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Performance of Various Distributor Designs in a Gas- Solid Fluidized Bed

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***Abstract*- The applications of fluidization are far reaching. Some of the applications are combustion, gasification, drying, exfoliation and coating. However, only a few publications are available on fluidized beds that operate with Geldart Type-D particles and its respective distributors. This study focuses on fluidization of Geldart Type-D particles with three novel design of gas distributor, designated as Square Pitch Distributor (SPD), Circular Pitch Distributor (CPD) Semi-Circular Pitch Distributor (SCPD). The analysis of the results indicate that for the given bed characteristics, SPD shows better performance. Lower pressure drops and better fluidization uniformity are obtained. The distributors are perforated plate type with 4 mm holes, giving a total open area ratio of 13%. The holes are laid out in square and circular pitch of 10 mm. The bed was filled with Geldart D spherical PVC particles with a mean diameter of 5.87 mm and a density 858.8 kg/m³. Experiments are conducted by using superficial velocity up to 7.2 m/s and the range of particle loading is 0.5 kg to 2.0 kg. The pressure drop across the bed is measured by a digital manometer and the fluidization quality is assessed through physical observation. The maximum bed pressure drop values obtained for the distributors are 0.4122 kPa for SPD, 0.463 kPa for CPD and 0.5138 kPa for SCPD, with minimum fluidization velocities of 3.475 m/s, 3.588 m/s and 3.492 m/s respectively. In conclusion, SPD is found to have the best hydrodynamic characteristics and is most suited for use in gas-solid fluidized beds.**

I. INTRODUCTION

Fluidized beds present high mass and heat transfer rates that make them suitable for many industrial gas-solid applications (such as drying and granulation) as well as in the combustion, pyrolysis or gasification of many solid fuels, where they offer advantages over other types of reactors. Nevertheless, depending on the application, fluidization is sometimes difficult to achieve due to the agglomeration or cohesion between particles and defluidization or non-uniform fluidization may occur.

The difficulty to fluidize particles, as well as the need to maintain a good mixing between phases and a high particle dispersion, has led many investigators to modify the conventional fluidized bed devices, alter the air supply system or try innovative designs. Flow pulsation to control the bubble size and enhance the quality of fluidization has been used in a few experimental studies. Other investigators have tried to overcome the difficulties in mixing between phases and between solids in the bed, by modifying the distributor layout.

A conventional gas fluidized bed is considered to have three zones, namely the grid zone, bubbling bed zone and bubble erupting zone. Any change in the characteristics of the grid zone of a gas fluidized bed subsequently affects the behavior of the zones above it. A gas distributor affects very much the grid zone [1].

The function of the distributor is to distribute the fluidizing gas across the bed inlet and initiate effective gas-solid contacting. Various types of distributor are designed to improve on the operational concerns that can be encountered in fluidized bed processes. These designs can influence the bed hydrodynamics and therefore potentially alter the rate of heat and mass transfer in fluidized bed processes, including dryers [2]. Inadequate design of gas distributor or their malfunction in operation is responsible for a substantial proportion of the difficulties encountered in fluidized bed processes [3].

The present work attempts to study several distributor configurations to understand the basic principle of conventional fluidization and determine the best configuration towards actual use. Though many studies are available on distributor design in fluidized beds, there is still room for improvements to promote better solid-gas contact through various configurations of new distributor designs. The current work aims to study several configuration of perforated-plate type distributor for fluidization of Geldart's type D (>2 mm diameter) particles. The findings are essential for future studies where the best configuration of bed will be used for biomass drying process. Biomass, though comes in variety of shapes and sizes, are generally large thus can be classified as type D particles under Geldart classification.

II. BACKGROUND AND RELATED STUDIES

A. Fluidization

Fluidization is defined as the process by which solid particles are transformed into a fluid like state through suspension in a gas or liquid [4]. Fluidization is a process in which solids are caused to behave like a fluid by blowing gas or liquid upwards through the solid-filled reactor. The application of fluidization is widely used in many commercial operations. That kind of application can be divided into two categories:

i. Chemical operations such as reaction of gases on solid catalysts, reactions of solids with gases, combustion, fluid catalytic cracking, etc and
ii. Physical operation, such as transportation, heating, absorption, drying and mixing of fine powders

Fluidization can roughly be classified into particulate fluidization or bubbling fluidization. Particulate fluidization occurs in liquids and bubbling fluidization occurs in gas-fluidized beds. In particulate fluidization, when the velocity of the liquid is increased past the minimum fluidization velocity, the bed expands uniformly and uniform conditions prevail in the liquid solid mixture. The bubbling fluidization occurs when the bed is fluidized; large pockets of gas, free of particles are seen to rise through the bed. Where there are particles, the bed void fraction is approximately at the value that prevails at the point of incipient fluidization. The bubbles grow until they fill the cross-section and then successive bubbles move up the column [5].

