction in the bed becomes more complex when the inlet diameter is decreased. This trend shows that a spouted bed with a larger gas inlet diameter acts as more a deterministic system. Fig. 4 also demonstrates that the intensity of instability increases with increasing the inlet diameter. In fact, in the case of 15 mm inlet diameter, axisymmetric and asymmetric instabilities were always present. When the inlet diameter is increased, the gas enters a larger area, causing a lower jet velocity which hinders spouting. In this case, momentum of the entering gas is less and a lower mean gas velocity provides less stability. Moreover, more particles become entrained into the spout when the gas inlet diameter is larger. This larger amount of particles may chock the spout, leading to the bed instability. With a larger gas inlet diameter, the spout continuously changes its position instead of being well defined at the center of the bed. The behavior of bed pressure fluctuations changes consistently with occurrence of these instabilities such that their amplitude increases and the fluctuations approach a periodic pattern. This implies a rapid reduction in the complexity of the bed dynamics which leads to a decrease in the information entropy.

Another conclusion that can be withdrawn from Fig. 4 is that the information entropy at various gas inlet diameters increases with increasing the gas velocity. This trend suggests an increase in the complexity of gas-solid dynamics with increasing the spouting gas velocity. As the spouting gas velocity is increased, the mean gas velocity through the spout increases and the bed becomes more stable. The increase in the information entropy is a result of gas turbulence near the bed inlet and intensive interactions between gas and particles.

4.3. Effect of particle size

Information entropy of pressure fluctuations is also influenced by the particle size. Fig. 5 shows the effect of particle size on the maximum information entropies of pressure fluctuations. It can be seen in this figure that the maximum information entropy is greater in the bed of larger particles. In other words, stable spouting can be achieved more easily in beds of larger particles. This conclusion is consistent with the results reported by Mollick et al. [40] and Olazar et al. [30] that if D_i/d_p is decreased, amplitude of pressure fluctuations would also decrease, indicating a stable spouting operation. Results of γ-ray tomography showed that decreasing the particle size leads to an increase in the solids holdup in the spout region at the same U/U_{ms}. This means that the number of particles in the spout increase as the particle size decreases. This leads to a longer contact time of small particles with the gas phase [41]. On the other hand, with increasing the particle size, the number of particles contributing to the spout decreases which can improve the stability of the spout due to the fact that the gas momentum dissipation is less when the spout is free of solids.

4.4. Effect of static bed height

The effect of static bed height on the operation stability was also investigated in this study. The maximum information entropy versus dimensionless velocity, U/U_{ms}, is plotted in Fig. 6 in beds operating with 1 and 2 mm glass beads. It can be observed in this figure that the maximum information entropy increases with increasing the static bed height in all cases. This implies that the bed stability increases by increasing the bed height. Increase in the bed height causes the flow in the spout to become more developed, with a higher centerline velocity, providing a more concentrated gas flow in the spout which leads to more stability of the bed. Moreover, Spreutels et al. [42] investigated the distribution of the mean height of penetration of the solid particles from the annulus to the spout and found that when the bed height is high, there is no solid particle penetration from the annulus to the spout in the upper part of the spout. This means that for a conical spouted bed with a high static bed height, most of particles enter the spout region at the bottom of the bed where the gas velocity is high enough to handle the particles which results in a higher stability of the bed. The increased stability can cause pressure fluctuations to become more significant with a greater information entropy. Olazar et al. [31] concluded that there is no maximum spoutable bed height for conical spouted beds, at least not in the same way observed in cylindrical spouted beds.

The mean gas velocity through the spout also changes with height in conical spouted beds. As a consequence, there is a minimum spoutable bed height, below which the velocity in the upper surface of the bed is higher than the minimum fluidization velocity, which is one of the causes of instability observed in the experiments [31]. Olazar et al. [31] proposed a correlation to estimate the minimum spoutable height for beds of glass beads. The bed height in the experiments of this work was higher than those predicted by the correlation of Olazar et al. [31]. The maximum predicted value for minimum spoutable bed height by the correlation was 25 mm, which is quite lower than the bed heights in this study. For a spouted bed with a lower bed height, a large fraction of the ascending gas passes in the annulus region where it percolates through the downward-moving particles, leading to slugging in the bed. By propagation of the surface instability created at the base of the bed, the shape of the spout changes continuously and it becomes unstable, which leads to a decrease in the information entropy of pressure fluctuations.

4.5. Effect of particle density

Effect of particle density on the bed stability was also investigated in this work. Maximum information entropy of pressure fluctuations measured in beds of various particles as a function of gas velocity for d_p = 1 mm, H_b = 100 mm and D_i = 12 mm is plotted in Fig. 7. This figure shows that the maximum information entropy decreases by increasing the particle density, indicating that beds containing lower density particles are more stable compared to higher density particles. For high-density particles, there are some instabilities which hinder the stable spouting of the bed. The momentum of spouting gas becomes easily dissipated by high density particles and the spout tends to oscillate when the gas loses its momentum. The continuous change of the spout position leads to large fluctuations in the pressure which results in a decrease in the information entropy.

