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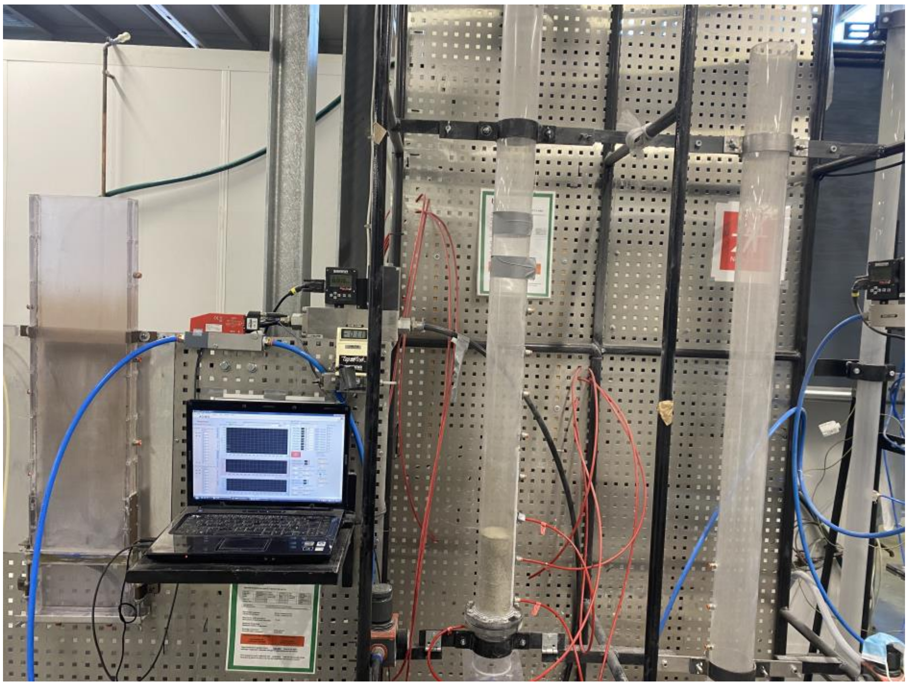
Process Technology

Fluidization behavior of sand particles with a size distribution



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Summary:

Fluidization technology has a wide range of applications in industries due to its unique ability to transport solid particles and for uniform heat transfer. But this technology is dependent on the properties of bed material. It is essential to determine the hydrodynamics behavior such as minimum fluidization velocity of bed material. During operation, particles with low mechanical strength experienced attrition. Particle attrition increases operating cost, instability, and decreases reactor or bed performance. Also, due to attrition minimum fluidization velocity will change.

The core aim of this study is to understand how minimum fluidization velocity will alter if particle size distribution changes due to particle attrition. In this work, a literature study about the minimum fluidization velocity of poly-dispersed particles, and developed correlations was conducted. Minimum fluidization velocity was determined from the experimental data of different-size particle samples. The minimum fluidization velocity of the original sample was compared with other samples.

The results show that minimum fluidization velocity decreases with the reduction of the size of particles. The presence of a considerable number of small particles can alter the minimum fluidization velocity of the sample. At packed bed condition, pressure drops show linear relation with gas velocity. The results also show that minimum fluidization velocity can be the same for different mean diameters. Finally, some correlations can predict the minimum fluidization velocity of particles with good accuracy.

Preface

This report is the outcome of the master's thesis work FM606. This study aims to understand the change in minimum fluidization velocity with the change in particle size distribution. It was an extraordinary experience to be involved with this kind of work.

First, I would like to express my gratitude towards almighty Allah, who gave me the strength and patience to finish this work.

I want to express my sincere gratitude towards my supervisor Janitha Bandara. Without his guidance, this work may not be possible to complete successfully. His advice and continuous support helped me to finish my work on time. His explanation and way of thinking showed me the right way.

I also want to express my gratitude to my other supervisor and my teacher, Britt M. E. Moldestad. Her way of teaching, sincerity, and kindness helped me to choose this work. Without her, it wouldn't be possible for me to become what I am today. I felt an interest in fluidization only because of her way of teaching and knowledge. I am very grateful to her.

I would like to give special thanks to my friend Jiyong Shin Alex. He also helped me during this work by sharing his knowledge and previous experience.

Finally, I am thankful to my wife who gave me mental support all the time.

Porsgrunn, 15/05/2023

S A Shibly Sadik

Contents

Nomenclature

Symbol	Description	SI Units
A	Cross sectional area of bed	m^2
Ar	Archimedes number	Dimensionless
d, d_p, d_m	Diameter of particle, particle mean diameter	m
d_A	Equivalent projected area diameter	m
d_s	Equivalent surface area diameter	m
d_v	Equivalent volume diameter	m
d_s	Mean diameter of sieve	m
F	Force exerted on a particle	N
g	Acceleration due to gravity	m/s^2
L_{mf}	Bed height at minimum fluidization	m
ΔP_{mf}	Pressure drops at minimum fluidization	Pa
Re_{mf}	Reynolds number	Dimensionless
u, u_0	Gas velocity, Superficial gas velocity	m/s
u_{mf}	Minimum fluidization velocity	m/s
u_{mb}	Minimum bubbling velocity	m/s

V_{mf}	Bed volume at minimum fluidization	m^3
w_s	Weight fraction	Dimensionless
ε, ε_{mf}	Void fraction, Void fraction at minimum fluidization	Dimensionless
μ	Dynamic viscosity of fluid	$Pa.s$
ρ_f	Density of fluid	kg/m^3
ρ_s	Density of solid particle	kg/m^3
ϕ	Sphericity of particle	Dimensionless

List of Figures

List of Tables

1 Introduction

1.1 Background

Fluidization technology was first used for the catalytic cracking process in the petroleum industry. But, nowadays, this technology is used in many industries because it offers uniform heat transfer and has a unique ability to move a wide range of solid particles in a fluid-like state. Some examples of industrial applications are gasification, calcination, and flue gas desulphurization, where this technology is used. Fluidized beds are complex to design, build, and operate. Different kinds of material, such as sand, are used as bed material in a fluidized bed reactor. Properties of bed material such as size, density sphericity affect the fluidization behavior. So it is essential to analyze the hydrodynamics of bed material, especially the minimum fluidization velocity, which affects the flow rate of the fluidizing agent, before designing and scaling up the fluidized bed reactor [1]–[3]. However, it is a common phenomenon that bed materials with low mechanical strength experience particle attrition due to inter-particle collision, a bed-to-wall impact during fluidization. Attrition increases the number of particles and reduces particle size in fluidized beds. It will alter the hydrodynamics behavior of the material if the properties of the particle change. Also, it will later lead to an error in the process. Fine particles may entrain along with fluidizing gas if no recovery is included in the design. This kind of loss will further lead to the reduction of the contact area between solid and gas. In a catalytic cracking process, it means conversion is low. Particle attrition affects fluidized bed or reactor performance, fluidizing properties, operating stability, and operating cost [4]–[7]. However, the aim of this study is to understand how minimum fluidization velocity will change if particle attrition happens during fluidization operation.

1.2 Objective

The main objective of this study is to analyze the change in minimum fluidization velocity due to the change in particle size distribution. Several correlations existed to predict the minimum fluidization velocity of a mono-size particle. In this work some of those correlations are listed out and tried to find the accuracy level concerning experimental results.

1.3 Overview of the work

During fluidization, particles attrite. But it is possible but difficult to predict when the hydrodynamic behavior of particles will alter. Due to time limitations, an alternative approach was taken during the experiment to complete this work. Particles with a wide range of sizes were selected at first. The sieving method was applied to create samples with different sizes with smaller ranges. Also, one sample with bigger particle sizes was created. In the actual scenario, it was the original sample. It was assumed that other samples were created during the fluidization operation from the original one. During the experiment, sand with a size range between several hundred was selected as a primary sample. By applying the sieving method, a sample called a parent sample with a range between 125 to 355 microns was created. From the parent sample, other sizes of narrow ranges were created. Figure 1.1 shows the actual process and approach taken for the experiment in short.

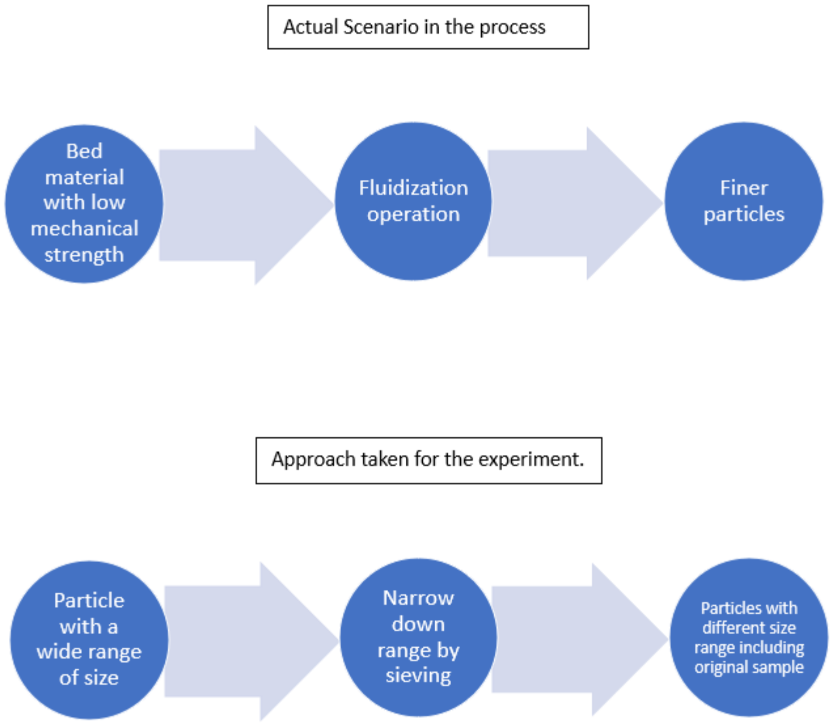

Figure 1.1: Actual process vs approach taken for the experiment.

