# Experimental and computational study of pressure drop and void fraction in a bubbling fluidized bed.

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## Abstract

The aim of this work is to study flow behaviour in a fluidized bed with different mixtures of particles. Mathematical simulation is an alternative way to study the fluidization behaviour. Experiments are performed in a cylindrical bed with a uniform air distribution. Spherical glass particles with different mixtures of particles are used in the experiments. The pressure and void fraction variations are observed for two different powders and mixtures of the powders. The commercial CFD code Fluent 6.3 is used for the corresponding simulations. Eulerian-Eulerian model are used to simulate a multiphase bubbling fluidized bed. The influence of particle size distribution on the bubble size, pressure and void fraction variation along the bed has been investigated computationally. The computational results are compared to the experimental data and the discrepancies are discussed.

*Keywords: fluidized bed, particle size distribution, pressure drop, CFD, fluent.*

## 1 Introduction

Fluidized beds are widely used in industry because of good mixing and large contact area between phases. It enhances the chemical reactions, heat transfer and mass transfer. Liquid like behaviour of the bed particles are giving smooth operation conditions and well mixed beds are obtaining isothermal properties, hence the operation can be easily controlled.

Particle mixing in a fluidized bed is very much depending on bubble size distribution and the particle characteristics [1]. The behaviour of particles in

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fluidized beds depends on a combination of the particle size and density. Geldart fluidization diagram [2] is used to identify characteristics associated with fluidization of powders. Geldart Group A particles are easily fluidized and give a high bed expansion which means high void fraction before bubbles appear. This type of powders is mostly used as catalyst in fluidization system. Geldart group B particles give low bed expansion, and bubbles will appear as soon as the gas velocity reaches the minimum fluidization velocity [3].

Earlier studies have shown that powders with a range of particle sizes cannot be characterized only based on mean diameter [4–7]. The fluidization properties are highly influenced of the bulk density and changes in bulk density with the particle distribution as well. The bubble behaviour and the bubble size depend on pressure and the void fraction variations along the bed. Pressure readings conveys the information regarding the hydrodynamics of the fluidized bed, detecting the regime transitions, to investigate the chaotic behaviour of the fluidized bed and monitoring the quality of fluidization [1].

In this work the pressure and void fraction variations for different mixtures of particles are studied.

## 2 Computational model

Computational studies have been performed on a two dimensional fluidized bed. The simulations are performed by using the commercial CFD code Fluent 6.3. The model is based on an Eulerian description of the gas and the particle phases. The combinations of models used in this work are presented in Table 1. Jayarathna et al. [7] made a computational study of the influence of particle size distribution on flow behaviour in fluidized beds and by studying different combinations of models they concluded that the combination presented in Table 1 gives the most realistic flow behaviour.

Table 1: Recommended combination of models [10].

| Property | Model |
|---|---|
| Drag | Syamlal and O’Brien |
| Granular viscosity | Syamlal and O’Brien |
| Granular bulk viscosity | Constant |
| Frictional viscosity | Schaeffer |
| Frictional pressure | Based-ktgf |
| Solid pressure | Ma-ahmadi |
| Radial distribution function | Ma-ahmadi |

The Syamlal and O’Brien drag model [13] is used to express the solid-gas interaction. The model is expressed in eqn. (1):

$$\Phi_{sg} = C_D \frac{3\varepsilon_s \varepsilon_g \rho_g \left| \vec{U}_g - \vec{U}_s \right|}{4 v_r^{\,2} d_s} \tag{1}$$

where $\varepsilon_g$ and $\varepsilon_s$ are the gas and solid fractions, $\rho_g$ is the gas density, $U_g$ and $U_s$ are the gas and solid velocities and $d_s$ is the particle diameter. The terminal velocity correlation for the solid phase, $v_r$, is a function of void fraction and Reynolds number [10]. The drag factor developed by Dalla Valle [11] is presented in eqn. (2):