4.6. Stability map

Although the particle properties (size and density), bed geometry (inlet diameter and bed height) and gas spouting velocity are important parameters that dictate the stability of operation of conical spouted beds, there is a lack of a stability map or a stability criteria that involves all these parameters in the literature. Figs. 8 and 9 summarize the dependency of conical spouted bed stability on all the parameters (particle diameter and density, inlet bed diameter, static bed height and spouting gas velocity) studied in this work by plotting the maximum information entropies obtained in all experiments. Another view of stability dependency on the studied parameters is shown in Fig. 9. This figure presents completely stable and unstable spouted beds by black and white boxes, respectively. For cases between stable and unstable operation, a gray box is used. This figure was constructed based on the visual observations during the experiments. As can be seen from this figure, stable spouting operation was observed in all cases with inlet gas diameter of 10 mm for 1 mm particles. The instability was less noticeable for a bed with 12 mm inlet gas diameter than for 15 mm. Some instabilities were noticed for the 12 mm inlet diameter while in the case of 15 mm inlet, the bed was always unstable.

As discussed earlier, larger particles were found to present more stable spouting. This fact is reflected in Figs. 8 and 9 as the maximum information entropy increases with the increase in particle size and the stable spouting is observed for 2 mm particles. Stable spouting was never observed for smaller particles at high inlet diameters. For 0.5 mm zirconia particles, stability was observed only for 8 mm inlet gas diameter and at high gas velocities. Moreover, the effect of bed height and particle density on the bed stability is clearly seen in Figs. 8 and 9. The stability of the bed increases with the increase in the bed height. Moreover, the number of the black boxes decreases with the increase in the particle density which indicates the instability intensification.

In light of the discussions presented above, it can be deduced that Figs. 8 and 9 can be used qualitatively to assess the stability of conical spouted beds. However, precise characterization of the bed stability requires also quantitative analysis. For this purpose, the maximum information entropy of pressure fluctuations was utilized and it was found that the conical spouted bed is completely stable as long as $IE_{\max} > 1.51$. For $IE_{\max}$ values between 1.43 and 1.51, the bed operates in between completely stable and unstable situations. Unstable spouting occurs if $IE_{\max} < 1.43$ due to the growth of instabilities in the bed. Thus, it can be concluded that in order to secure a stable operation in conical spouted beds, the maximum information entropy should be greater than 1.51.

As mentioned in the introduction section, the dimensionless parameters D_o/D_i and D_o/d_p were used to characterize the spouted bed stability by Olazar et al. [30]. However, it was shown in the present investigation that three other parameters, i.e., H_b, U/U_{ms} and ρ_p, also affect the stability of conical spouted beds. Moreover, it was shown that for stable spouting in a conical spouted bed, maximum information entropy parameter can be used as a stability criterion. Thus, the following correlation for evaluation of the maximum information entropy based on the influential parameters such as inlet diameter, static bed height, particle diameter, particle density and spouting gas velocity can be proposed:

$$IE_{max} = f\left(\frac{D_o}{d_p}, \frac{H_b}{D_i}, \frac{U}{U_{ms}}, \frac{\rho_s - \rho_g}{\rho_g}\right) = a_1 \left(\frac{D_o}{d_p}\right)^{a_2} \left(\frac{H_b}{D_i}\right)^{a_3} \left(\frac{U}{U_{ms}}\right)^{a_4} \left(\frac{\rho_s - \rho_g}{\rho_g}\right)^{a_5} \quad (7)$$

A power law form was used for this correlation and its constants were determined by fitting this equation to randomly selected 216 experimental data points:

$$IE_{max} = 4\left(\frac{D_o}{d_p}\right)^{-0.205} \left(\frac{H_b}{D_i}\right)^{0.269} \left(\frac{U}{U_{ms}}\right)^{0.142} \left(\frac{\rho_s - \rho_g}{\rho_g}\right)^{-0.116} \quad (8)$$

The remaining 54 experimental data points, which were not used in the calculation of the constants of this correlation, were used for the validation of this correlation. The predictive accuracy of this correlation is presented in the parity plot given in Fig. 10. In this figure, the data points used for calculating the constants of correlation are shown in blue and the one used only for validation are shown with red marker. It can be seen in this figure that the proposed correlation agrees well with the experimental data.

In summary, the IE_{max} value can be calculated by using the proposed correlation knowing the static bed height, inlet gas diameter, particle density, particle diameter and spouting gas velocity, then the stability situation of the bed can be predicted based on the calculated IE_{max} value and following ranges:

$$\begin{cases} IE_{max} > 1.51 & Stable \\ 1.43 < IE_{max} < 1.51 & Between\ stable\ and\ unstable \\ IE_{max} < 1.43 & Unstable \end{cases} \quad (9)$$

5. Conclusions

Experiments were carried out with three different types of particles (glass beads, alumina and yttria-stabilized zirconia particles) in a conical spouted bed and the effects of inlet gas diameter, particle size, static bed height, particle density and spouting gas velocity on the stability of the bed was investigated through maximum information entropies of pressure fluctuations. Bed height of greater depth, larger particles and higher gas velocities provide more stable spouting. On the other hand, unstable spouting tends to occur at large gas inlet diameters and particles with high densities.

The results show that the maximum information entropy of pressure fluctuations is significantly different for stable and unstable beds reflecting the characteristics of gas-solid flow in spouted beds. The spouted bed at an unstable operation is a deterministic periodic system since the maximum information entropies are low. On the other hand, the pressure fluctuations in a stable bed are quite random and their maximum information entropies are high. The results indicate that the maximum information entropy helps to grasp the complex dynamics of conical spouted bed, therefore can be used as a stability criterion. The assessment of the information entropies shows that to achieve a stable spouting it is necessary to ensure that $IE_{\max}$ >1.51. For information entropies lower than 1.43, the bed is completely unstable.