However, this work is described in a few chapters in this report. Each chapter also contains one or more sub-chapters. Chapter two summarizes the literature review on fluidization, minimum fluidization, different fluidization regimes, developed correlations to find minimum fluidization, particle size distribution, and technique to determine the distribution of particles. Chapter three describes the whole experimental procedure including the experimental setup. Chapter four presents all experimental results and discusses these results. Finally, chapter five concludes the entire work.

2 Literature Review

A brief description of fluidization, different fluidization regimes, minimum fluidization velocity, and several developed correlations are provided in this chapter. Also, the classification of particle, and size distribution are discussed elaborately.

2.1 Literature review on fluidization

Fluidization is an operation where solid particles are transformed into a fluidlike state by blowing gas or liquid upwards through the solid-filled bed. This operation is widely used in several commercial operations such as chemical synthesis, pneumatic transportation, chemical regeneration, powder mixtures, etc. All these operations can be divided into two categories.

- Physical operation – transportation, heating, absorption, mixing of fine powder.
- Chemical operation – reaction of gases with solid catalysts and the reaction of solids with gases.

Fluidization is one of the most powerful methods of handling particulate materials in the industry [8]–[11].

2.1.1 Principal of fluidization

Fluid is passed upward through a bed of fine particles in the fluidization process [8]. Figure 2.1 illustrates how particles fluidize due to upward-flowing gas. Upward-flowing gas imposes enough drag forces on particles to overcome the downward force of gravity of particles. At the same time, particles impose equal and opposite drag forces on flowing fluid. These drag forces affect the local gas velocity around the particles [3]. At a low flow rate, upward-flowing gas cannot get through the void spaces between stationary particles or, in other words, fixed beds. At a higher flow rate, the bed of particles starts to expand. If the flow rate is increased a bit more than at a certain point, upward-flowing gas suspends all the particles. At that point, the weight of the particle's counterbalanced by the frictional force between the particle and the fluid.

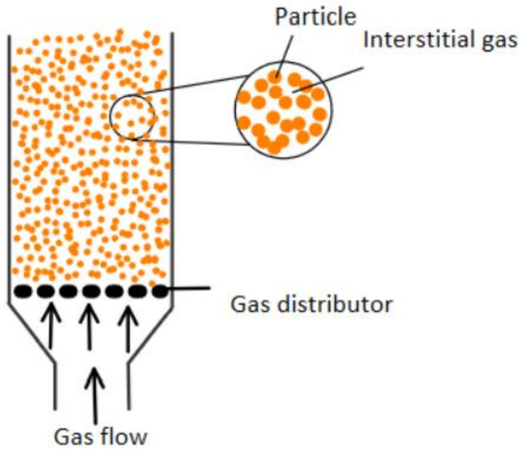

Figure 2.1: Basic principle of fluidization [12].

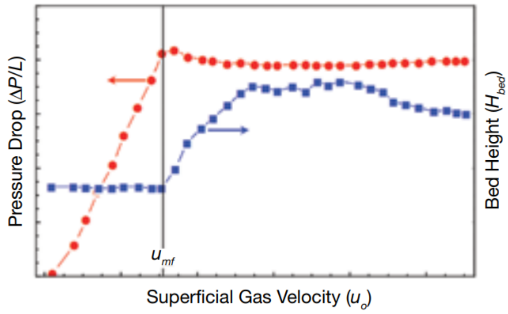

Figure 2.2: Pressure drop vs superficial gas velocity [3].

Particle-to-particle compressive force disappears, and pressure drop at any section of the bed equals the weight of the fluid and particles. At this point, the bed is just fluidized [8]. Figure 2.2 shows how pressure drop behaves with increasing superficial gas velocity (u_0) through a fixed bed particle. Pressure drops start to increase with the increment of superficial gas velocity (u_0) at the beginning. When the gas velocity is high enough that the drag force on the particle counterbalances the weight of the particle, the bed becomes fluidized. Higher gas velocity does not create a higher pressure drop at this point, the pressure is dropped only because of the suspended bed [3]. Initially bed pressure drop is proportional to the gas velocity. Once the bed is fluidized, the pressure drop of the bed decreases a little and then stabilizes at the static bed pressure. The bed of particles stay in the pressure until entrainment starts [1].

2.1.2 Fluidization regimes

The state of a fluidized bed depends on the fluid flow rate. Due to velocity differences, different regimes are created in fluidized beds [3]. Figure 2.3 illustrates the various regimes found in a fluidized bed due to different flow rates.

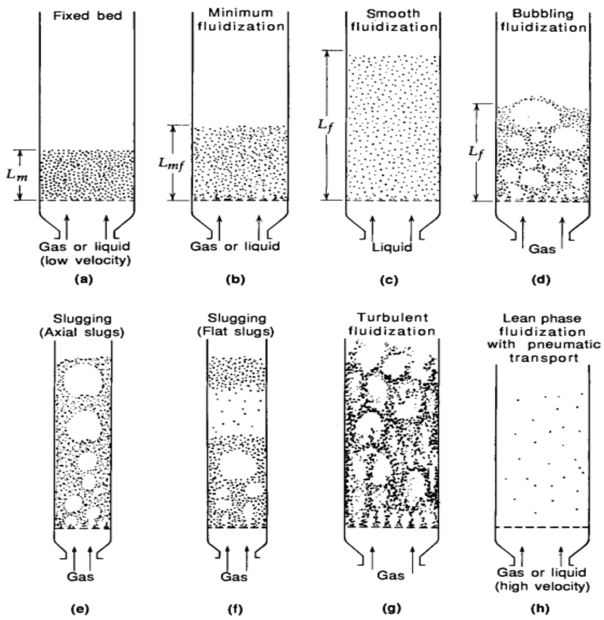

Figure 2.3: Fluidized bed regimes [8].

- **Fixed bed** – When fluid is passed through a bed of particles (figure – 2.3a), and if the superficial gas velocity (u_0) is lower, than it is difficult for the fluid to percolate through the void spaces between stationary particles. A few particles in the bed may vibrate, but still, they remain at the same height.
- **Minimum fluidization** – With the increase of superficial gas velocity (u_0), a point is reached where all particles are suspended by upward-flowing gas. The weight of the particle is counterbalanced by upward fluid flow. At this point, the bed is just fluidized, and the velocity of the fluid is called minimum fluidized velocity or incipient fluidization velocity (u_{mf}). Figure 2.3b illustrates the minimum fluidization regime.
- **Smooth or homogenous fluidization** – An increase in the fluid flow above minimum fluidization results in smooth expansion of the bed (figure 2.3c). The bed of particles expands homogeneously with the increase of fluid velocity until superficial gas velocity (u_0) reaches minimum bubbling velocity (u_{mb}).
- **Bubbling fluidization** – In this regime, clear bubbles are formed and grow by coalescence. The bed does not expand much beyond its volume, and such a bed is called a bubbling fluidized bed (figure 2.3d).
- **Slugging** – Further increase in superficial gas velocity (u_0) creates more bubbles. Gas bubbles merge and grow bigger. Sometimes bubble's diameter is the same as the bed's diameter. This is called slugging (figures 2.3e and 2.3f).
- **Turbulent fluidization** – When particles are fluidized due to high enough gas velocity, the upper surface of the bed disappears. Instead of bubbles, the turbulent motion of solid clusters and the void of gas of various sizes and shapes can be noticed. Figure 2.3g illustrates the turbulent fluidization regime.
- **Pneumatic transport** – With a further increase of superficial gas velocity (u_0), particles are carried out from the bed with the gas. In this state, the fluidized bed is a dilute, lean phase, or disperse (figure 2.3h) [8], [11], [12].