$$C_D = \left( 0.63 + \frac{4.8}{\sqrt{\mathrm{Re}_s / v_r}} \right)^2 \tag{2}$$

The granular viscosity includes a collisional and a kinetic viscosity term. The kinetic term is given in eqn. (3):

$$\mu_{s,kin} = \frac{\varepsilon_s d_s \rho_s \sqrt{\Theta_s \pi}}{6(3e_{ss} - 1)} \left[ 1 + \frac{2}{5}(1 - e_{ss})(3e_{ss} - 1)\varepsilon_s g_{0,ss} \right] \tag{3}$$

and the collisional term is presented in eqn. (4):

$$\mu_{col} = \frac{4}{5} \varepsilon_s d_s \rho_s g_{0,ss} (1 + e_{ss}) \sqrt{\frac{\Theta_s}{\pi}} \tag{4}$$

where $d_s$ $e_s$ and $\Theta_s$ are the particle diameter, elasticity coefficient and the granular temperature of solid phase s respectively. The radial distribution function is presented by $g_{0,ss}$. The radial distribution function included in the Syamlal and O'Brien [13] symmetric equation is expressed by Ma and Ahmadi [12].

Two particle phases are included in the simulations of mixtures. Syamlal-O'Brien symmetric is used to express the particle-particle momentum exchange [13].

# 3 Experimental and computational set-up

Experiments and corresponding simulations are performed. The set up is presented in this chapter.

## 3.1 Experimental set-up

A lab-scale fluidized bed with a uniform air distribution is constructed. The bed is cylindrical and is made of Lexan glass. The diameter and the height of the bed are 0.072 and 1.4 m respectively. The gas flow rate is controlled by a pressure reduction valve, and measured by a digital flow meter. The pressure can be measured at eight positions in the bed.

Glass particles with two different mean particle sizes are used in this study. The particles have the size range 100–200 μm (small particles) and 400–600 μm (large particles). The particle density is 2485 kg/m$^3$. The bed and particle parameters are presented in Table 2.

Experiments have been performed with 100% small particles, 100% large particles and mixtures of small particles with 20, 40, 50, 60 and 80% of large particles. The aim is to study how the different fractions of particle sizes influence on the minimum fluidization velocity and the bed expansion. Before the experiments with the mixtures started, the powders were well mixed and 2 litres of a compact mixture were weighted and filled into the bed. The void fractions at start and at minimum fluidization were calculated based on the weight and the volume.

Table 2: Experimental data.

| **Bed design** | | | |
|---|---|---|---|
| Height<br>Diameter | | 1.4 m<br>0.072 m | |
| **Particles (Spherical glass particles)**<br>Density: 2485 kg/m$^3$ | | | |
| Particle range | 100–200 µm (small) | 400–600 µm (medium) | Mixture |
| Mean particle size | 154 µm | 488 µm | |
| % large particles | | | 20, 40, 50, 60, 80 |

### 3.2 Computational set-up

The simulations are performed with particles with diameters equal to the mean diameters of the glass powders used in the experiments. The simulations are performed with mixtures of 0%, 20%, 40%, 50%, 60%, 80% and 100% large particles. Two particle sizes are used to simulate the mixtures of two powders with different mean particle size. The simulations are run with the same velocities and initial bed heights as used in the experiments. Two-dimensional Cartesian co-ordinate system is used to describe the geometry. The width and the height of the computational bed are 0.072 m and 1.4 m respectively. A grid resolution test is performed to find a suitable grid size. The grid is uniform and the size of a cell is 3x3 mm. The simulations have been run for 7 seconds. The simulations have been run with different gas flow rates.

## 4 Results

This chapter presents the experimental and computational pressure fluctuations and average void fractions variations of the different particles mixtures with different superficial air velocities.

### 4.1 Void fraction variations

All the particle samples are having an identical maximum compact volume. The volume of the particles has expanded when it is filled smoothly in to the fluidized bed. Figure 1 shows the void fractions and the compositions of large and small particles in the mixtures. It is possible to observe that the samples with only small and only large particles have higher void fractions than the particle mixtures with both large and small particles. This may be due to the repulsive forces between the small particles [2]; which means that they are having some barriers to reduce the voids as shown in Figure 2(a). The large particle cannot reduce the voids between the particles, because of their geometry as shown in Figure 2(b). The repulsive forces are not significant for large particles.