A correlation for maximum information entropy as function of operating and design parameters (i.e., inlet diameter, particle diameter, bed height, particle density and spouting gas velocity) was developed in this study. The predictive accuracy of the correlation was found to be satisfactory. Therefore, it can be used in prediction of the stability of the conical spouted beds operating with low and also high density particles.

Nomenclature

D_c	column diameter, m
D_i	cone bottom diameter, m
D_o	gas inlet diameter, m
d_p	particle diameter, m
H_0	height of the smallest region
H_b	static bed height, m
H_c	height of conical section, m
H_i	height of each region
I_i	information amount in each region
IE_{max}	maximum information entropy
IE_{total}	total information entropy
N_r	number of visits in each region
P_i	probability of signals ‘s visit
U	inlet gas velocity, m/s
U_{ms}	minimums spouting velocity, m/s

Greek letters

γ	cone angle, rad
ρ_g	gas density, kg/m^3
ρ_s	particle density, kg/m^3

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Table 1. Conditions of the experiments

Particle type	d_p (mm)	D_o (mm)	H_b (mm)	U/U_{ms}
Glass Bead	1	10 12 15	80, 100, 120	1, 1.1, 1.3, 1.45, 1.6, 1.75
	2	10 12 15		
Alumina	1	10 12 15		
	2	10 12 15		
Zirconia	0.5	8 10 12 15		
	1	10 12 15		

Table 2. Properties of the particles

Material	d_p (mm)	ρ_s (kg/m^3)	Geldart Classification
Glass bead	1	2470	D
	2	2470	D
Alumina	1	3690	D
	2	3690	D
Zirconia	0.5	6050	B
	1	6050	D