2.1.3 Minimum fluidization velocity (MFV)

The superficial gas velocity for which a particle of a packed bad starts to fluidize is called minimum fluidized velocity (u_{mf}), and the state is called minimum fluidization or incipient fluidization [9]. At this state, the drag force exerted on a particle is equal to its net weight. As far as the whole bed is concerned, the drag force can be calculated from the product of bed pressure drop (ΔP_{mf}) and the cross-sectional area of bed. So,

$$F = \Delta P_{mf} A \tag{2.1}$$

Also, the net bed weight is the product of bed volume ($V_{mf} = A\, L_{mf}$), net density ($\rho_s - \rho_f$), the fraction of the bed ($1 - \varepsilon_{mf}$), which is occupied by the particles. So, at minimum fluidization velocity,

$$\Delta P_{mf}\, A = A\, L_{mf}(\rho_s - \rho_f)(1 - \varepsilon_{mf})g \tag{2.2}$$

$$\Delta P_{mf} = L_{mf}(\rho_s - \rho_f)(1 - \varepsilon_{mf})g \tag{2.3}$$

The density of the fluidized solids is equal to the difference between particle density and fluid density. The fraction of the bed ($1 - \varepsilon_{mf}$) occupied by the particles is used because only the particles contribute significantly to the pressure drop. The value of ε_{mf} is 0.4, as per

Richardson (1971), for spherical particles. The superficial gas velocity and consequent pressure drop relationship help to predict MFV. But modeling this relationship is difficult because of the irregular shape of particles, void spaces, and twisting flow path of the fluid. However, the Ergun equation is an accurate, widely used, and semi-empirical equation used to determine MFV. This equation is for pressure drop per unit length of the bed and contains two terms [13]. The Ergun equation may be expressed as,

$$\frac{\Delta P}{L} = \frac{150\,(1-\varepsilon)^2 \mu u}{\epsilon^3 \phi^2 d^2} + \frac{1.75(1-\varepsilon)\rho_f u^2}{\epsilon^3 \phi d} \tag{2.4}$$

At minimum fluidization and assuming spherical particles, The Ergun equation can be rearranged as below.

$$\frac{\Delta P_{mf}}{L_{mf}} = \frac{150\,(1-\varepsilon_{mf})^2 \mu u_{mf}}{\varepsilon_{mf}^3 d^2} + \frac{1.75(1-\varepsilon_{mf})\rho_f u_{mf}^2}{\varepsilon_{mf}^3 d} \tag{2.5}$$

Combining equation 2.3 and 2.5 and we get,

$$(\rho_s - \rho_f)g = \frac{150\,(1-\varepsilon_{mf})\mu u_{mf}}{\varepsilon_{mf}^3 d^2} + \frac{1.75\rho_f u_{mf}^2}{\varepsilon_{mf}^3 d} \tag{2.6}$$

Multiplying both side by $\frac{\rho_f d^3}{\mu^2}$ and we get,

$$\frac{(\rho_s - \rho_f)\, g d^3 \rho_f}{\mu^2} = \frac{150\,(1-\varepsilon_{mf})\rho_f u_{mf} d}{\varepsilon_{mf}^3 \mu} + \frac{1.75\,\rho_f^2 d^2 u_{mf}^2}{\varepsilon_{mf}^3 \mu^2} \tag{2.7}$$

Or,

$$Ar = \frac{150\,(1-\varepsilon_{mf})}{\varepsilon_{mf}^3} Re_{mf} + \frac{1.75}{\varepsilon_{mf}^3} Re_{mf}^2 \tag{2.8}$$

Where,

$$Ar = \frac{(\rho_s - \rho_f)\, g d^3 \rho_f}{\mu^2} \tag{2.9}$$

And,

$$Re_{mf} = \frac{d u_{mf} \rho_f}{\mu} \tag{2.10}$$

In equation 2.9, Ar is the short form of Archimedes Number. It is possible to find minimum fluidization velocity (u_{mf}) by solving equations 2.3 and 2.8 for the known properties of the particle, known properties of fluidized gas, and minimum fluidization voidage [13]. However, Wen and Yu developed two expressions to solve minimum fluidization voidage based on experimental data [12].

$$\frac{(1-\varepsilon_{mf})}{\phi^2 \varepsilon_{mf}^3} \approx 11 \;\; and \;\; \frac{1}{\phi \varepsilon_{mf}^3} \approx 14$$

Combining Wen and Yu expression with Ergun equation, we obtain

$$Re_{mf} = \frac{\rho_f u_{mf} d}{\mu} = \sqrt{33.7^2 + 0.0408 \frac{(\rho_s - \rho_f)\, g d^3 \rho_f}{\mu^2}} - 33.7 \qquad (2.11)$$

Also, simpler method can be obtained when Reynolds number is below 20 [12].

$$u_{mf} = \frac{(\rho_s - \rho_f)\, g d^2}{1650\mu} \qquad (2.12)$$

2.1.4 Developed correlations.

The minimum fluidization velocity (MFV) has the greatest influence on the behavior of the particle bed, also vital to the operation of fluidization. Till now, a lot of research effort has been given to predicting it [13]. The MFV of a bed of mono-component particles or a binary mixture of particles can be predicted using different correlations. MFV of the particles with the same size and density can be predicted using correlations developed from the Ergun equation and is independent of void fraction [14]. Hundreds of correlations are developed for predicting minimum fluidized velocity. Most of them are functions of the dimensionless Reynolds (Re_{mf}) and Archimedes (Ar) number and they are defined by equation 2.9 and equation 2.10. Anantharaman et al. [15] summaries lots of correlations suitable for Geldart Group A, B, and D. Those correlations are suitable for mono-components particles. In table 2.1, some of the correlations relavent with this thesis are listed. These correlations are selected based on particle diameter, density and Geldart Group which are similer to this work. In addition to this, this correlations are not the fuction of void fraction.

Table 2.1: Developed correlations suitable for this work [15].

Author	Correlation	Particle Diameter, d_p (μm)	Particle Density, ρ_s (kg/m^3)	Geldart Group
Bourgeis and Grenier	$Re_{mf} = (25.46^2 + 0.0382Ar)^{0.5} - 25.46$	86 – 25000	1200 - 19300	A, B, D
Babu, Shah and Talwalker	$Re_{mf} = (25.25^2 + 0.0651Ar)^{0.5} - 25.25$	50 – 2411870	2560 - 3920	A, B, D
Vaid and Sen Gupta	$Re_{mf} = (24^2 + 0.0546Ar)^{0.5} - 24$	114 – 1829	1669 - 4332	B, D

Bin	$Re_{mf} = (27.31^2 + 0.0386Ar)^{0.5} - 27.31$	40 – 2120	1600 - 7500	A, B, D

2.2 Literature review on particle size and distribution

In this section, a detailed overview of particle classification and particle size distribution is given.

2.2.1 Classification of particle

Geldart (1973) was the first person to classify the behavior of solid particles based on their size and density. He distinguished particles into four categories. He also discussed the effect of particle size and its distribution on fluidized bed in his work [1], [9]. However, the properties of all four types of particles are summarized in table 2.1.

Table 2.2: Classification of particles with their properties [9].

Group Type	Properties
Group A	1. Aeratable Particle. 2. Small mean particle size (d_p > 30 μm. 3. Low particle density (< 1.4 g/cm^3) 4. Fluidized easily at low gas velocity without formation of bubble.
Group B	1. Sand like particles 2. Size between 150 μm to 500 μm and density between 1.4 to 4 g/cm^3. 3. When MFV is exceeded, excess gas appears in the form of bubble.
Group C	1. Cohesive and very fine powder. 2. Sizes are less than 30 μm. 3. Difficult to fluidized.
Group D	1. Very large or very dense. 2. Difficult to fluidize in deep beds. 3. When velocity increases, a jet can be formed in the bed and materials may than be blown out.

Not every particle can be fluidized. The classification of particles can be more visualized in Figure 2.3. One can identify the type of fluidization for any solid of known density and mean particle size from the figure. Also, this figure helps to predict other properties like bubble diameter, bubble velocity etc. [9].

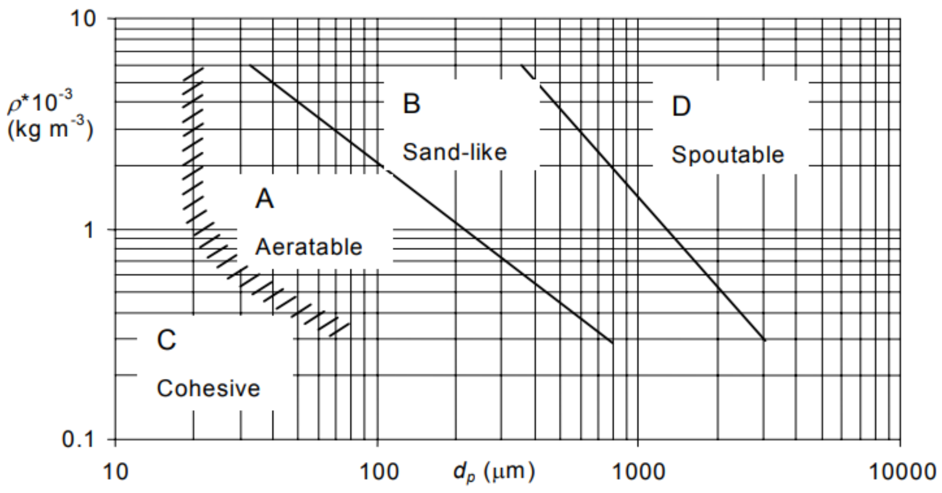

Figure 2.4: Geldart classification of particles [9].

2.2.2 Particle size and distribution

Particles have complex, irregular geometry therefore difficult to define. In bulk solids, billions of particles with different shapes and sizes are present. In most of the theoretical work, particles are spherical, although they are not. So, the concept of using an equivalent diameter is rather practical than using the diameter of a sphere. Equivalent diameter is the diameter of a sphere having the same value as the physical attribute of a particle such as volume, surface area, or projected area. Many equivalent diameters can be defined, and some are listed in table 2.3 [16].

Table 2.3: List of equivalent diameters used for particle size distribution [16].