B. *Fluidized Beds*

When the solid particles are fluidized, the fluidized bed behaves differently as velocity, gas and solid properties are varied. It has become evident that there are number of regimes of fluidization. Fig. 1 shows schematic representation of fluidized beds in different regimes. Fixed bed (Fig. 1A) occur when the flow of a gas passed through a bed of particles is increased continually, a few vibrate, but still within the same height as the bed at rest.

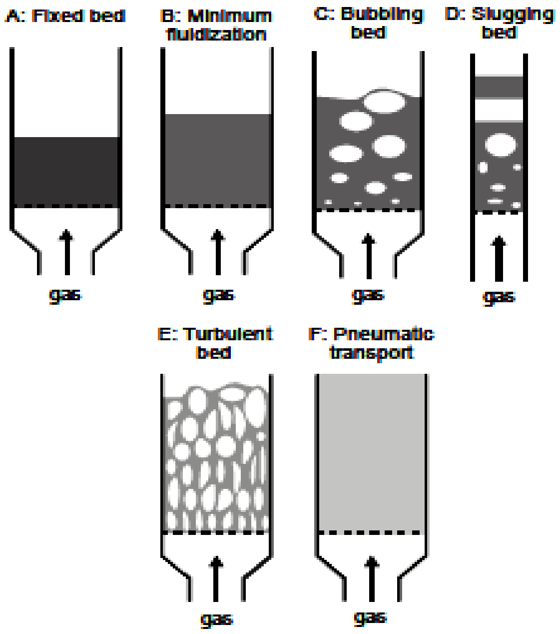


Fig.1. Schematic representations of fluidized beds in different regimes

With increasing gas velocity, a point is reached where the drag force imparted by the upward moving gas equals the weight of particles and the voidage of the bed increases slightly: this is the onset of fluidization and is called minimum fluidization (Fig. 1B) with a corresponding minimum fluidization velocity, U_{mf}. A bubbling fluidized bed (Fig, 1C) occurs when the formation of fluidization bubbles sets in while the gas flows further increased [5].

As the velocity is increased further still, the bubbles in a bubbling fluidized bed will coalesce and grow as they rise. If the ratio of the height to the diameter of the bed is high enough, the size of bubbles may become almost the same as the diameter of the bed. This is called slugging (Fig. 1D). If the particles are fluidized at a high enough gas flow rate, the velocity exceeds the terminal velocity of the particles. The upper surface of the bed disappears and instead of bubbles, one observes a turbulent motion of solid clusters and voids of gas of various sizes and shapes. Beds under these conditions are called turbulent bed as shown in Fig. 1E. With further increase of gas velocity, eventually the fluidized bed becomes an entrained bed in which we have disperse, dilute or lean phase fluidized bed, which amounts to pneumatic transport of solids.

Therefore, a fluidized bed is a packed bed through which fluid flows at such a high velocity that the bed is loosened and the particle-fluid mixture behaves as though it is a fluid. Thus, when a bed of particles is fluidized, the entire bed can be transported like a fluid, if desired. Gas and liquid flows can be used to fluidize a bed of particles. Basically, a fluidized bed consists of 3 major parts, the plenum chamber which supplies the fluidizing gas into the bed, the distributor which supports the bed of particles and distributes the fluidizing gas inside the bed and the column which holds the bed. As the current study emphasizes on the distributor design, the following section will discuss various aspects of the distributor.

C. *Distributor*

The choice and good design of gas distributors are essential for the satisfactory performance of fluidized beds and for successful industrial applications that use fluidization techniques. Intensive research work is still going on, to satisfy inadequate design of gas distributors and their malfunction in operation. A good distributor design should meet many requirements that include uniform distribution of gas into the fluidized bed, operation at as low a pressure drop a possible to minimize power consumption, sufficient strength to withstand both thermal and mechanical stresses, prevention of particle fall back, reduction in particle attrition and prevention of plate erosion. Some of these requirements are contradictory and their relative importance may change with the process requirements [6].