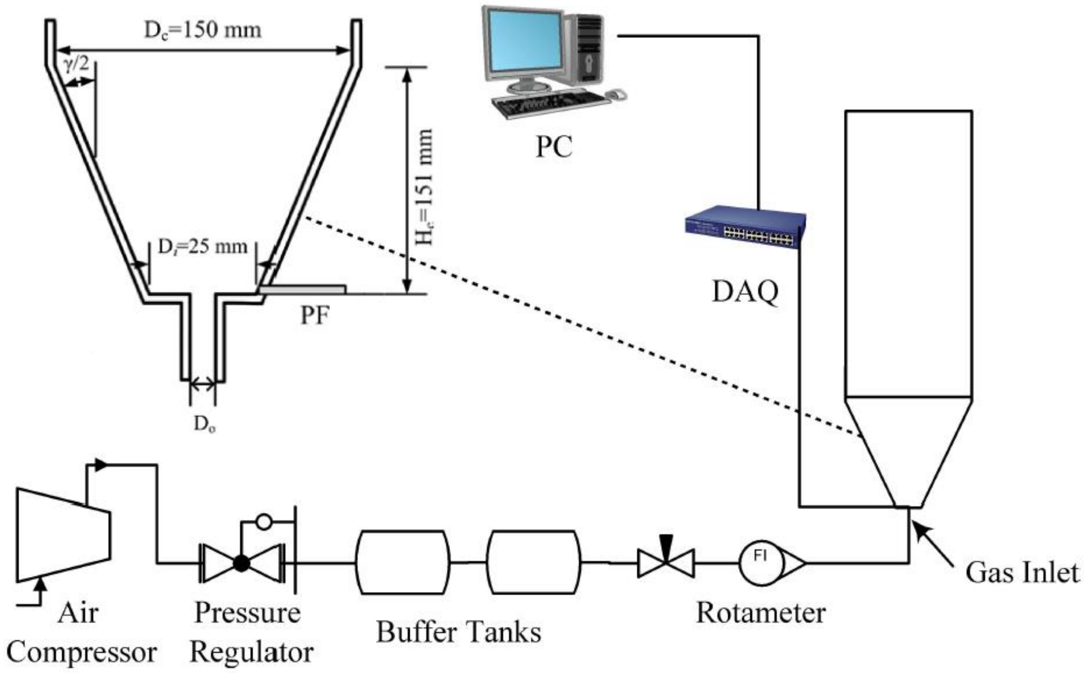

Fig. 1. Geometric sketch of conical spouted bed system

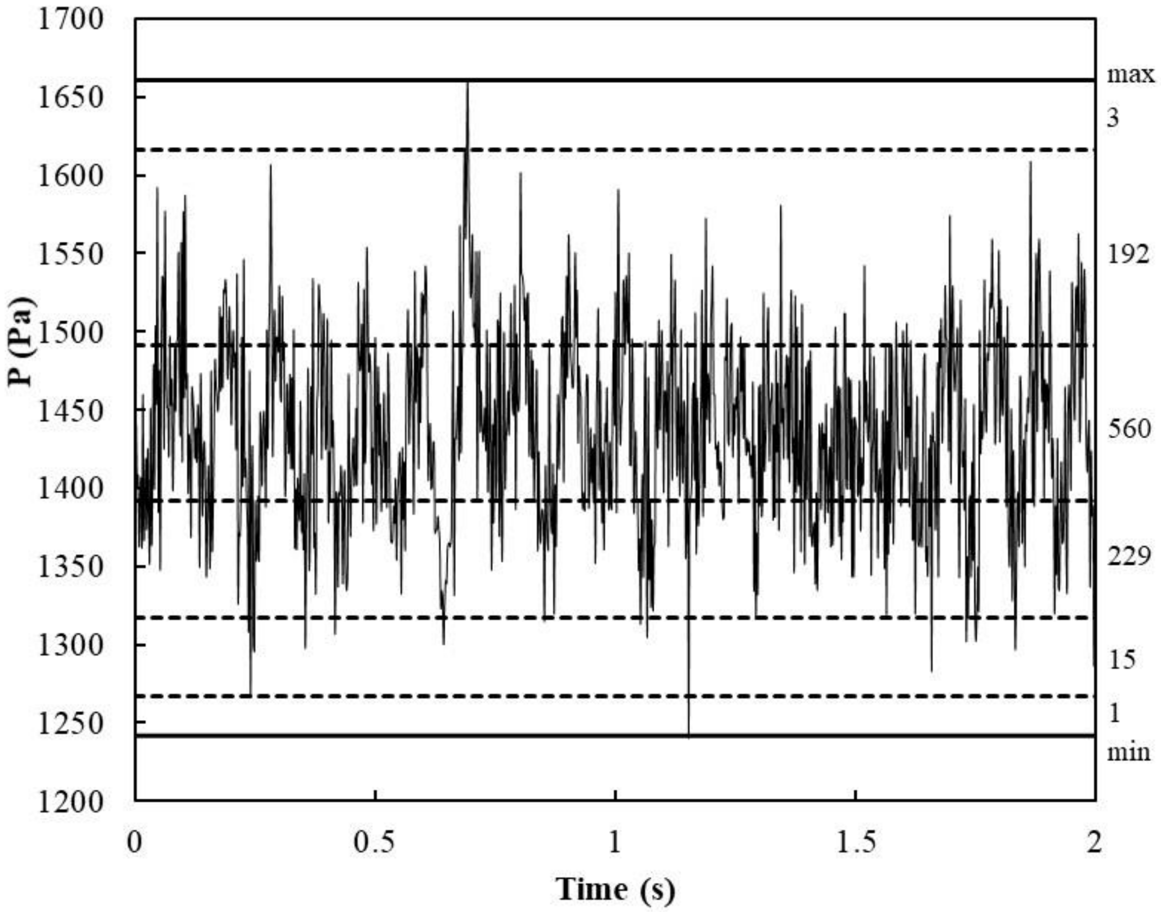

Fig. 2. Example of the pressure fluctuation time series data in the bed for a step size equal to 25 Pa (alumina particles, d_p = 1 mm, D_o = 15 mm, H_b = 120 mm)