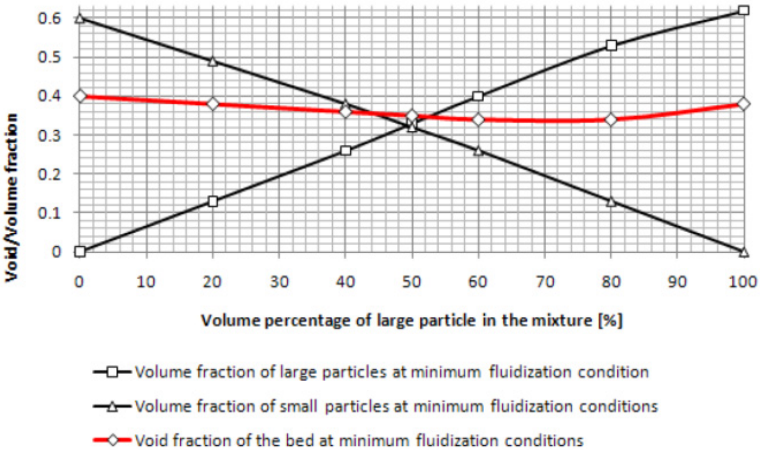



Figure 1: Void fractions and compotions of particles.

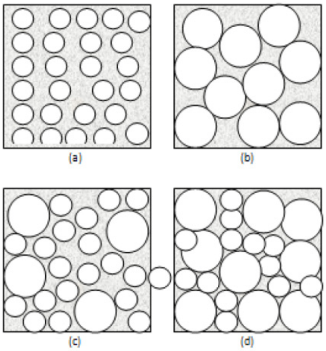



Figure 2: Possible particles location with two different sizes of particles.

In the mixtures of both small and large particles, lower void fractions are observed. The lowest void fractions are observed for the mixtures with 50% to 90% large particles. The minimum void fraction is found for the mixture of 70% large and 30% small particles. That means the mixtures of both large and small particles are more packed than the mono sized particle samples. There may be less space between particles in the mixtures with more large particles than in the mixtures with more small particles as shown in Figure 2(c) and (d).

### 4.2 Pressure variation

The pressure (gauge) is measured and calculated at height 3.5 cm, 33.5 cm and 63.5 cm in the fixed bed. Figure 3 shows the experimental and computational variations in the pressure versus percentage of large particles in the sample at different heights. The simulations give slightly lower pressure than the experiments. This may be because the particle samples used for experiments consist of a wide range of particle sizes while the simulations consider only the mean particle size to represent each mixture. The pressure along the bed is decreasing from the bottom to the top due to the weight of the particles above the measuring point [3].

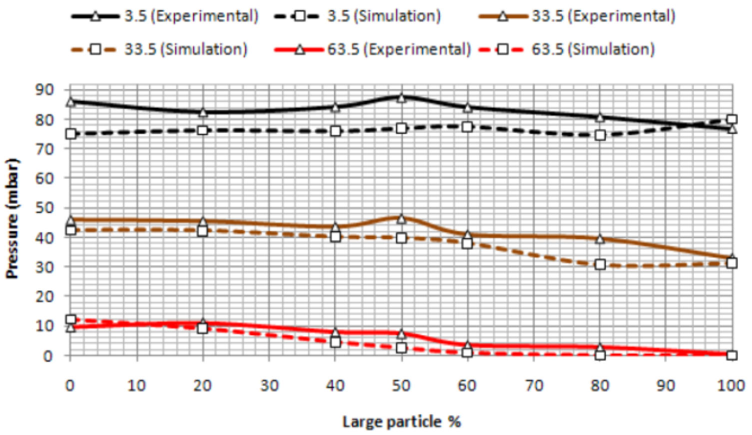



Figure 3: Pressure variations of the observations and the computations at three different bed heights. Fixed bed.