It is well known that if a gas distributor gives a pressure drop which is too low, the result is poor fluidization resulting in maldistribution; that is, some part of the bed will receive much less gas than the others, and may be temporarily or permanently defluidized, whilst in other parts the gas forms semi-permanent spouts or channels [3]. Therefore, the distributor pressure drop has to be large enough to overcome the small local pressure disturbances of the fluidized bed.

Distributors can be classified into various types depending on their design geometry and construction. Alternatively, distributors can be classified on the basis of their functional characteristics and the nature of the fluidizing such as the conventional distributors for gas or liquid, improved gas-liquid distributors, common distributors for gas and liquid, advanced gas-liquid distributors, and pressure-drop-dependent distributors to name a few. Fig. 2 shows some of the distributors mentioned above:

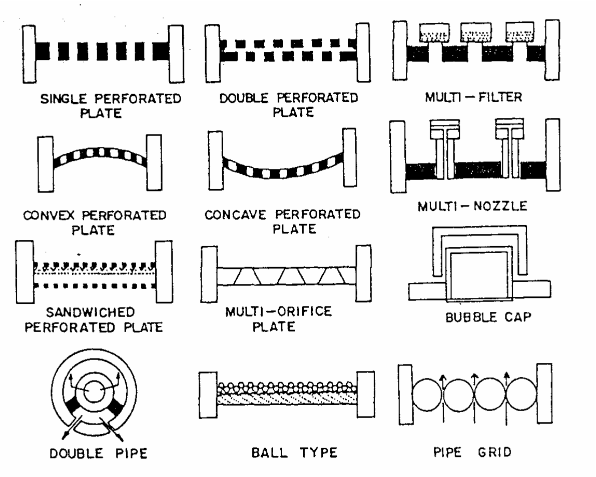


Fig. 2. Distributors for gas and liquids for fluidized beds

Conventional distributors for gas or liquid were most commonly used distributor in the laboratory viz, the porous-type distributor, which can be made of either a sintered ceramic or a metal. Apart from the distributor types mentioned above, a variety of new generation distributors have been designed, tested and reported [7-10]. These designs were studied with respect to their applications, fluidization uniformity, gas jetting characteristics, bubble behaviour, existence of dead zone and solids motion at the distributor, size, spacing and orientation of orifices and holes and solids back flow and non-dimensional analysis.

D. Distributor Pressure Drop, Δp_d

The most important parameter in characterizing a distributor is its pressure drop, Δp_d apart from its design and configuration. There is no universal value for distributor pressure drop as it depends on various operating parameters such as fluidizing gas flow rate, type and size of particle, particle attrition and elutriation and others. However, researchers have reported a variety of pressure drop values from their findings.

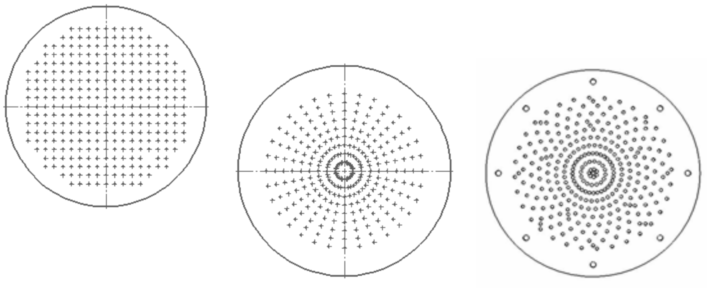
Agarwal et. al [11] proposed that Δp_d should be approximately 10% of the bed pressure drop and never less than about 3400 Pa (350 mmH_2O). Other researchers [12,13] propose minimum values for distributor to bed pressure drop, $\Delta p_d / \Delta p_b$ from 0.1 to 0.5, with 0.3 as a widely quoted value. The current work adopted this range of pressure drop for the purpose of comparison and benchmarking the developed annular distributor.

III. METHODOLOGY

Perforated-plate type gas distributor with different designs have been developed and tested for performance. The following section describes the distributor designs and the experimental set-up used in the current work.

