

Hydrodynamic Characteristics of Group D Particles (Paddy Grains) in a Conical-Based Spouted Bed with and Without Draft Tube

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Abstract: In this study, a laboratory scale spouted bed unit was constructed and used to study the spouted bed hydrodynamics of a paddy. Two internal arrangements were employed, namely a bed with and without a draft tube. Bed pressure drop and minimum spouting velocity were determined at different bed heights. The results showed that by introducing draft tube in the spouted bed, the minimum spouting velocity was lower than that without draft tube. The values of minimum spouting velocity were experimentally determined and compared with values predicted from existing correlation. A new and modified correlation was proposed to predict the minimum spouting velocity close to the experimental values.

Key words: Draft tube • Group D particles • Hydrodynamic • Minimum spouting velocity • Solids circulation • Spouted bed

INTRODUCTION

Agricultural grains such as paddy, included in group D from Geldart classification of powders, are difficult to fluidize properly because of the problems experienced with large bubble formation and slugging. Instead of using high operating air velocity, modifications such as agitation [1, 2], insertion of baffles [3], addition of inert materials [4] and spouted beds [5] may improve the hydrodynamic behavior of the particles. One of the frequently used techniques for processing coarse particles is the spouted bed.

The spouted bed was originally known as a modified version of fluidized bed. This modification arose from the poor fluidization quality of fluidization associated with coarse particles. The spouted bed has the special characteristic of performing certain cyclic operations on solid particles which cannot be performed in a fluidized bed. If fluid is injected vertically through a small opening at the base of the spouted bed, the fluid jet causes a stream of particles to rapidly rise in a hollowed central core within a bed of solids. These particles rain back onto the annular region between the hollowed core

and the column wall, where they slowly travel downward. As the fluid travels upward, it flares out into the annulus. A cyclic pattern of solids movement is thus established [5].

Due to their unique hydrodynamic system, spouted beds have been widely used in many applications such as drying [6-8], gasification [9, 10], combustion [11], pyrolysis [12, 13] and coating [14, 15]. A recent application of spouted beds has been mechanical extraction of natural dye extract [16].

Despite the wide applications and advantages, conventional spouted bed has some operating limitations such as the maximum spoutable bed height and the formation of dead zones in the annulus. Many modifications have been proposed to improve its operability. One modification is the introduction of a draft tube [17]. This modification allows the flow rates of gas and solids to be controlled independently and makes it possible to operate in higher bed as well as to handle even small particles [18].

The hydrodynamic characteristics of different types of particles in a spouted bed installed with draft tube have been subject of interest for many researchers.

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Nagashima *et al.* [18] experimentally investigated the hydrodynamic performance of irregular and angular silica sand particles and regular and round glass beads particles in a spouted bed equipped with a draft tube. The effect of four different types of draft tubes on the flow characteristics in the spouted bed was examined. They found that a conical-cylindrical porous draft tube was the best option for solid-gas contact and solids circulation.

José *et al.* [8] used a conical spouted bed for the drying of sludge wastes from pulp and paper industry. They investigated the influence of operational parameters such as the presence of a non-porous draft tube, the entrainment zone height, the draft tube diameter to gas inlet diameter ratio and waste moisture content on bed stability. They concluded that the introduction of draft tube in the spouted bed dryer improved the uniformity of bed moisture content. Use of a draft tube narrowed the frequency distribution of particle cycle times; the higher the entrainment zone, the smaller the average cycle time of the particles.

Makibar *et al.* [13] studied the hydrodynamic performance of a pilot scale conical spouted bed reactor used in the fast pyrolysis of biomass waste. Their study aimed to select the internal draft tube that best fulfilled the objectives of good mixing and a low fluidization flow rate. They found that a non-porous draft tube conferred high stability to the bed and, furthermore, reduced the fluidizing agent flow rate. A draft tube using a conical spouted bed operated with a suitable flow rate, leading to very good mixing, elutriation of light particles and short gas residence times.