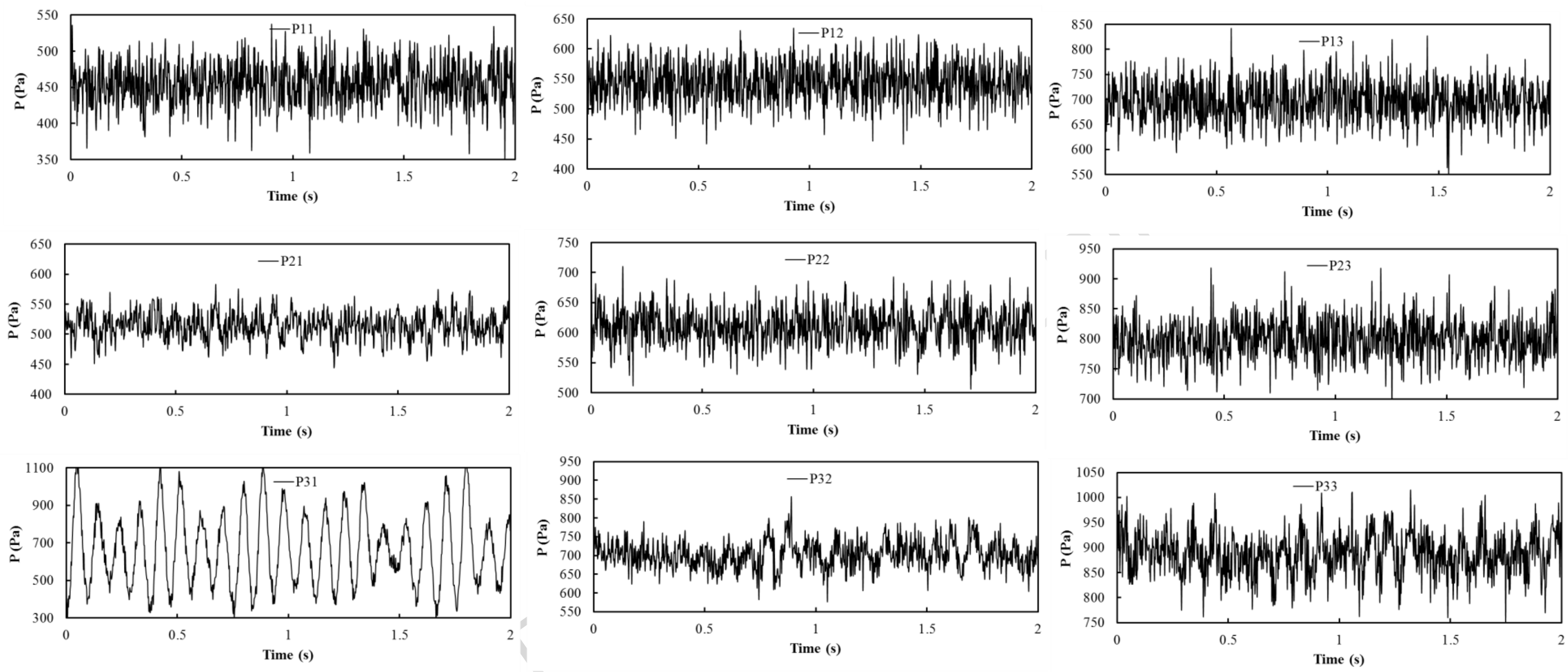

Fig. 3. Effects of static bed height (H_b) and inlet gas diameter (D_o) on the time series of pressure fluctuations in a spouted bed operating at 1.3U_{ms} with 1 mm glass beads (P_{11}: D_o = 10 mm and H_b = 80 mm; P_{12}: D_o = 10 mm and H_b = 100 mm; P_{13}: D_o = 10 mm and H_b = 120 mm; P_{21}: D_o = 12 mm and H_b = 80 mm; P_{22}: D_o = 12 mm and H_b = 100 mm; P_{23}: D_o =12 mm and H_b = 120 mm; P_{31}: D_o = 15 mm and H_b = 80 mm; P_{32}: D_o = 15 mm and H_b = 100 mm; P_{33}: D_o = 15 mm and H_b = 120 mm)

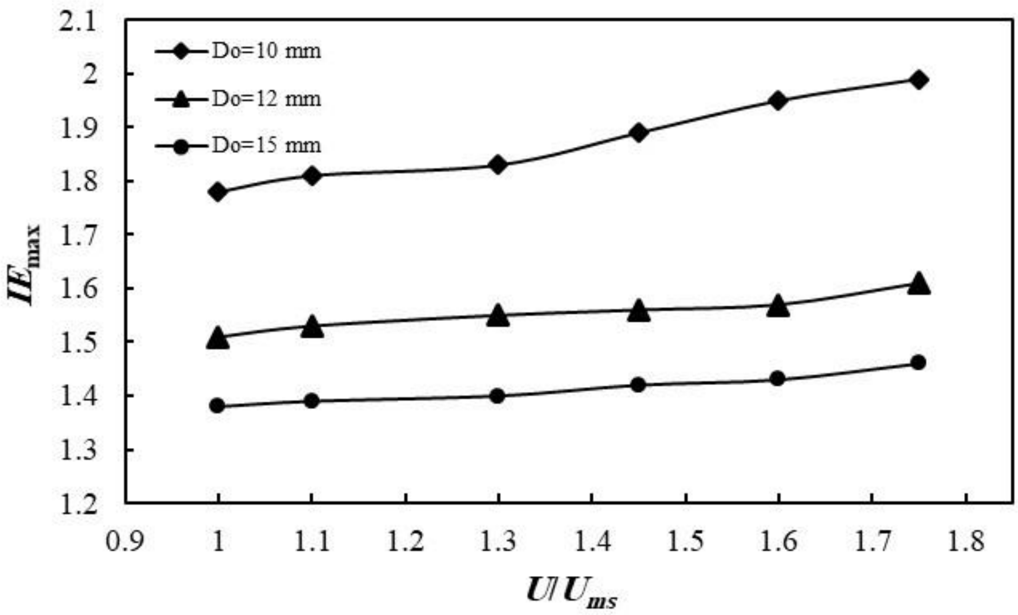

Fig. 4. Effect of gas inlet diameter on the change of IE_{max} with U/U_{ms} (Glass bead, d_p = 1 mm, H_b = 100 mm)