A. Distributor Design

In the current study, three different types of perforated plate type distributor have been designed and fabricated from 5 mm thick acrylic plate. These distributors have same fraction of open area (FOA), about 13% which were made by a number of 4 mm diameter holes drilled through. The same FOA is important to ensure equal comparison was being made during testing. Each distributor differs in terms of pattern and pitch. These distributors are designated as the square-pitch distributor (SPD), circular pitch distributor (CPD) and semi-circular pitch distributor (SCPD). Though the distributor plates are 260 mm in diameter, the effective area for fluidization was limited by 200 mm, in accordance to column diameter which encloses the bed. Fig. 3 shows the distributor



(a) (b) (c)

Fig. 3. Distributor design, (a) square pitch distributor (SPD), (b) circular pitch distributor (CPD) and (c) semi-circular pitch distributor (SCPD)

B. Experimental Set-up

The schematic of the experimental set-up is shown in Fig. 4.

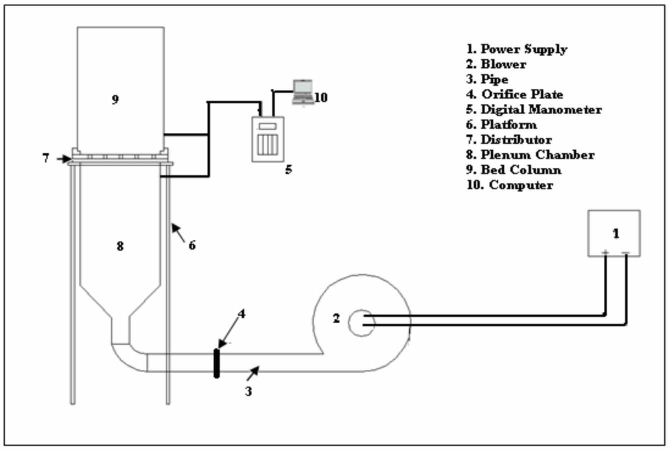


Fig. 4. Schematic diagram of the experimental set-up

The experimental set-up consists of 25 hp radial-blower with variable speed motor to provide fluidizing air, orifice plate to measure the volume flow rate of air from the blower, plenum chamber, distributor plate, column and digital manometer with 1 Pa least count and 0.1% full scale accuracy to measure pressure drops. The particles used as bed were PVC particles which is 5.8 mm in diameter and having a density about 860 kg/m^3. These particles are type-D, according to Geldart classification. Experiments were conducted on all three distributor plates with four bed weights ranging from 0.5 kg to 2 kg. The blower speeds were regulated to achieve superficial velocity up to 7.2 m/s. In each run, minimum fluidization velocity, bed pressure drop and distributor pressure drop values are acquired while the uniformity of fluidization are recorded visually using video camera. These are necessary to bring out the hydrodynamic characteristics and fluidization quality to analyze and evaluate the performance of each distributor.

IV. RESULTS AND DISCUSSION

As mentioned in the previous section, the recorded data were analyzed to obtain the performance criteria which are the pressure drop values for various particle loading, bed pressure drop to distributor pressure drop ratio in the superficial velocity range and uniformity of fluidization inside the bed. The data are plotted and shown in the graphs below:

A. Distributor Pressure Drop

Pressure drop values against superficial velocity for all three distributors, SPD, CPD and SCPD are shown in Fig. 5.

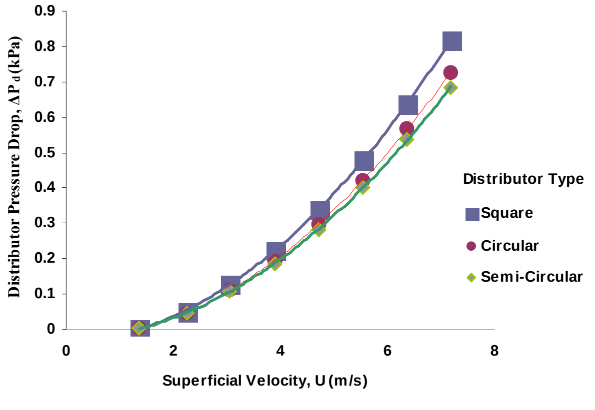


Fig. 5. Distributor pressure drop against superficial velocity

All three distributors show the same behaviour with semi-circular pitch distributor (SCPD) having the lowest pressure drop values in the velocity range studied. However, the fluidization uniformity in the bed was poorest compared to SPD and CPD. Though SPD has requires slightly more potential energy to fluidize the PVC particles, a uniform bubbling bed was observed. This proves that uniformity in bed comes with the expense of pumping power from the blower.