For drying applications, the spouted bed has been used for processing soybean, wheat and corn [19, 20]. The objective of the present study was to examine the spouted bed hydrodynamic characteristics of paddy, which will provide a reference for the spouted bed drying of paddy. The effect of insertion of draft tube on the bed pressure drop was observed. Finally, the minimum spouting velocity was determined and the values were compared with theoretical prediction from the literature.

MATERIALS AND METHODS

Spouted Bed Column: Figure 1a shows the spouted bed column used in this study. The bottom part of the column (DRY) which is the cone is connected to blower (BLW), whereas the upper part of the column is the exhaust gas and dust outlet into the cyclone separator (CYC) and filter bag (FLT). The entire device made of stainless steel

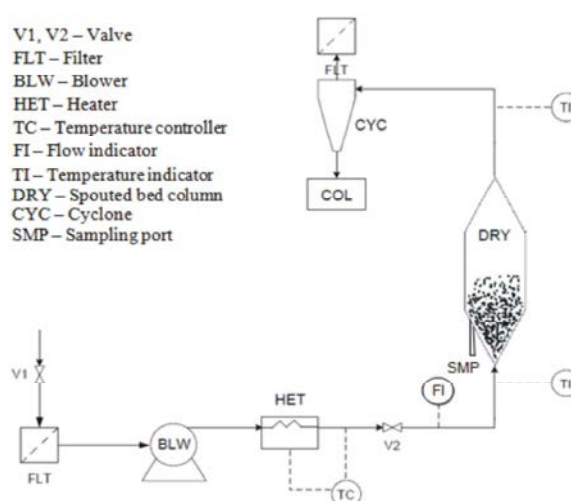


Fig. 1a: Spouted bed diagram

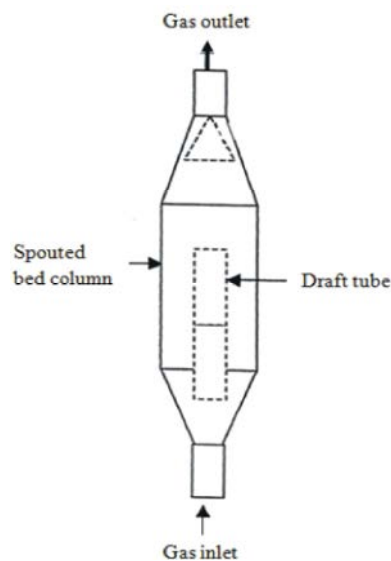


Fig. 1b: Schematic diagram of draft tube

including cyclone has a total height of about 4 m from the floor. The tool used for measuring the bed pressure drop is water manometer (PI). The blower is driven by a motor of 20 hp. The height of the cylindrical column is 75 cm and the height of the cone (gas inlet) is 30.5 cm. Diameter of the cylinder is 30 cm and the diameter of the nozzle cone with an angle of 40° is 7.5 cm. Draft tube (Figure 1b) with diameter of 10 cm is installed in the centre of the column. It is installed at 15 cm from the bottom of the bed so that the particle circulation is not hindered. The draft tube is made from stainless steel with holes of 2 mm in diameter. The tube length is 28 cm for sample with weight of less than 10 kg and 58 cm for bed height of more than twice the diameter of the column.

Materials: Spouted bed is suitable for coarse-sized particles that are classified as group D from the Geldart's classification of particles. Paddy was used in these experiments. It was obtained from BERNAS, a rice miller plant in Selangor, Malaysia. The average moisture content of paddy is about 11% wet basis.

Hydrodynamic Experimental Methodology: A total of 5 kg, 8 kg, 10 kg, ..., 18 kg of paddy was used in the hydrodynamic experiments of spouted bed, without or with draft tube installed. At each increasing air flow rate, the pressure drop reading between the bottom and the surface of the bed was observed using a water manometer with accuracy of ± 2 mm. The maximum pressure drop and minimum spouting velocity for each sample bed height was also identified.