Figure 4 shows the total pressure at bed height 23.5 cm as a function of superficial air velocity for several selected particle mixtures. The figure includes both experimental and computational results. The curves from the experiments have steep gradients until they reach very high velocities whereas the gradients of the curves from the simulations are less steep. In both the experiments and simulations the total pressure at height 23.5 cm is increasing with increasing superficial air velocity. This is due to the bed expansion and the change in bubble distribution in the bed when the velocity is increased. The main contribution to the variation in pressure is the weight of the particles above the measuring point. The distribution of voids and bubbles depends on the particle mixture and the superficial velocity. Bubble distribution for different flow conditions are further discussed in Chapter 4.3. The 40% experimental curve is rather flat at higher superficial air velocities which indicates that the average void fraction in the lower part of the bed is rather constant when the velocity exceeds about 0.2 m/s.

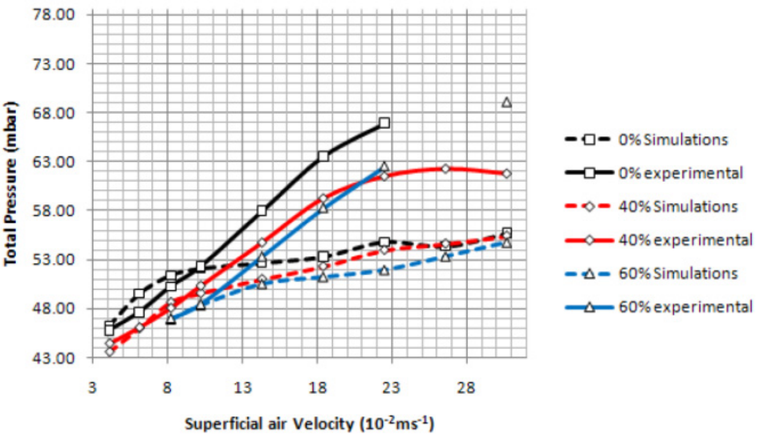



Figure 4: Pressure variations of observations and computations with respect to superficial air velocity at 23.5cm bed height.

### 4.3 Analysis of fluidized bed behaviour based on simulations

Fluidized bed behaviour is analyzed based on computer simulations for different particle mixtures. The simulations are performed for different superficial velocities with the lowest velocity as the minimum fluidization velocity observed in the experiments. Figure 5 shows the simulated fluidized bed of 100% small particles for three different gas velocities. No bed expansion is observed at velocity 0.029 m/s which is the experimental minimum fluidization velocity for the corresponding particle mixture. The computational minimum fluidization velocity is observed at superficial gas velocity 0.05 m/s. The bed expands to almost the double of the initial height when the velocity is increased to 0.307 m/s. It is possible to observe large air bubbles and very high bed expansions for the samples with 0%, 20% and 40% large particle mixtures as shown in Figure 5 and 6. These particle mixtures give slugging and turbulent beds at high superficial gas velocities.

Figure 7(a) shows the bed behaviour for a mixture of 50% small and 50% large particles after 7 seconds. The initial bed height is 0.511 m and the superficial velocities are varied from 0.039 m/s to 307 m/s. These simulations are performed for a mixture with a total volume fraction of large and small particle phases of 0.32 and 0.35 respectively. The initial and boundary conditions are the same as used in the experiments with the same particle mixture. The experimental minimum fluidization value for this particle mixture is 0.039 m/s whereas the minimum fluidization velocity in the simulation is observed at velocity 0.055 m/s. The deviation can be due to the several different particle sizes in the real mixture. In the simulation with air velocity of 0.039 m/s the gas percolates through the void spaces between stationary particles. This means the bed is at fixed bed conditions. At the next simulation the air flow of 0.045m/s is used, particles moved apart and they moved in restricted regions. This time the