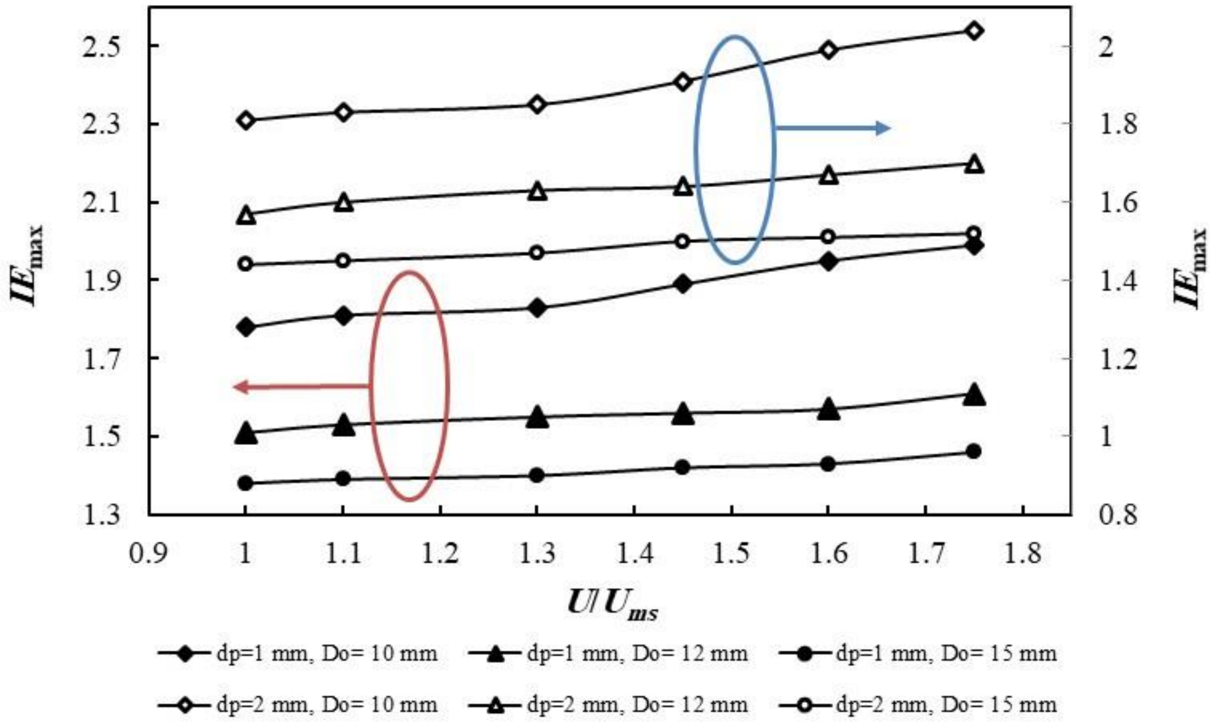

Fig. 5. Effects of gas inlet and particle diameter on the change of IE_{max} with U/U_{ms} (Glass bead, H_b = 100 mm)

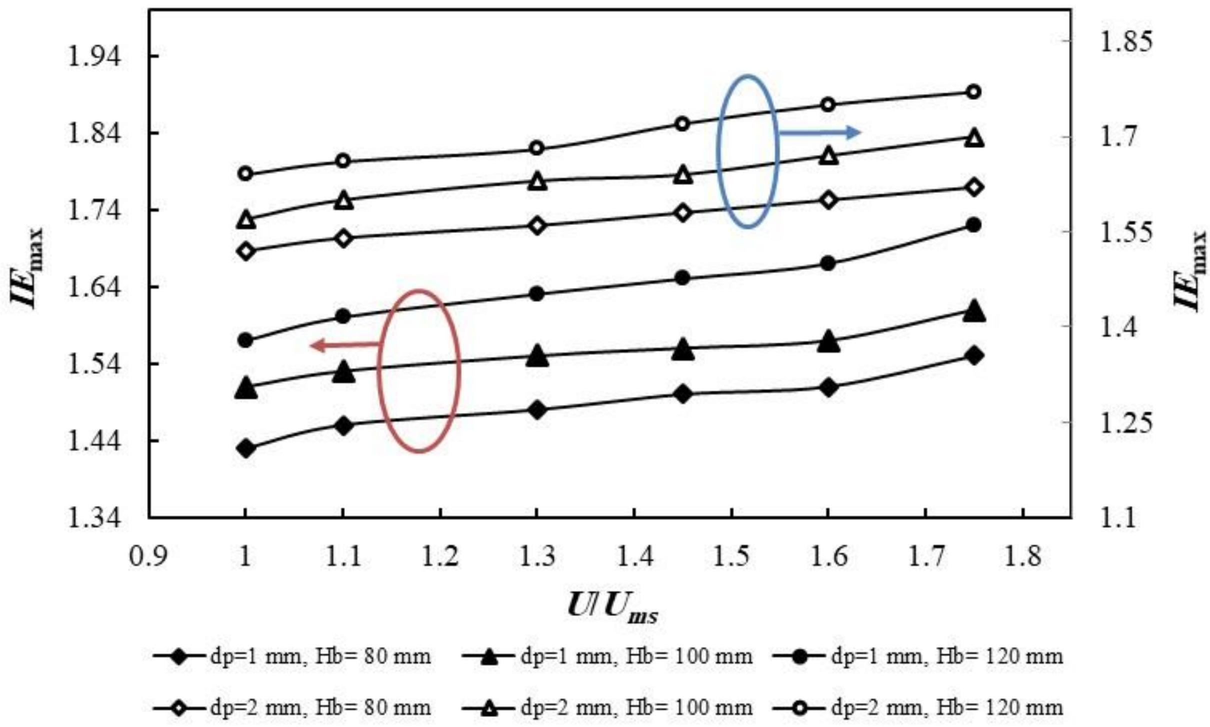

Fig. 6. Effects of bed height and particle diameter on the change of IE_{max} with U/U_{ms} (Glass bead, D_o = 12 mm)