Experiments were performed at room temperature using paddy with moisture content of 10% to 13% wet basis. The gas flow rate was gradually increased and the pressure drop changes were recorded by water manometer. When the bed of paddy started to exhibit a steady fountain and particle distribution, the pressure drop was also recorded while the gas flow rate was slowly reduced.

For experiments with draft tube, the draft tube was installed at 15 cm from the center of the column, while the length of the draft tube was 28 cm and 58 cm. The bed surface in this case was made slightly lower than the draft tube for better particle circulation. Hence, the appropriate bed height was about 42 cm and 72 cm, or $1.4D_c$ and $2.4D_c$.

RESULTS AND DISCUSSION

The mechanism of transition from a static bed to a spouted bed can be described with reference to a plot of bed pressure drop versus superficial air velocity [5]. The minimum spouting condition can be identified from this plot.

Hydrodynamic Without Draft Tube: The pressure drop versus gas velocity curves for various bed heights without draft tube are shown in Figure 2. It was observed that at the beginning of increasing gas flow rate (full line), the pressure drop was identical for different bed heights. Subsequent increase in gas velocity showed that each different bed heights reached different maximum pressure. The highest pressure drop of 4500 Pa was achieved when the materials were spouted at bed height of 62 cm (2 times the diameter of the column D). High energy is required to

break the arrangement of particles in the bed before it can push the particles upward. Further increased in gas velocity beyond this point of maximum pressure resulted in sharp decreased in the bed pressure drop. After this stage, spouting and particle distribution became steady and further increase in the gas velocity did not significantly change the pressure drop.

The dotted line shows the case in which gas velocity was gradually reduced. By the decreasing gas velocity method, it was observed at certain point, there was sudden increased in pressure drop and the particles stopped to spout. Further decrease in gas velocity caused the particle bed returned into fixed bed and was no longer able to push the particles upwards. However, the pressure drop curve in this method was lower than that when the gas flow rate was increased (full line). Bed pressure drop and minimum spouting velocity were observed to increase with bed height.

Hydrodynamic with Draft Tube: Figure 3 shows the pressure drop versus gas velocity for various spouted bed heights with draft tube. The gradual increase in gas flow rate at the beginning (full line) shows that the pressure drop was approximately equal to that without draft tube. Bed height of 40 cm ($1.3D_c$) achieved a pressure drop of about 1.5 kPa before being stabilized at 700 Pa. The pressure drop of deep bed of 64 cm ($2.1D_c$) and 70 cm ($2.3D_c$) reached 3.6 kPa and 4.3 kPa, respectively, before declined sharply and stabilized at velocities above 1.6 m/s. The changes in pressure drop showed that the bed experienced expansion and contraction at velocity of less than or equal the U_{ms} .

As depicted in Figure 2, the gradual decrease in gas flow rate (dotted line) in Figure 3 also shows that the pressure drop suddenly increased at a certain velocity and the bed condition became a fixed bed again. The hydrodynamic characteristics of spouted bed with draft tube were similar to that of conventional spouted bed; that is, the maximum bed pressure drop increased with bed load, whereas the pressure drop curve was lower during the decreasing gas velocity method. However, when the bed spouting condition was steady, the pressure drop was not affected by bed load.