Name	Definition	Equation
Equivalent projected area diameter (d_A)	Diameter of a circle with the same area as the projected area of the particle, A.	$d_A = (\frac{4A}{\pi})^{0.5}$
Equivalent surface area diameter (d_S)	diameter of a sphere with the same surface area, S, as the particle.	$d_S = (\frac{S}{\pi})^{0.5}$
Equivalent volume diameter, (d_V)	he diameter of a sphere with the same volume, V, as the particle	$d_V = (\frac{6V}{\pi})^{1/3}$

However, many methods and instruments have already developed to determine particle size. Sieving is one of the most widely used techniques to identify particle size. In this method, a stack of sieves is arranged in such a way that mesh size decreases as the height decreases. A sample of particles is placed on the top sieve and shaken. Some particles got stuck in each sieve. A mass of particles with diameters between each sieve size is obtained. Although this method is widely used but it has some limitations. During operation, particles can be broken, mesh stretching due to overload, sieve blocking etc. normally leads error in results [16]. Figure 2.5 illustrates how sieving works.

Figure 2.5: Determination of particle size distribution by sieving method.

3 Methodology

This chapter briefly describes the experimental setup, including instruments used for the experiment and experimental procedure. This chapter is divided into two sections. In one section, the experimental setup and description of instruments are given. Another section describes the experimental procedure.

3.1 Experimental setup

In this section, detailed information about the experimental setup and the apparatus used for this experiment is given.

3.1.1 Sieve analysis and sample preparation

A vibratory sieve analysis machine, shown in Figure 3.1, was used to sieve sand during the preparation of the sample. Different size sieves, shown in Figure 3.2, were used to identify particle size distribution and to prepare samples. The weight of the particles was measured by a precise weighing scale (figure 3.3).

Figure 3.1: Sieve shaker

Figure 3.2: Different size sieves

Figure 3.3: Weighing scale.

3.1.2 Fluidized Bed

A lab-scale fluidized bed was used to measure the minimum fluidization velocity during the experiment. The bed is a cylindrical shape transparent tube. The body of the tube was made from Lexan plastic. The height and diameter of the tube are respectively 140 cm and 8.4 cm. A total of nine pressure sensors are connected to the bed. The distance between two consecutive sensors is 10 cm. One air distributor is connected at the bottom of the column. Red-y gas flow controller was used to control the flow rate. A LabVIEW® program was used in the PC to log the data via a controller unit. Figure 3.4 and Figure 3.5 show the complete setup of the fluidized bed used for this experiment. Figure 3.6 shows the controller used to control the flow rate of the fluidizing agent.

Figure 3.4: Total setup of fluidized bed.

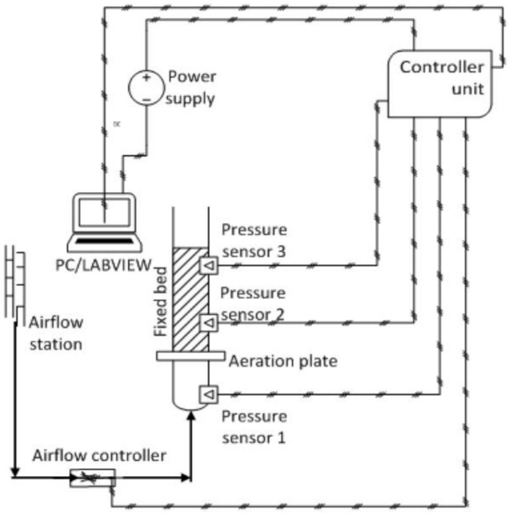

Figure 3.5: Fluidized bed system [17] .

Figure 3.6: Air flow controller.

3.2 Experimental procedure

3.2.1 Sieve analysis and particle size distribution

The main objective of this study is to analyze the change in minimum fluidization velocity due to the change in particle size distribution during the fluidization operation. It is difficult to predict the time when a particle with lower mechanical strength will start to break into smaller particles. So, a mixture of different sizes of particles was created to overcome this problem. The sand was used as the sample in this experiment. Sand samples with a wide range of size between 100 to 400 micron was selected as a primary basis. Sieving analysis was done on the primary sample and a batch of a sample of a narrow range (125 to 355 microns) was made. The distribution of particles was measured. After that, a 200-micron sieve was used to shake the parent sample for five seconds which will sieve out part of the particles below 200 microns. This sample was saved in a box. Again, a 200-micron sieve was used to shake the parent sample for twenty seconds, and thirty seconds which will sieve out more particles below 200 microns. All samples were saved in different boxes and their particle size distribution was determined. From the parent sample, a batch of narrow range (200 – 355 microns) was created by the sieving method. A 200-micron sieve was used this time to sieve out all particles below 200 microns. Now, the parent sample is in a range of between 200 – 355 microns. A 300-micron sieve was used to shake the parent sample for ten seconds, twenty seconds and thirty seconds. Finally, another sample with a narrow range (300 to 355 microns) was created from the parent sample by sieving out all particles below 300 microns. Particle size distribution was measured each time. Figure 3.7 illustrates the experimental procedure done during the sample preparation.

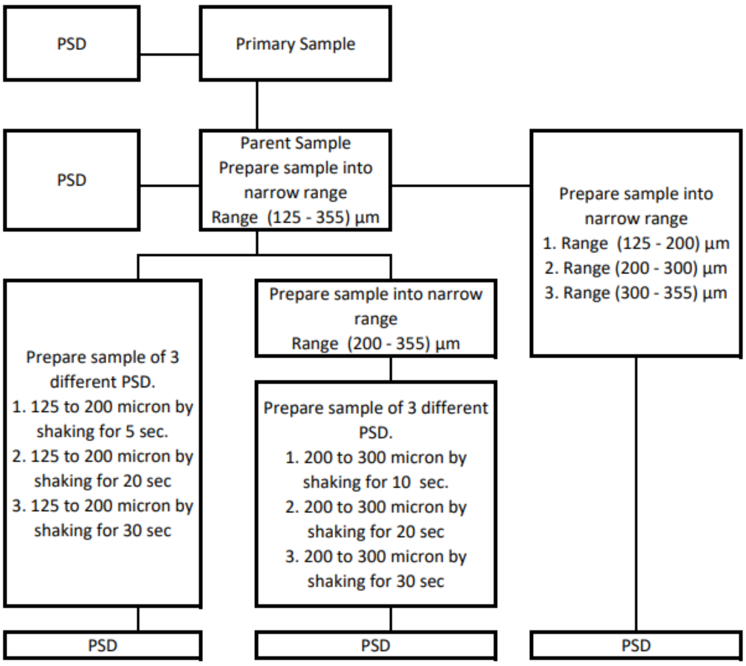

Figure 3.7: Experimental procedure done for sample preparation.

During the measurement of particle size distribution, all data were saved in excel file. Particles' mean diameter were calculated using the equation 3.1.

$$d_m = \frac{1}{\Sigma(\frac{w_s}{d_s})_i} \tag{3.1}$$

The size distribution of bed material calculated during the experiment is presented in Appendix B.

3.2.2 Determination of minimum fluidization velocity

To determine the incipient fluidization velocity for all saved samples, an in-house built fluidized bed was used. Particles were poured from the top in the bed column. In every experiment 1000 ml sand was used. Superficial gas velocity increased gradually. A LabVIEW program was run to write pressure. Each time, after waiting for 60 seconds, 60 data was tabulated. Pressure drop was calculated by subtracting pressure calculated from pressure sensor 2 and 3.

All technical information related to the experiment is tabulated in table 3.1.

Table 3.1: All technical information related to the experiment.

Fluidized rig		Bed material		Fluidization medium	
Height (m)	1.5	Material	Sand	Material	Air
Diameter (m)	0.084	Category	Geldart B type	Condition	Atmospheric
Material	Lexan Plastic	Particle size range (μm)	125 – 355	Density (kg/m^3)	1.22
		Mean particle diameter (μm)	250	Viscosity ($Pa.s$)	1.8×10^{-5}
		Density (kg/m^3)	2650		

4 Results and Discussion

In this chapter all the results and graphs obtained from experiments are presented. Also, all the results and graphs are analyzed and discussed. First, the effect on minimum fluidization velocity due to size change in same range of particle and different range of particle are analyzed. Finally, by using some correlations, MFV of particles are predicted and compared with the experimental one.

4.1 Effect on minimum fluidization velocity

In this section, visual representation, and final summary of how MFV deviates from the original is given to understand the effect on minimum fluidization due to particle size change. All data from where all the graphs and summary are extracted can be found in Appendix C.

4.1.1 Size range between 200 to 300 microns

Figure 4.1 shows how incipient fluidization velocity will change if particle size changes in same range of particle.