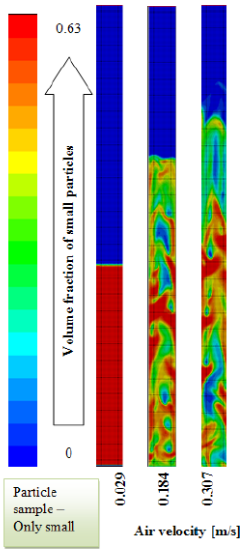



Figure 5: Simulated fluidized beds for several superficial air velocities for small particles.

bed has converted to an expanded bed and it is possible to observe a small increment of the bed height. The bed starts to fluidized when the air flow is increased to 0.055m/s. At higher velocities (0.102m/s and 0.143m/s) slugging started and the bed height is increased further, gas bubbles coalesce and grow as they rise. Figure 7(b) shows the flow behaviour for a mixture of 60% large particles. This mixture gives about the same bed expansion and bubble behaviour as the mixtures with a lower content of large particles. It is also observed that mixtures of 0%, 20%, 40%, 50% and 60% large particles have about the same minimum fluidization velocities [14, 15]. This indicates that the smallest particles in the mixture influence significantly on the flow behaviour even when the fraction of small particles are lower then the fraction of large particles.

Figure 8(a) and (b) show the flow behaviour for mixtures of 80% and 100% large particles respectively. These powders give a low bed expansion and smaller and more isolated bubbles. By studying Figure 8(a), it can be seen that still with only 20% small particles the flow behaviour are very much influenced by the small particles. The mixture with 80% large particles has started to fluidize at velocity 0.080 m/s whereas the 100% large particles start to fluidize at a velocity above 0.184 m/s.

At slugging conditions bubbles are moving upward by using a zigzag path as shown in Figure 9. This can be clearly visualized from the computer animations. All the generated air bubbles at the bottom of the bed are moving into low pressure zones. Bubbles are moving upward because of the generated highest pressure at bottom of the bed. When the bed is extremely narrow, bubbles are having a Zigzag path to escape from the bed as it is having obstacles to move directly upward.

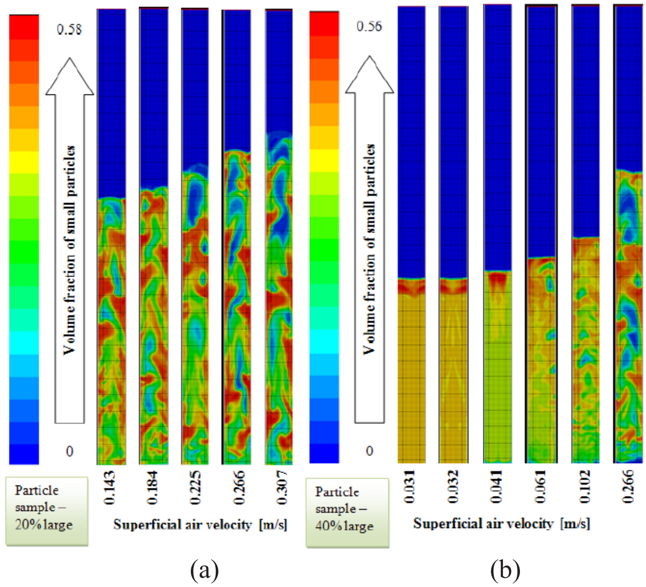



Figure 6: Simulated fluidized beds for several superficial air velocities for 20% (a) and 40% (b) large particle mixture.