Comparison of Hydrodynamics of Spouted Bed with and Without a Draft Tube: Figure 4 compares the hydrodynamic of spouted bed installed with draft tube to ordinary spouted bed. By the increasing gas velocity method, the differences on the maximum pressure drop

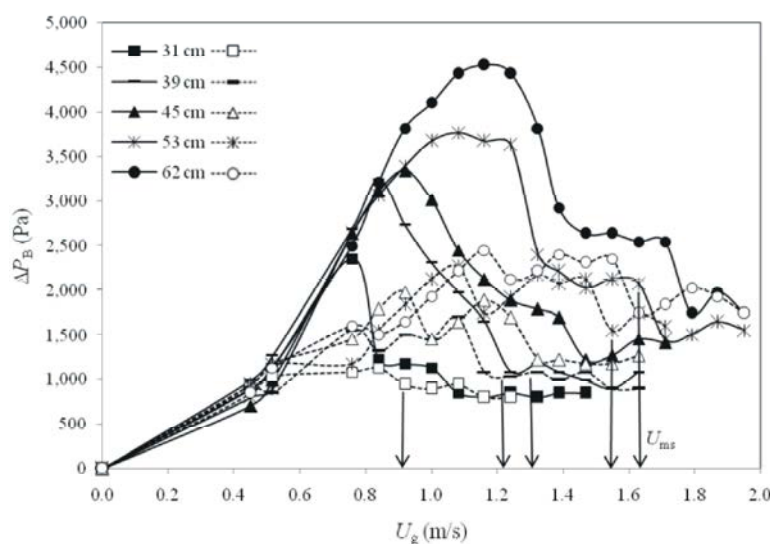


Fig. 2: Pressure drop versus gas velocity curve at various bed heights without draft tube (full line shows increasing air velocity; dotted line shows reducing air velocity)

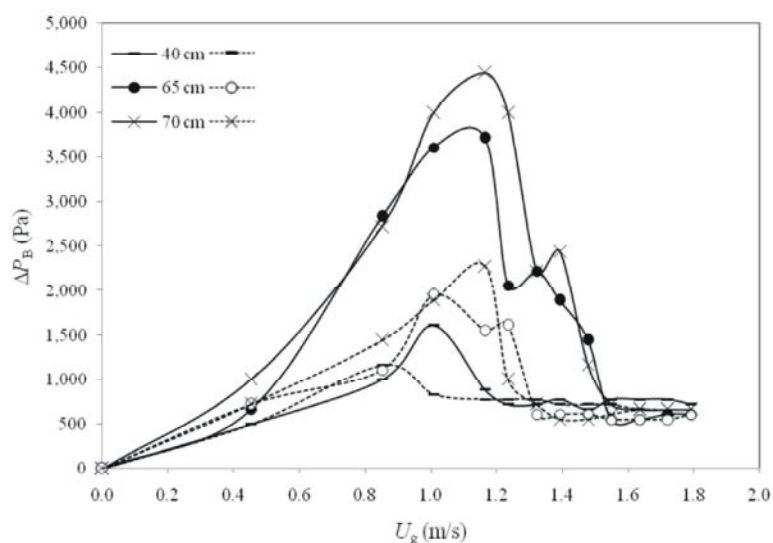


Fig. 3: Pressure drop versus gas velocity curve at various bed heights with draft tube (full line shows increasing air velocity; dotted line shows reducing air velocity)

between two different bed loads and the difference between the beds without draft tube with the bed installed with draft tube were distinctive. However, at steady spouting state, the pressure drop of spouted bed installed with draft tube was lower than that without draft tube. The lower bed pressure drop at bed height of 65 cm than that at 40 cm was due to the geometric nature or bed properties which will be described in more detail in Section 3.4.

As reported in Kalwar and Raghavan [20], the use of draft tubes caused a lower spouted bed pressure drop during the steady spouting process. This is because 70%

of the gas inlet flowed through the draft tube and forced particles to move vertically on the center core of the bed. Therefore, the energy required for good particle circulation in the spouted bed with draft tube was lower than that without the draft tube. Vieira Neto *et al.* [21] stated that the insertion of a draft tube in the central region of the spouted bed causes a modification of the normal flow patterns in the bed. They concluded that some advantages for the use of this central draft tube include greater flexibility in the operation, lower pressure drop, narrower residence time distribution and better control of solids circulation.