B. Pressure Drop Ratio against Velocity Ratio

A non-dimensional plot is between pressure drop ratio and velocity ratio was made to characterize the bed-distributor behaviour as in Fig. 6, 7 and 8. Pressure drop ratio ΔP_R, is the ratio of bed pressure drop to distributor pressure drop ($\Delta P_b/\Delta P_{d)}$) as addressed in section II-D while the velocity ratio, U_R, was simply the ratio of superficial velocity to minimum fluidization velocity, (U_s/U_{mf}). These non-dimensional plots were imperative as they resemble both bed and distributor pressure drop values as suggested in [11–13]. Apart from that, equal comparison can be made between all distributors to distinguish individual performances since each distributor behaves differently with the same values of superficial velocity.

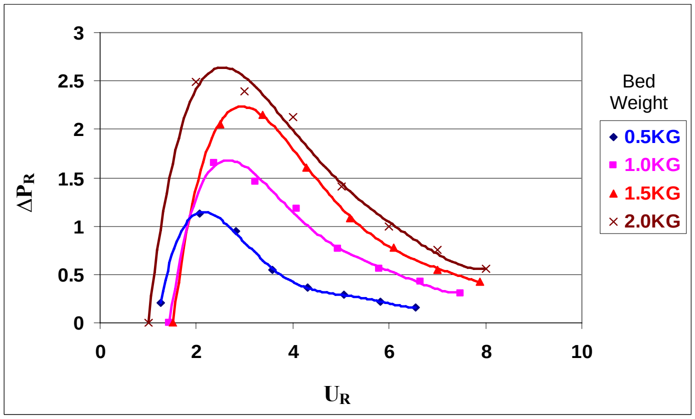


Fig. 6. Pressure drop ratio, ΔP_R against velocity ratio, U_R for Square Pitch Distributor, SPD.

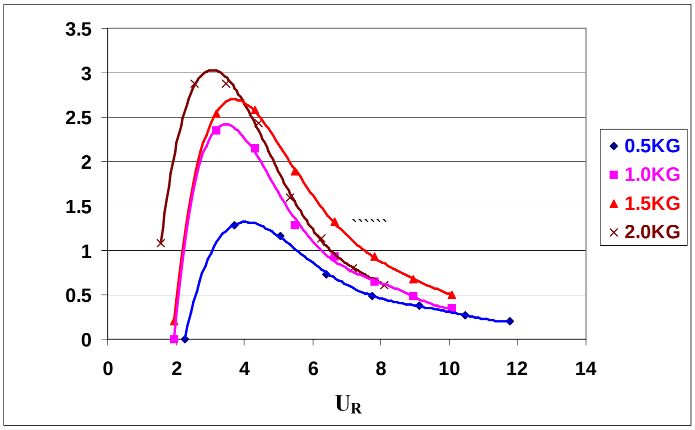


Fig. 7. Pressure drop ratio, ΔP_R against velocity ratio, U_R for Circular Pitch Distributor, CPD.

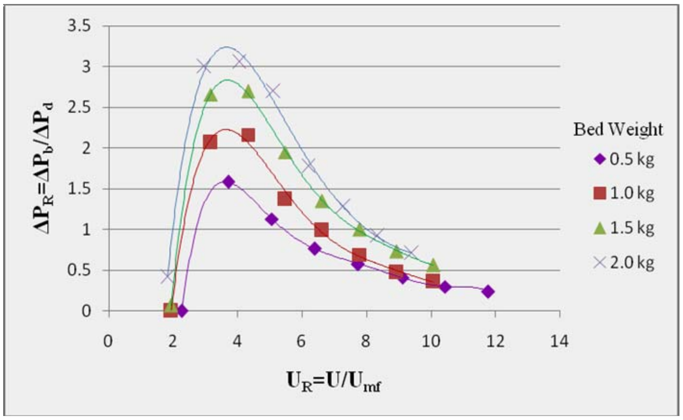


Fig. 8. Pressure drop ratio, ΔP_R against velocity ratio, U_R for Semi-Circular Pitch Distributor, SCPD.