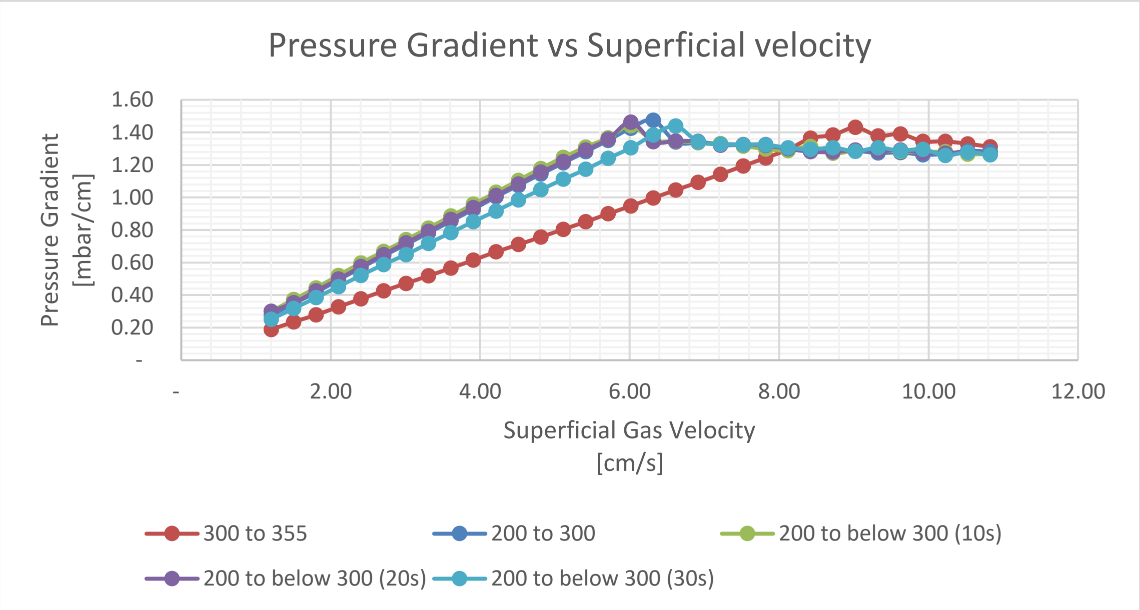

Figure 4.1: Change of MFV due to the change in size distribution.

From Figure 4.1, due to particle size change, the MFV of particles shifted from right to left. The minimum fluidization velocity decreases linearly as the size of the particle decreases. The pressure drops of the bed show a linear relationship with gas velocity in all cases during fixed bed conditions. Also, after analyzing Figure 4.1, it can be said that bed pressure drop is almost the same for all sizes of particles, and it is because the mass of the bed is almost constant for all cases. Figure 4.1 also illustrates that at fixed bed conditions, the gradient of the curve is steep for smaller-size particles, and which means that it will be fluidized at lower gas velocity. However, the analysis also says that the minimum fluidization velocity of the original sample is 0.0902 m/s. But if particle attrition happens and creates finer particles within a range between

200 to 300 microns, then the minimum fluidization velocity reduces from 0.0902 m/s to 0.0632 m/s. This reduction in velocity is almost 30% from the original incipient velocity. However, further analysis of Figure 4.1 shows that the change in MFV is negligible if particle size changes within the same range. Also, table 4.1 shows how much MFV will deviate from the actual if the size of particles changes in the same range. The deviation of minimum fluidization velocity from the original is in the range of 27% to 33%.

Table 4.1: List of minimum fluidization velocity of samples including their deviation from original.

Name of the sample	Mean Diameter m	Measured MFV m/s	Deviation
300 to 355	0.000318	0.0902	
200 to 300	0.000239	0.0632	30%
200 to below 300 (10s)	0.000234	0.0601	33%
200 to below 300 (20s)	0.000236	0.0601	33%
200 to below 300 (30s)	0.000237	0.0662	27%

4.1.2 Size range between 125 to 200 microns

Figure 4.2 and table 4.2 also show how minimum fluidization velocity will change if particle size changes in same range. If more finer particles are created from the original sample, which is in range between 125 to 200 microns, then the MFV will reduce by almost 67%.

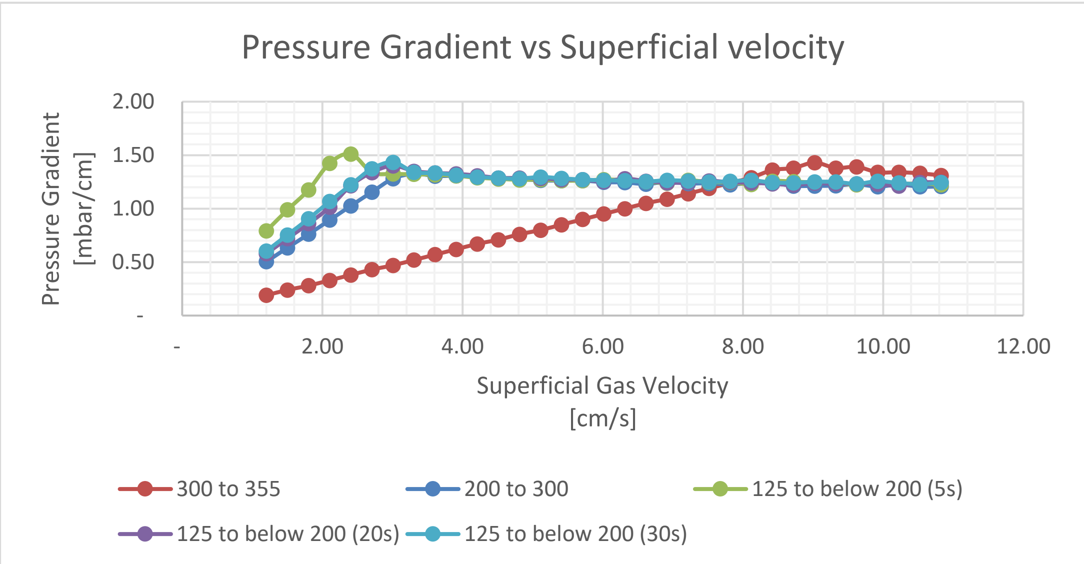

Figure 4.2: Change of MFV due to the change in size distribution.

Like the first case, the change in minimum fluidization velocity is almost the same if the particle size changes within the same range. In this case, the pressure drop is also the same for all sizes of particles. In Figure 4.1, the gradient of the curve for smaller particles is steeper. Comparison between figures 4.1 and 4.2 also indicates that the gradient of the curve for smaller particles shows high steepness. Also, pressure drops show a linear relationship at fixed bed conditions, just like in the first case.

Table 4.2: List of minimum fluidization velocity of samples including their deviation from original.

Name of the sample	Mean Diameter m	Measured MFV m/s	Deviation
300 to 355	0.000318	0.0902	
125 to 200	0.000161	0.0331	63%
125 to below 200 (5s)	0.000161	0.0241	73%
125 to below 200 (20s)	0.000167	0.0301	67%
125 to below 200 (30s)	0.000159	0.0301	67%

4.1.3 Size range between 125 to 355, 125 to 200, and 200 to 300 and 300 to 355 microns

In Figure 4.3, the minimum fluidization velocity of the original sample was compared with three different particle size ranges.

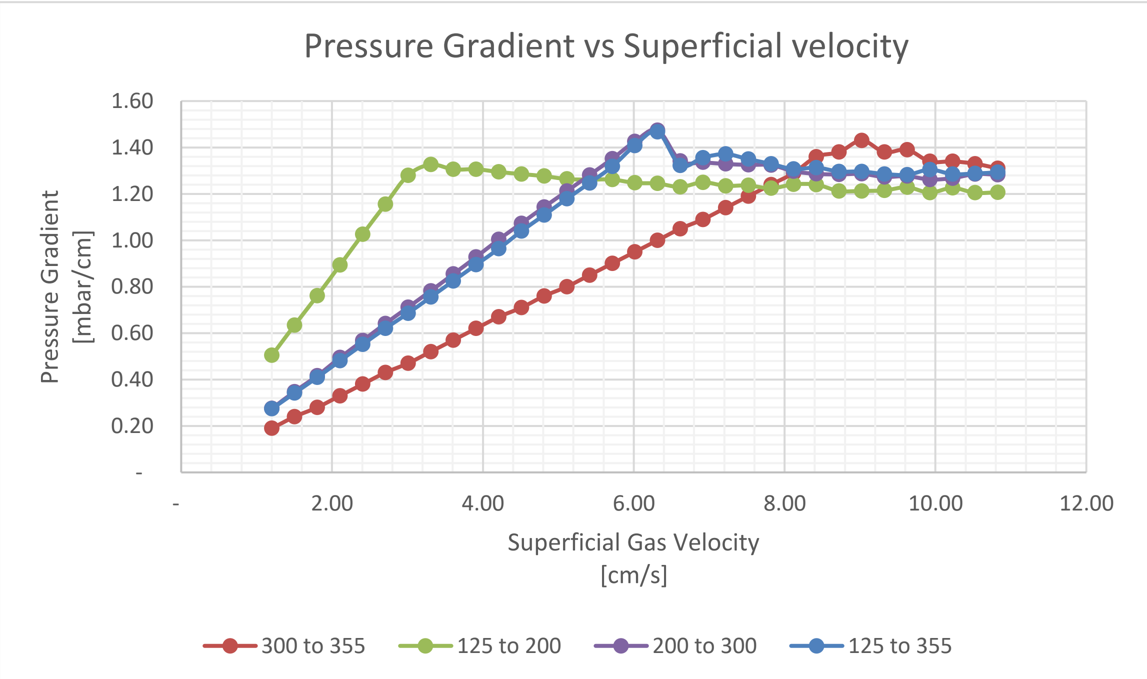

Figure 4.3: Change of MFV due to the change in size distribution.