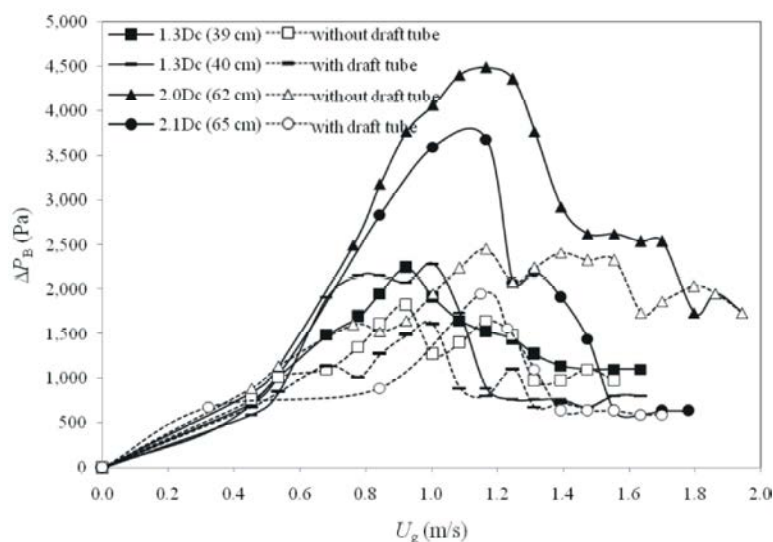


Fig. 4: Pressure drop versus gas velocity curves for bed heights of $1.3D_c$ and $2.3D_c$ in conventional spouted bed compared to spouted bed equipped with draft tube (full line shows increasing air velocity; dotted line shows reducing air velocity)

Table 1: Minimum spouting velocity for various bed heights of paddy in the spouted bed with and without draft tube

Bed height (cm)	Without draft tube					With draft tube	
	31	39	45	53	61	40	62
Measured U_{ms} (m/s)	0.91	1.22	1.30	1.53	1.61	1.14	1.45

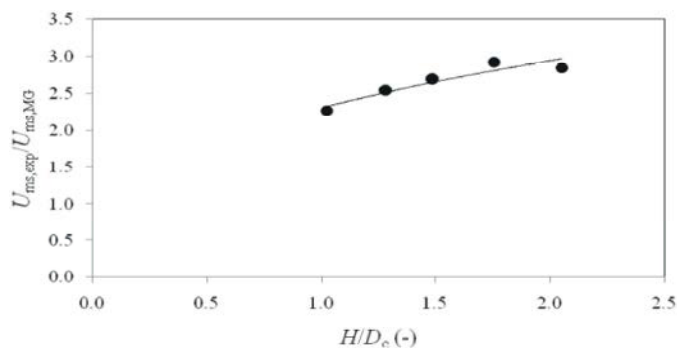


Fig. 5: Ratio of minimum spouting velocity from experiments to Mathur and Ghisler (1955) correlation, $U_{ms,exp}/U_{ms,MG}$ against ratio of bed height to the column diameter, H/D_c .

Minimum Spouting Velocity: Table 1 lists the results of minimum spouting velocity from experiments using spouted beds with and without draft tubes for various bed paddy heights. In these experiments, the minimum spouting velocity was determined before the bed returned to the fixed bed condition; that is, before the pressure drop increased rapidly while gas velocity was gradually reduced (Figure 2 and 3).

It can be observed from the experimental results shown in Table 1 that insertion of a draft tube caused a decrease in minimum spouting velocity.

For the case of $2.1D_c$ (bed height of 61 – 62 cm), the minimum spouting velocity decreased from 1.53 to 1.45 m/s by inserting the draft tube. In other words, the decrease was about 8%. While for bed height of $1.3D_c$ (39 – 40 cm), the decrease was about 7%. Similar trend was also observed by Barrozo *et al.* [16] with higher percentage of decrease in the minimum spouting velocity of 40 – 45%. They stated that the presence of the draft tube channels the air to the spout region, increasing both the air and particle velocity in this region.