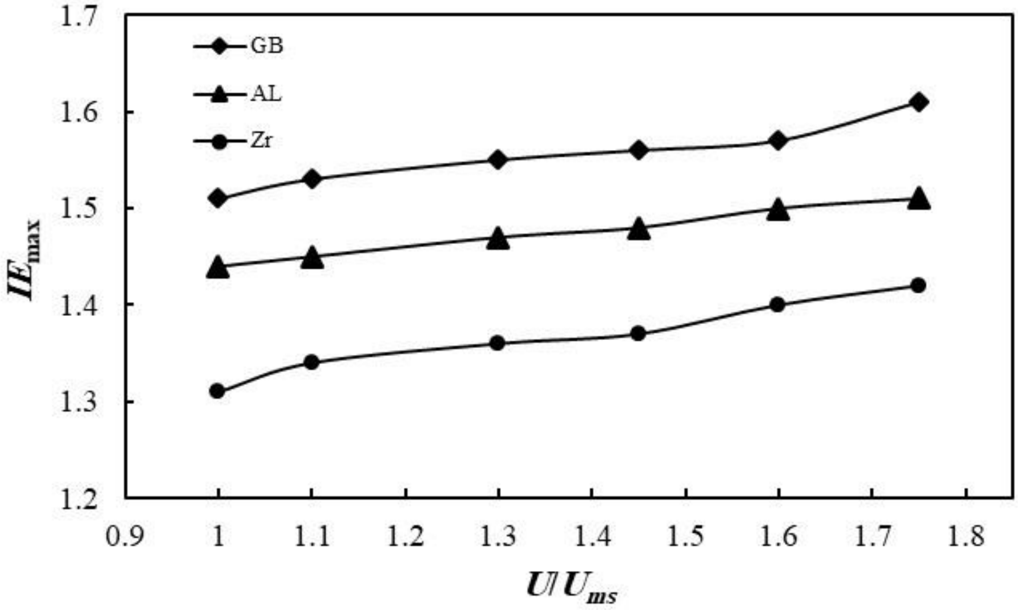

Fig. 7. Effect of particle density on the change of IE_{max} with U/U_{ms} (d_p = 1 mm, H_b = 100 mm, D_o = 12 mm)

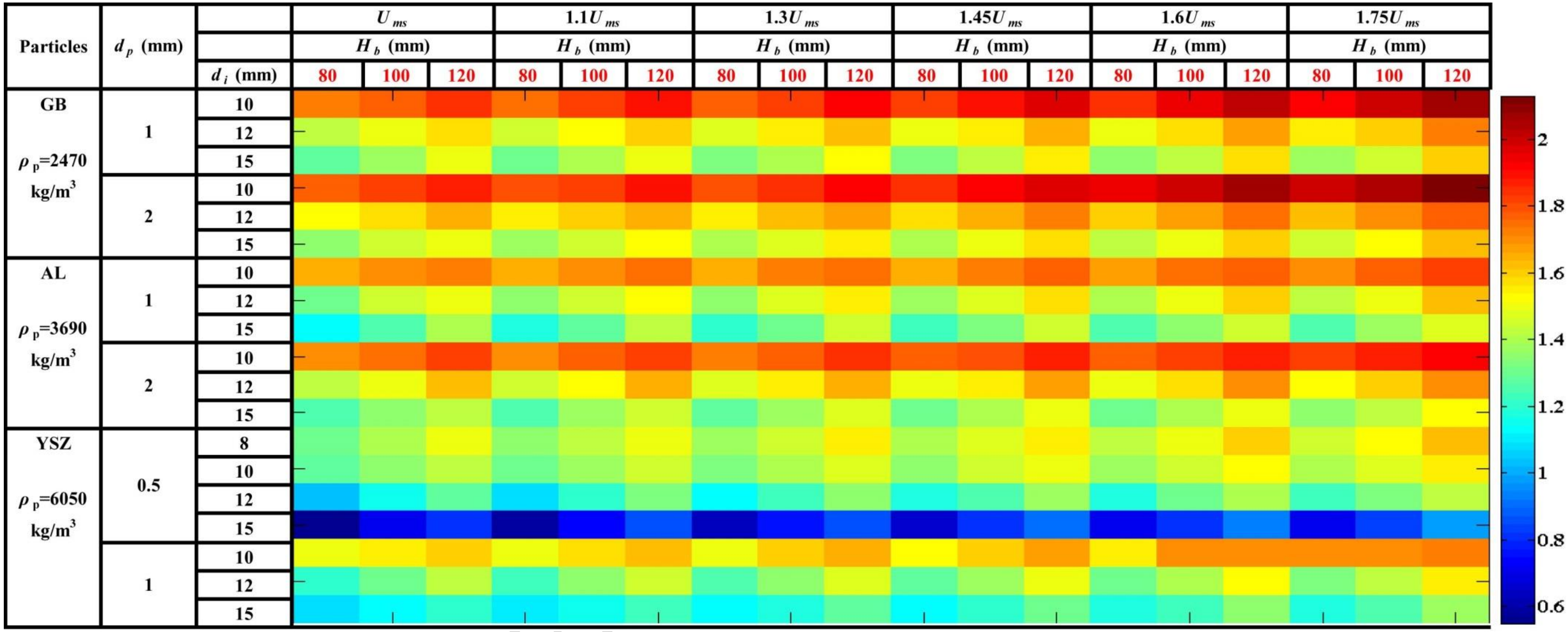

Fig. 8. Maximum information entropy values obtained at all experiments conducted in this study