increased steeply until reaches a maximum value, before decreases gently. Generally, the pressure drop ratio increases with bed weight owing to the larger drag force to fluidize the bed. The maximum pressure drop for all bed configurations occur at different velocity ratio for given bed weight, except for SCPD where the maximum pressure drop value happens to be around a constant velocity ratio of 3.8. These peak values in the plots are the instances where the bed consumes most energy for fluidization during operation. Here, momentum transferred inside the bed is at its maximum compared to the amount of momentum used to overcome distributor resistance. Upon reaching the peak values, all bed configuration shows gentle reduction in pressure drop ratios. This is so as the bed pressure drop remains fairly constant after fluidization but the distributor pressure drop increases proportionally with superficial velocity.

From literature [3,5,6,12,13], the normal range of superficial velocity during operation in a typical fluidized bed is about 2-4 times its minimum fluidizing velocity, U_{mf}. The maximum pressure drop ratio for all distributors studied falls within this range, indicating that power consumed for fluidization of Geldart type-D particles is eventually high. Nevertheless, it is recommended here to operate the bed at this range since higher amount of kinetic energy was being transferred into the bed rather than overcoming distributor pressure drop as mentioned above. Therefore, the bed will have better energy efficiency.

It can clearly be seen here that SPD shows superiority over CPD and SCPD as the ΔP_R value are relatively low for all bed weights. For instance, in the case of bed weight = 2kg, the maximum ΔP_R for SPD is only 2.5 while for the CPD and SCPD is 3.113 and 3.25 respectively. Upon reaching a maximum values, the ΔP_R reduces gently as discussed above.

During experiments, the bubbles were observed to be random in nature for all three distributors studied, while its frequency and size kept increasing in accordance to superficial velocity. These bubbles cause the particles to continuously mix and thereby promote uniformity for the desired gas-solid contact, but should be controlled to avoid excessive bypass of unreacted fluidizing gas and also entrainment of particles.

In the current work, again SPD was seen to show superiority in terms of uniformities of bubble across the bed, compared to CPD and SCPD. Bed operating with SPD also reaches fluidization much easier compared to the other two. Unlike other particles according to Geldart classification, fluidization is relatively easy for all distributor and bed configuration. Though bubble growth can be seen, slugging phenomenon does not occur, owing to the uniform geometry of the spherical particles and the relatively low bed heights. Low bed height results in short residence time of bubbles in the bed where they reach the bed surface before coalescing and become slugging.

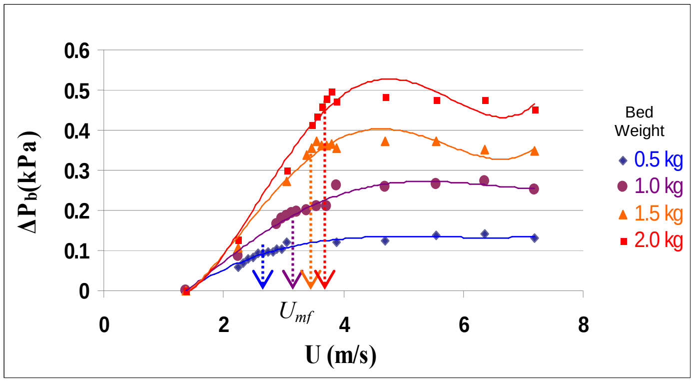


Fig. 9. Bed pressure drop, ΔP_b against superficial velocity, U for Square Pitch Distributor, SPD.

C. *Bed Pressure Drop against Superficial Velocity*

The following are results from experiments conducted to determine the minimum fluidization velocity of the bed. Fig. 9, 10 and 11 shows the broad sequence of event as the air flow increases progressively from zero.