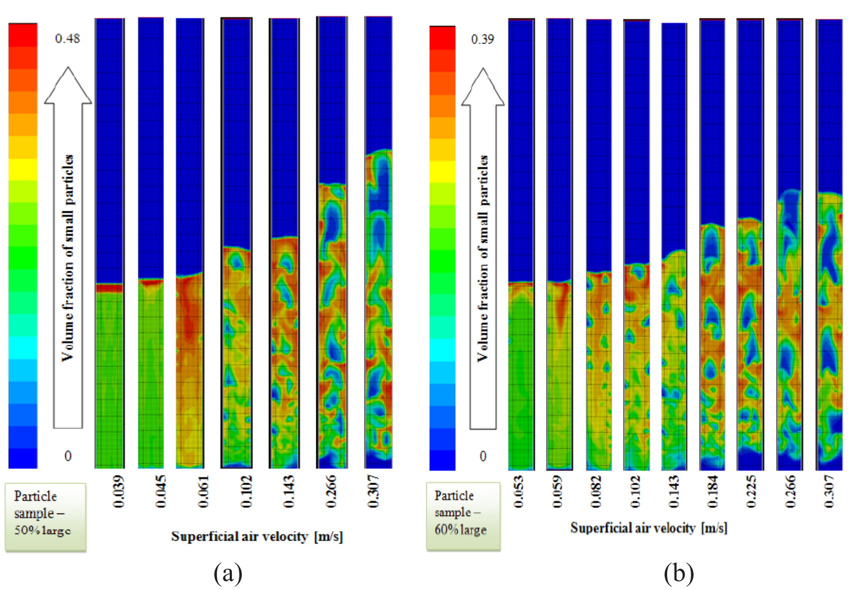
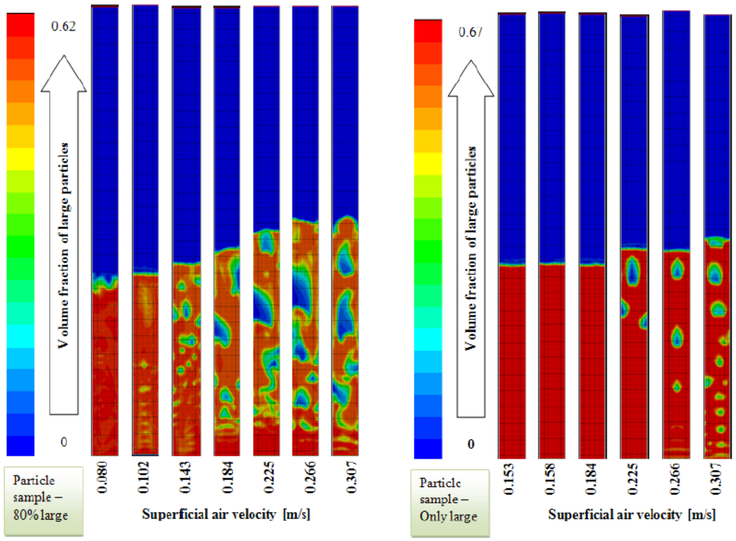



Figure 7: Simulated fluidized beds for several superficial air velocities for 50% (a) and 60% (b) large particle mixture.




(a) (b)

Figure 8: Simulated fluidized beds for several superficial air velocities for 80% (a) and 100% (b) large particle mixture.

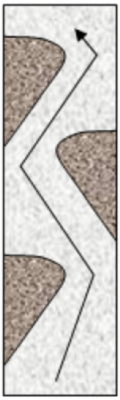


Figure 9: Zig zag bubble leaving pattern.

## 5 Conclusion

A series of experiments and simulations are carried out. Experiments are performed in a cylindrical bed with a uniform air distribution. Different mixtures of spherical glass particles with mean diameter of 154µm (small particles) and 488µm (large particles) are used in the experiments. Corresponding simulations are performed by using the commercial CFD code Fluent 6.3. In addition to the pressure variations along the bed, and void fraction is calculated at minimum fluidization velocity. The void fractions for only small and only large particles are higher than for the mixtures of both particles sizes. Lowest void fractions are observed for the mixtures with 50%-90% large particles.

Fluidized bed behaviour is analyzed based on computer simulations for different particle mixtures and different superficial velocities. The highest bed expansion is observed for only small particles and the lowest for only large particle samples. Big air bubbles and high bed expansion are observed for the 0%, 20%, 40% and 60% large particle mixtures. More isolated and relatively small bubbles are formed in the fluidized bed with only larger particles. The fluidization and bubble behaviour are influenced significantly more by the small particles than then of the large particles in a mixture. At the slugging conditions bubbles are moving upward by using a zigzag path. According to the observation, the computational fluidized bed behaviour agrees well with the experimental data.

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