After analyzing Figure 4.3, it can be said that finer particles in a sample show a higher reduction in minimum fluidization velocity. Sample with a range between 125 to 200 microns shows a great deviation of almost 63%. On the other hand, samples with a range between 200 to 300 show a 30% deviation from the original one. If it is assumed that the original sample creates a mixture of finer particles ranging from 125 to 355 (mean diameter is 0.00025 m) shows the same deviation as the sample range between 200 to 300 (mean diameter is 0.000239 m). However, it also indicates that if smaller particles are present in a bed of particles with bigger sizes, it will alter the minimum fluidization velocity of that bed of particles.

Table 4.3: List of minimum fluidization velocity of samples including their deviation from original.

Name of the sample	Mean Diameter m	Measured MFV m/s	Deviation
300 to 355	0.000318	0.0902	
125 to 200	0.000161	0.0331	63%
200 to 300	0.000239	0.0632	30%
125 to 355	0.000250	0.0632	30%

4.1.4 Comparison between mean diameter and Experimental MFV

Further analysis between mean diameter and experimental minimum fluidization velocity shows that it is possible that minimum fluidization velocity can be almost same for two different mean diameters.

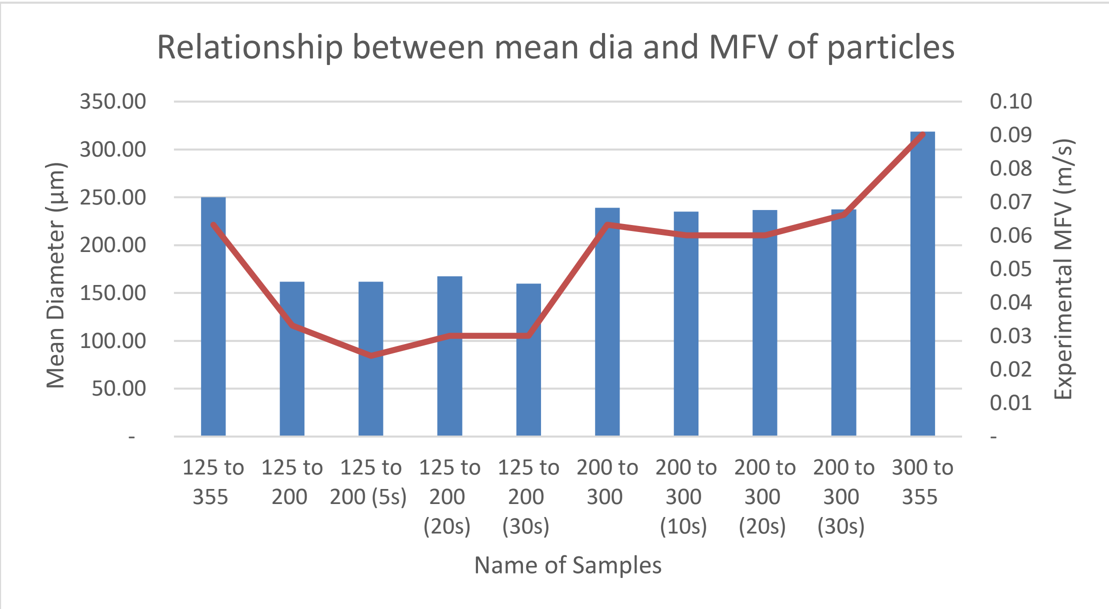

Figure 4.4: Relationship between mean diameter and MFV of particles.

Figure 4.4 shows that minimum fluidization velocity of sample 125 to 200 micron (20s) and 125 to 200 microns (30s) are almost similar although they have different mean diameters. The mean diameter of 125 to 200 microns (30s) is lower than the other two samples, 125 to 200 (5s) and 125 to 200 microns (10s). It may be possible due to particle segregation or an error during calculation of particle size distribution. But Same scenario also repeated between sample 200 to 300 microns (10s) and 200 to 300 microns (20s) where the figures shows that minimum fluidization velocity for both samples are almost similar. Also, it is possible that

MFV can be same for different mean diameter samples. For instance, 125 to 200 microns sample's MFV is higher than the MFV of 125 to 200 microns (5s) sample. But their mean diameter is the same.

4.2 Measurement of minimum fluidization velocity by using some correlations

Hundreds of correlations are created to predict the minimum fluidization velocity of a mono-size particle. Some of them are listed in section 2.1.4 in this report. In this section, an effort was made to use those correlations to measure MFV of particles based on the calculated mean diameter of different ranges of particles. Also, measured MFV was compared with the experimental results.

Table 4.4: Accuracy level of correlation with respect to experimental results

Name of samples	MFV from experiment (m/s)	Bourgeis and Grenier		Babu, Shah and Talwalker		Vaid and Sen Gupta		Bin	
		MFV (m/s)	Deviation %	MFV (m/s)	Deviation %	MFV (m/s)	Deviation %	MFV (m/s)	Deviation %
125 to 355	0.0632	0.0663	5%	0.1123	44%	0.0993	36%	0.0626	1%
125 to 200	0.0331	0.0282	17%	0.0483	31%	0.0426	22%	0.0266	24%
200 to 300	0.0632	0.0607	4%	0.1029	39%	0.0910	31%	0.0573	10%
300 to 355	0.0902	0.1053	14%	0.1758	49%	0.1559	42%	0.0997	10%
125 to 200 (5s)	0.0241	0.0282	15%	0.0483	50%	0.0426	43%	0.0266	9%
125 to 200 (20s)	0.0301	0.0302	0%	0.0517	42%	0.0456	34%	0.0285	6%
125 to 200 (30)	0.0301	0.0275	10%	0.0470	36%	0.0415	27%	0.0259	16%
200 to 300 (10s)	0.0601	0.0586	3%	0.0995	40%	0.0880	32%	0.0554	9%
200 to 300 (20s)	0.0601	0.0595	1%	0.1009	40%	0.0893	33%	0.0562	7%
200 to 300 (30s)	0.0662	0.0597	11%	0.1013	35%	0.0896	26%	0.0564	17%
Average deviation from the experimental (%)			8%		40%		33%		11%
Level of accuracy			92%		60%		67%		89%

In table 4.4, all measured MFV from correlations are listed and compared with the experimental results. Table 4.4 shows the accuracy level of those correlations for samples that were prepared for this work. It can be concluded that among the four correlations, Bourgeis and Grenier's correlation shows the highest accuracy. On average, the accuracy level is 92%. However, the correlation developed by Bin also shows good accuracy too (89%). The other two correlation's accuracy level is 67% and 60%.

5 conclusion

Particle attrition during fluidization operation affects the hydrodynamic behavior of particles which is minimum fluidization velocity. The effect of particle size and particle size distribution on the incipient fluidization velocity was analyzed after the experiment was done in a cold fluidized bed. The material of the bed was sand. The sieving operation was done to create samples with different ranges and to determine particle size distribution. The minimum fluidization velocity for each sample was determined from the pressure drop versus superficial gas velocity graph.

Minimum fluidization velocity changes if particle size changes. It decreases with the reduction of sizes. MFV does not show high deviation within the same range of particle size. Also, MFV can be the same for different mean diameters of particles. However, the presence of smaller particles in the bed alters the minimum fluidization velocity considerably. In every case, pressure drop shows a linear relationship with the superficial gas velocity at fixed bed conditions.

Four correlations for mono-component particles among hundreds were listed. The mean diameter of particles was used to predict MFV. Predicted values from correlations and experimental values were compared. Among the four, the correlation developed by Bourgeis and Grenier showed the highest accuracy. Bin’s correlation also gave good results.

Finally, it is possible to evaluate and experience the particle attrition phenomenon and its effect on minimum fluidization velocity by fluidizing particles for a long time in the bubbling regime and fast fluidization regime and comparing initial and final particle size distribution.

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Appendices A: Task Description

University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

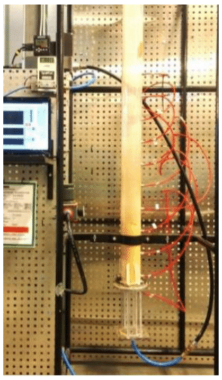
Title: Fluidization behaviour of sand particles with a size distribution

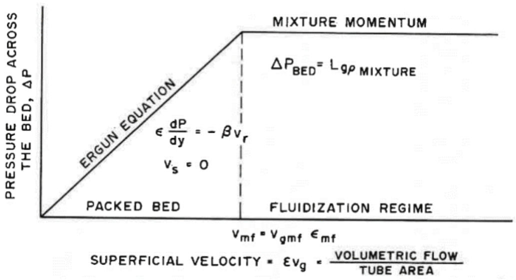
USN supervisors: Janitha Bandara, Britt M. E. Moldestad

External partner: None

Task background:
Fluidization is an interesting phenomenon used in many industries from fluid catalytic cracking (FCC) to energy generation. Heat and mass transfer in solid state is restricted and therefore, considerable temperature gradients are possible unless the material is extensively mixed. Mechanical agitators are cumbersome, especially in high temperature applications. Fluidization is a simple process, which uses and upward fluid flow across the particle bed. Depending on the particle and fluid properties along with aspect ratio of the particle bed, it can be either, homogeneous, bubbling, slugging or fast fluidization regimes.

During the operation, particles with low mechanical strength, such as sand (bed material i.e. biomass gasification) and dolomite (catalyst), can break into fine fractions. Consequently, the fluidization conditions can be altered. Minimum fluidization velocity (MFV) is the fundamental parameter related to fluidization, which can be experimentally tested by measuring the bed pressure drop and plotting it against the superficial gas velocity across the bed. A simple illustration is given in the figure. The main objective of this study is to analyse the change in MFV experimentally as the particle size distribution is changed.