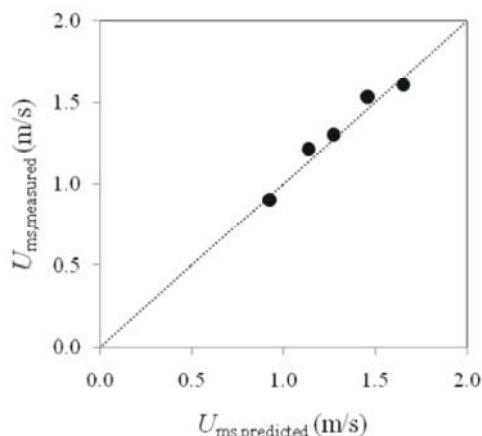


Fig. 6: Comparison of minimum spouting velocity from experiments, $U_{ms,exp}$ with the new equation of minimum spouting velocity, $U_{ms,new}$.

The well-known Mathur and Gihler [22] correlation was used to predict the minimum spouting velocity $U_{ms,MG}$ in Eq. (1):

$$U_{ms,MG} = \left(\frac{d_p}{D_c} \right) \left(\frac{D_i}{D_c} \right)^{1/3} \left(2gH \frac{\rho_s - \rho_g}{\rho_g} \right)^{1/2} \quad (1)$$

where d_p is the particle diameter (m), D_c is the diameter of the spouted bed column (m), D_i is the diameter of the gas inlet section (m), H is bed height (m), ρ_s is the particle density (kg/m^3), ρ_g is the gas density (kg/m^3) and g is the acceleration of gravity (m/s^2). When the ratio of the minimum spouting velocity from experiments, $U_{ms,exp}$ to the theoretical minimum spouting velocity, $U_{ms,MG}$ was plotted against the ratio of bed height to the column diameter, H/D_c , as shown in Figure 5, a power relation was obtained.

Eq. (2) is the new proposed equation for prediction of minimum spouting velocity ($U_{ms,new}$) from power relationship ($R^2 = 0.9$) with empirical constants K_1 and K_2 of 2.3 and 0.353, respectively. The accuracy of this relationship as shown in Figure 6 is in the range of $\pm 5\%$.

$$U_{ms} = U_{ms,MG} K_1 \left(\frac{H}{D_c} \right)^{K_2} \quad (2)$$

where H is the bed height (m), D_c is the column diameter (m) and K is the empirical constants.

CONCLUSION

The hydrodynamic behavior of paddy in a spouted bed represented group D particles. Hydrodynamics of

paddy in a conventional spouted bed was similar with the spouted bed equipped with draft tube; that is, the bed pressure drop and the minimum spouting velocity increased with bed height. The minimum spouting velocity in spouted bed with draft tube was lower than the minimum spouting velocity of bed without draft tube. However, these two types of spouted beds achieved the same maximum pressure drops before the spouting and particle circulation began. The values of minimum spouting velocity predicted by the new modified correlation had a good agreement with the measured values from experiments, with a deviation of less than $\pm 5\%$.

Nomenclature:

D_c	Diameter of the spouted bed column (m)
D_i	Diameter of the gas inlet section (m)
d_p	Particle diameter (m)
g	Acceleration of gravity (m/s^2)
H	Bed height (m)
K	Empirical constants (-)
U_g	Gas velocity (m/s)
U_{ms}	Minimum spouting velocity (m/s)
$U_{ms,exp}$	Minimum spouting velocity measured from experiments (m/s)
$U_{ms,MG}$	Minimum spouting velocity calculated from Mathur & Gishler correlation (m/s)
$U_{ms,new}$	Minimum spouting velocity calculated from new correlation (m/s)

Symbol:

ρ_g	gas density (kg/m^3)
ρ_s	particle density (kg/m^3)
μ_g	fluidizing gas viscosity (kg/m/s)

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