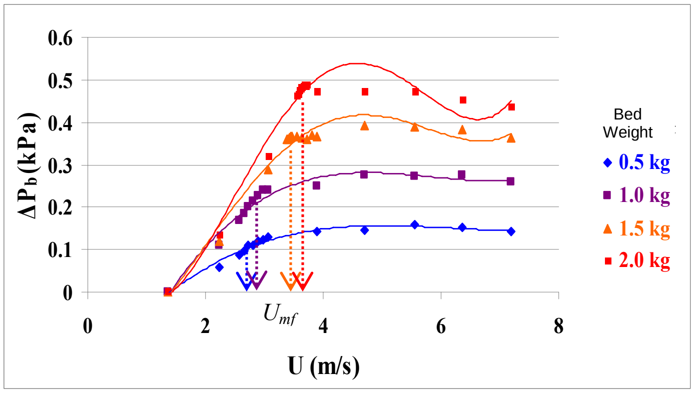


Fig. 10. Bed pressure drop, ΔP_b against superficial velocity, U for Circular Pitch Distributor, CPD.

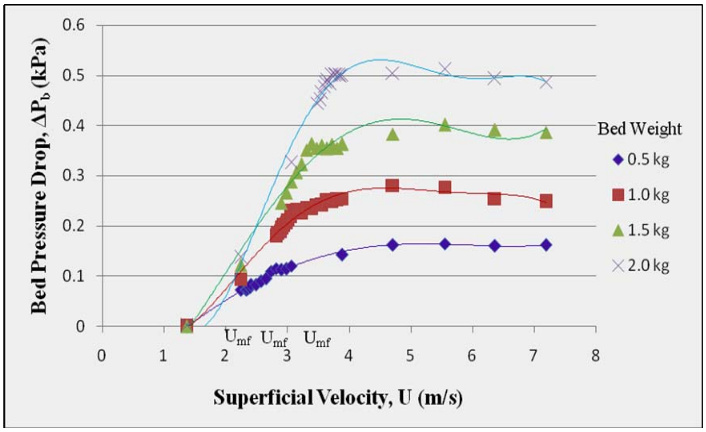


Fig. 11. Bed pressure drop, ΔP_b against superficial velocity, U for Semi Circular Pitch Distributor, SCPD

At first, the appearance of the bed does not change and the pressure drop rises with the flow rate, where the bed is said to be in packed region. Then, the bed reaches a maximum pressure drop value, at the point which is known as minimum fluidization velocity. Here, the drag force from the air balances the bed weight, and the particles inside the bed start to behave like a fluid. Increasing the velocity above the minimum fluidization velocity U_{mf} does not result in an increase in bed pressure drop. At first the particles tend to rearrange themselves to provide more space around them so as to accommodate the extra air flow, the bed voidage increases, so that the bed as a whole expands to a greater depth.

From Fig. 9, for fluidized bed using square pitch distributor SPD, the minimum fluidization velocity, U_{mf}, obtained at 2.244 m/s for bed weight, W_B is 0.5 kg and the ΔP_b is 0.0588 kPa. The U_{mf} naturally increased with larger bed weights, 2.898 m/s for 1.0 kg, 3.475 m/s for 1.5 kg and 3.511m/s for bed weight of 2 kg with corresponding pressure drop of 0.47 kPa.

Similar findings can be seen for CPD and SCPD from Fig. 10 and 11. The U_{mf} value for both, however, is higher than SPD for all bed weights. Combined with the better fluidization quality of SPD as discussed in section IV-B above, the findings lead to the conclusion that SPD is indeed has the best performance from all three distributors while SCPD had the worst performance as it has the maximum pressure drop values for all cases studied. Therefore, SPD configuration is suggested to be used in an actual fluidized bed.

CONCLUSION

Distributors play crucial role in a fluidized bed. Not only do they function to introduce the fluidizing medium into the bed of particles, but also ensure good mixing between solid and fluid and promotes uniformity in terms of bubble distribution across the bed. In the current work, the performances of three perforated type gas distributor have been studied in terms of pressure drop and quality of fluidization with Geldart type-D particles. The distributors, designated as the Square Pitch Distributor (SPD), Circular Pitch Distributor (CPD) and Semi-Circular Pitch Distributor (SCPD) differs in their design though having same fraction of open area. From the experiments conducted with spherical PVC particles, it was found that SPD was having the best performance. The pressure drop ratio between bed and distributor is about 2.5 with corresponding velocity ratio of 2. Therefore, by operating the bed at superficial velocity of only twice its minimum fluidizing velocity, the bed has the best energy efficiency together with good bubble distribution. However, it is suggested here that more experiments be conducted with SPD towards further improving its performance, especially to establish the optimum fraction of open area with the current distributor design.

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