Task description:
Initially, a particle sample should be selected with a size distribution between several hundred (i.e. 200-500µm).

The thesis includes the following tasks:

- A Literature study in minimum fluidization velocity of poly-dispersed particles and developed correlations.
- Sieve the particles into narrow ranges (i.e. 200-250 µm, 250-300 µm… 450-500 µm) and experimentally measure the MFV.
- Partly sieve out the narrow particle size in different fractions and experimentally measure the MFV (i.e. sample 01 – sieve out 20% of 200-250 µm, sample 02 – sieve out 30% of 200-250 µm ……).
- Try to develop correlations for the MFV as a function of size in the particle mixture.
- Try to understand the particle size segregation by bed pressure drop at packed bed conditions.

Student category: EET or PT students

Is the task suitable for online students (not present at the campus)? No

Practical arrangements: At USN

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature):

Student (write clearly in all capitalized letters): S A Shibly Sadik

Student (date and signature): 07/05/2023

Appendices B: Particle Size Distribution

Primary Sample

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.0005625	300.26	300.31	0.05	0.000496	0.88
2	425	0.0004625	415.91	420.36	4.45	0.044121	95.40
3	355	0.00039	257.67	276.99	19.32	0.191553	491.16
4	300	0.0003275	411.56	431.84	20.28	0.201071	613.96
5	250	0.000275	278.69	296.16	17.47	0.173210	629.86
6	200	0.000225	268.79	286.72	17.93	0.177771	790.09
7	180	0.00019	286.64	295.04	8.40	0.083284	438.34
8	125	0.0001525	239.91	250.26	10.35	0.102617	672.90
9	90	0.0001075	389.76	391.48	1.72	0.017053	158.64
10	Pan		357.42	358.31	0.89	0.008824	

1. Total (g)	100.86		3,891	
2. Weight of the actual sample (g)	100.88	Mean Diameter	0.0002570	m
3. Deviation (g)	(0.02)		257	µm

Parent Sample – 125 to 355 microns

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.0005625	300.27	300.28	0.01	0.000020	0.04
2	425	0.0004625	416.01	416.09	0.08	0.000161	0.35
3	355	0.00039	257.72	258.19	0.47	0.000945	2.42
4	300	0.0003275	411.76	577.76	166.00	0.333749	1,019.08
5	250	0.000275	278.75	403.12	124.37	0.250050	909.27
6	200	0.000225	268.84	403.58	134.74	0.270900	1,204.00
7	180	0.00019	286.66	320.82	34.16	0.068680	361.47
8	125	0.0001525	239.93	276.58	36.65	0.073686	483.19
9	90	0.0001075	389.78	390.68	0.90	0.001809	16.83
10	Pan		394.70	394.70	-	-	

1. Total (g)	497.38		3,997	
2. Weight of the actual sample (g)	497.46	Mean Diameter	0.0002502	m
3. Deviation (g)	(0.08)		250	µm

125 to below 200 microns (5s)

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.000563	300.28	300.29	0.01	0.000020	0.04
2	425	0.000463	416.07	416.09	0.02	0.000040	0.09
3	355	0.00039	257.76	257.81	0.05	0.000100	0.26
4	300	0.000328	411.69	411.92	0.23	0.000459	1.40
5	250	0.000275	278.77	279.03	0.26	0.000519	1.89
6	200	0.000225	268.80	277.89	9.09	0.018152	80.68
7	180	0.00019	286.68	428.62	141.94	0.283449	1,491.84
8	125	0.000153	239.92	583.96	344.04	0.687036	4,505.15
9	90	0.000108	389.77	394.87	5.10	0.010185	94.74
10	Pan		357.43	357.45	0.02	0.000040	

1. Total (g)	500.76		6,176	
2. Weight of the actual sample (g)	500.80	Mean Diameter	0.0001619	m
3. Deviation	(0.04)		162	µm

125 to below 200 microns (20s)

#	Sieve Number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.00056	300.29	300.29	-	-	-
2	425	0.00046	416.08	416.08	-	-	-
3	355	0.00039	257.76	257.77	0.01	0.00002000	0.05
4	300	0.00033	411.69	411.86	0.17	0.00034002	1.04
5	250	0.00028	278.77	278.87	0.10	0.00020001	0.73
6	200	0.00023	268.83	311.26	42.43	0.08486509	377.18
7	180	0.00019	286.68	460.13	173.45	0.34692082	1,825.90
8	125	0.00015	239.95	516.81	276.86	0.55375323	3,631.17
9	90	0.00011	389.78	396.72	6.94	0.01388083	129.12
10	Pan		357.43	357.44	0.01	0.00002000	

1. Total (g)	499.97		5,965.19	
2. Weight of the actual sample (g)	500.06	Mean Diameter	0.00016764	m
3. Deviation (g)	(0.09)		167.64	µm

125 to below 200 microns (30s)

#	Sieve Number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.00056	300.27	300.27	-	-	-
2	425	0.00046	415.94	415.94	-	-	-
3	355	0.00039	257.72	257.72	-	-	-
4	300	0.00033	411.64	411.65	0.01	0.00009917	0.30
5	250	0.00028	278.73	278.76	0.03	0.00029750	1.08
6	200	0.00023	268.82	269.30	0.48	0.00476002	21.16
7	180	0.00019	286.66	312.69	26.03	0.25813169	1,358.59
8	125	0.00015	239.92	312.48	72.56	0.71955573	4,718.40
9	90	0.00011	389.77	391.50	1.73	0.01715589	159.59
10	Pan		357.42	357.42	-	-	

1. Total (g)	100.84		6,259.12	
2. Weight of the actual sample (g)	100.90	Mean Diameter	0.00015977	m
3. Deviation (g)	(0.06)		159.77	µm

200 to below 300 microns (10s)

#	Sieve Number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.000563	300.27	300.27	-	-	-
2	425	0.000463	415.96	415.96	-	-	-
3	355	0.00039	257.72	257.76	0.04	0.000397	1
4	300	0.000328	411.60	412.08	0.48	0.004770	15
5	250	0.000275	278.70	311.55	32.85	0.326443	1,187
6	200	0.000225	268.82	326.90	58.08	0.577164	2,565
7	180	0.00019	286.65	295.11	8.46	0.084070	442
8	125	0.000153	239.92	240.63	0.71	0.007056	46
9	90	0.000108	389.75	389.76	0.01	0.000099	1
10	Pan		357.42	357.42	-	-	

1.	Total (g)	100.63		4,257.49	
2.	Weight of the actual sample (g)	100.65	Mean Diameter	0.00023488	m
3.	Deviation (g)	(0.02)		234.88	µm

200 to below 300 microns (20s)

#	Sieve Number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.00056	300.27	300.27	-	-	-
2	425	0.00046	415.96	415.96	-	-	-
3	355	0.00039	257.71	257.74	0.03	0.00	0.77
4	300	0.00033	411.58	412.18	0.60	0.01	18.27
5	250	0.00028	278.71	315.10	36.39	0.36	1,319.58
6	200	0.00023	268.83	323.03	54.20	0.54	2,402.16
7	180	0.00019	286.64	294.96	8.32	0.08	436.67
8	125	0.00015	239.91	240.65	0.74	0.01	48.39
9	90	0.00011	389.76	389.76	-	-	-
10	Pan		357.42	357.42	-	-	

1. Total (g)	100.28		4,225.84	
2. Weight of the actual sample (g)	100.29	Mean Diameter	0.00023664	m
3. Deviation (g)	(0.01)		236.64	µm

200 to below 300 microns (30s)

#	Sieve Number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.000563	300.27	300.28	0.01	0.00	0.18
2	425	0.000463	415.95	415.95	-	-	-
3	355	0.00039	257.70	257.75	0.05	0.00	1.28
4	300	0.000328	411.59	412.31	0.72	0.01	21.93
5	250	0.000275	278.73	316.33	37.60	0.38	1,364.14
6	200	0.000225	268.86	321.82	52.96	0.53	2,348.38
7	180	0.00019	286.65	294.81	8.16	0.08	428.49
8	125	0.000153	239.92	240.65	0.73	0.01	47.76
9	90	0.000108	389.76	389.76	-	-	-
10	Pan		357.42	357.42	-	-	

1. Total (g)	100.23		4,212.15	
2. Weight of the actual sample (g)	100.28	Mean Diameter	0.00023741	m
3. Deviation (g)	(0.05)		237.41	µm

125 to 200 microns

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.0005625	300.27	300.27	-	-	-
2	425	0.0004625	415.94	415.94	-	-	-
3	355	0.00039	257.69	257.71	0.02	0.000199	0.51
4	300	0.0003275	411.59	411.65	0.06	0.000596	1.82
5	250	0.000275	278.74	278.80	0.06	0.000596	2.17
6	200	0.000225	268.85	269.55	0.70	0.006955	30.91
7	180	0.00019	286.65	317.84	31.19	0.309917	1,631.14
8	125	0.0001525	239.92	307.08	67.16	0.667329	4,375.93
9	90	0.0001075	389.76	391.20	1.44	0.014308	133.10
10	Pan		357.42	357.43	0.01	0.000099	

1. Total (g)	100.64		6,176	
2. Weight of the actual sample (g)	100.67	Mean Diameter	0.0001619	m
3. Deviation (g)	(0.03)		162	µm