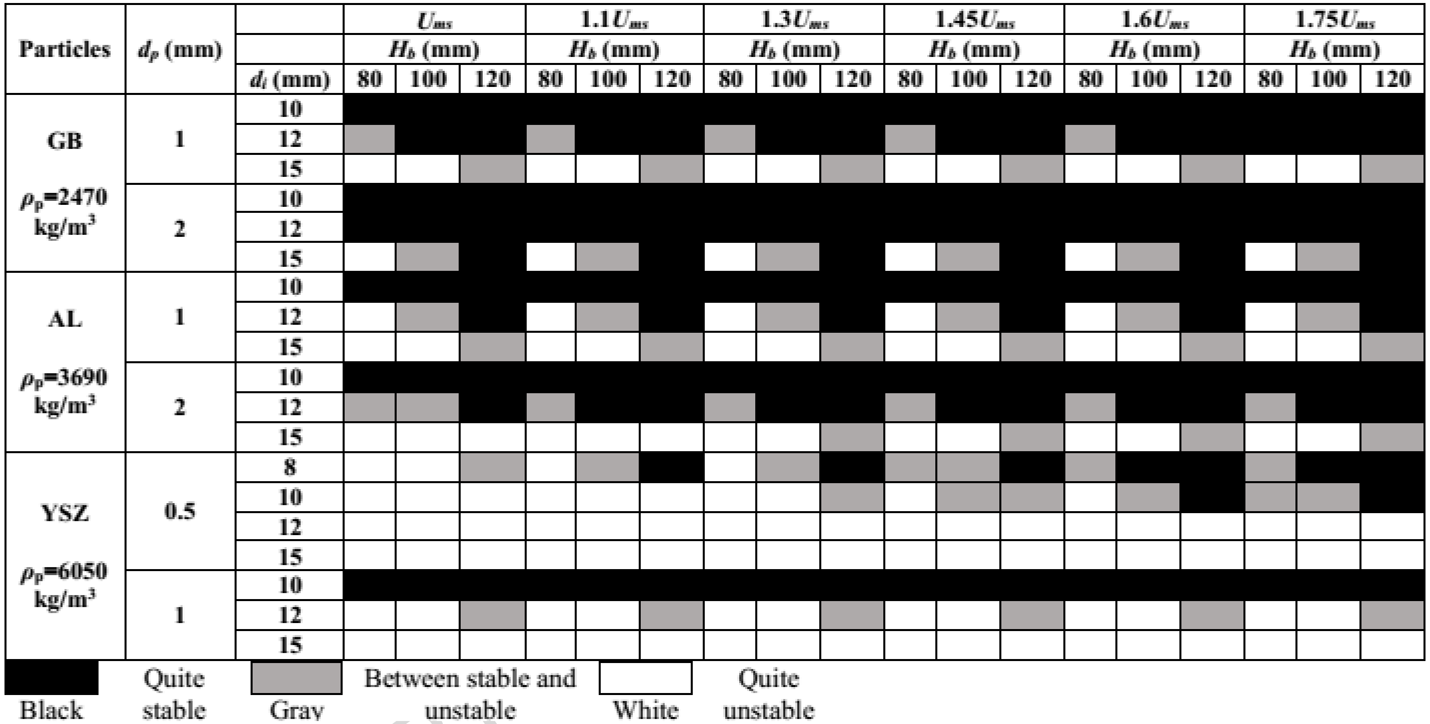

Fig. 9. Stability map of conical spouted bed

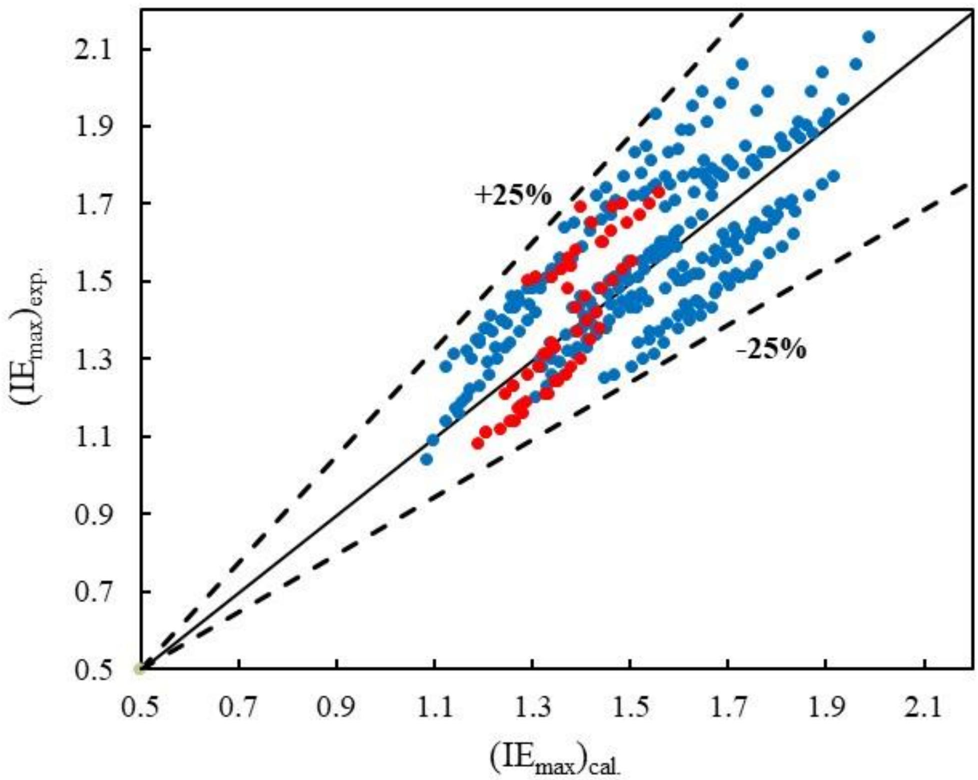

Fig. 10. Comparison of maximum information entropy experimental data with calculated data from the proposed correlation

- The maximum information entropy of pressure fluctuations was used as a stability criterion.
- The stability of the bed increases with increase in the maximum information entropy.
- The bed stability increases with increase in the particle size and static bed height.
- The stability of the bed decreases with increasing in gas inlet diameter and particle density.
- A correlation for prediction of maximum information entropy of the bed was proposed.