200 to 300 microns

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diameter
1	500	0.0005625	300.27	300.27	-	-	-
2	425	0.0004625	415.93	415.95	0.02	0.00020	0.43
3	355	0.00039	257.68	257.78	0.10	0.00100	2.56
4	300	0.0003275	411.58	412.21	0.63	0.00629	19.20
5	250	0.000275	278.73	317.09	38.36	0.38283	1,392.12
6	200	0.000225	268.83	323.17	54.34	0.54232	2,410.29
7	180	0.00019	286.66	293.08	6.42	0.06407	337.22
8	125	0.0001525	239.92	240.24	0.32	0.00319	20.94
9	90	0.0001075	389.75	389.76	0.01	0.00010	0.93
10	Pan		357.42	357.42	-	-	

1. Total (g)	100.20		4,184	
2. Weight of the actual sample (g)	100.21	Mean Diameter	0.0002390	m
3. Deviation (g)	(0.01)		239	µm

300 to 355 microns

#	Sieve number	Diameter m	Empty Weight g	Weight with sample g	Weight of sample g	Weight Fraction	Weight Fraction/ Diemeter
1	500	0.0005625	300.26	300.27	0.01	0.000	0.18
2	425	0.0004625	415.93	415.97	0.04	0.000	0.86
3	355	0.00039	257.70	258.17	0.47	0.005	12.05
4	300	0.0003275	411.57	496.56	84.99	0.850	2,595.37
5	250	0.000275	278.73	292.89	14.16	0.142	514.96
6	200	0.000225	268.86	269.18	0.32	0.003	14.22
7	180	0.00019	286.66	286.66	-	-	-
8	125	0.0001525	239.93	239.93	-	-	-
9	90	0.0001075	389.76	389.76	-	-	-
10	Pan		357.41	357.41	-	-	

1. Total (g)	99.99		3,138	
2. Weight of the actual sample (g)	100.02	Mean Diameter	0.0003187	m
3. Deviation (g)	(0.03)		319	µm

Appendices C: Comparison of Minimum Fluidization velocity between different size particles

Size range between 200 to 300 microns

#	Superficial Gas Velocity [cm/s]	300 to 355	200 to 300	200 to below 300 (10s)	200 to below 300 (20s)	200 to below 300 (30s)
		Pressure Gradient [mbar/cm]				
1	1.20	0.19	0.28	0.30	0.30	0.25
2	1.50	0.24	0.35	0.37	0.35	0.32
3	1.80	0.28	0.42	0.44	0.43	0.38
4	2.11	0.33	0.49	0.52	0.50	0.45
5	2.41	0.38	0.57	0.60	0.57	0.52
6	2.71	0.43	0.64	0.67	0.65	0.59
7	3.01	0.47	0.71	0.74	0.72	0.65
8	3.31	0.52	0.78	0.81	0.79	0.72
9	3.61	0.57	0.85	0.89	0.86	0.78
10	3.91	0.62	0.93	0.96	0.94	0.85
11	4.21	0.67	1.00	1.03	1.01	0.92
12	4.51	0.71	1.07	1.11	1.08	0.98
13	4.81	0.76	1.14	1.18	1.15	1.05
14	5.11	0.80	1.21	1.25	1.22	1.11
15	5.41	0.85	1.28	1.31	1.29	1.17
16	5.71	0.90	1.35	1.37	1.36	1.24

17	6.01	0.95	1.43	1.44	1.46	1.30
18	6.32	1.00	1.47	1.35	1.34	1.38
19	6.62	1.05	1.34	1.35	1.35	1.44
20	6.92	1.09	1.34	1.34	1.34	1.34
21	7.22	1.14	1.33	1.33	1.32	1.33
22	7.52	1.19	1.33	1.32	1.32	1.32
23	7.82	1.24	1.32	1.30	1.32	1.32
24	8.12	1.29	1.30	1.29	1.30	1.30
25	8.42	1.36	1.29	1.31	1.28	1.29
26	8.72	1.38	1.28	1.27	1.28	1.31
27	9.02	1.43	1.29	1.29	1.29	1.28
28	9.32	1.38	1.27	1.29	1.28	1.31
29	9.62	1.39	1.28	1.28	1.29	1.29
30	9.92	1.34	1.26	1.28	1.28	1.30
31	10.23	1.34	1.27	1.28	1.27	1.26
32	10.53	1.33	1.29	1.27	1.28	1.28
33	10.83	1.31	1.28	1.27	1.27	1.26

Size range between 125 to 200 microns

#	Superficial Gas Velocity [cm/s]	300 to 355	125 to 200	125 to below 200 (5s)	125 to below 200 (20s)	125 to below 200 (30s)
		Pressure Gradient [mbar/cm]				
1	1.20	0.19	0.50	0.79	0.58	0.60
2	1.50	0.24	0.63	0.99	0.72	0.76
3	1.80	0.28	0.76	1.18	0.86	0.91
4	2.11	0.33	0.89	1.42	1.01	1.07
5	2.41	0.38	1.03	1.51	1.22	1.22
6	2.71	0.43	1.15	1.34	1.34	1.37
7	3.01	0.47	1.28	1.32	1.40	1.43
8	3.31	0.52	1.33	1.32	1.35	1.34
9	3.61	0.57	1.31	1.32	1.33	1.33
10	3.91	0.62	1.31	1.31	1.33	1.31
11	4.21	0.67	1.29	1.29	1.31	1.30
12	4.51	0.71	1.29	1.28	1.29	1.29
13	4.81	0.76	1.28	1.27	1.29	1.28
14	5.11	0.80	1.26	1.27	1.28	1.30
15	5.41	0.85	1.26	1.26	1.27	1.28
16	5.71	0.90	1.26	1.26	1.27	1.27
17	6.01	0.95	1.25	1.27	1.25	1.26
18	6.32	1.00	1.24	1.27	1.28	1.26
19	6.62	1.05	1.23	1.25	1.26	1.25

20	6.92	1.09	1.25	1.24	1.24	1.26
21	7.22	1.14	1.23	1.27	1.24	1.26
22	7.52	1.19	1.24	1.25	1.26	1.25
23	7.82	1.24	1.22	1.24	1.25	1.26
24	8.12	1.29	1.24	1.23	1.24	1.26
25	8.42	1.36	1.24	1.26	1.23	1.24
26	8.72	1.38	1.21	1.25	1.22	1.24
27	9.02	1.43	1.21	1.24	1.24	1.25
28	9.32	1.38	1.22	1.24	1.23	1.25
29	9.62	1.39	1.23	1.22	1.23	1.23
30	9.92	1.34	1.21	1.25	1.23	1.26
31	10.23	1.34	1.23	1.23	1.21	1.24
32	10.53	1.33	1.20	1.23	1.24	1.23
33	10.83	1.31	1.21	1.22	1.25	1.25

Size range between 125 to 355 microns

#	Superficial Gas Velocity [cm/s]	300 to 355	125 to 200	200 to 300	125 to 355
		Pressure Gradient [mbar/cm]			
1	1.20	0.19	0.50	0.28	0.27
2	1.50	0.24	0.63	0.35	0.34
3	1.80	0.28	0.76	0.42	0.41
4	2.11	0.33	0.89	0.49	0.48
5	2.41	0.38	1.03	0.57	0.55
6	2.71	0.43	1.15	0.64	0.62
7	3.01	0.47	1.28	0.71	0.69
8	3.31	0.52	1.33	0.78	0.76
9	3.61	0.57	1.31	0.85	0.83
10	3.91	0.62	1.31	0.93	0.89
11	4.21	0.67	1.29	1.00	0.96
12	4.51	0.71	1.29	1.07	1.04
13	4.81	0.76	1.28	1.14	1.11
14	5.11	0.80	1.26	1.21	1.18
15	5.41	0.85	1.26	1.28	1.25
16	5.71	0.90	1.26	1.35	1.32
17	6.01	0.95	1.25	1.43	1.41
18	6.32	1.00	1.24	1.47	1.47
19	6.62	1.05	1.23	1.34	1.32
20	6.92	1.09	1.25	1.34	1.36

21	7.22	1.14	1.23	1.33	1.37
22	7.52	1.19	1.24	1.33	1.35
23	7.82	1.24	1.22	1.32	1.33
24	8.12	1.29	1.24	1.30	1.31
25	8.42	1.36	1.24	1.29	1.31
26	8.72	1.38	1.21	1.28	1.30
27	9.02	1.43	1.21	1.29	1.30
28	9.32	1.38	1.22	1.27	1.29
29	9.62	1.39	1.23	1.28	1.28
30	9.92	1.34	1.21	1.26	1.30
31	10.23	1.34	1.23	1.27	1.29
32	10.53	1.33	1.20	1.29	1.29
33	10.83	1.31	1.21	1.28	1.29

Appendices D: Measured MFV from correlations

Parent Sample – 125 to 355 microns

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
	Density of Particle	ρ_s	kg/m^3	2,650
$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscosity of Fluid	μ	$Pa. s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$	Mean Diameter	d	m	0.000250
$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$	Ar	1,532.47		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	1.12	0.06633
Babu, Shah and Talwalker	1.90	0.11226
Vaid and Sen Gupta	1.68	0.09931
Bin	1.06	0.06265

125 to 200 microns

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
$$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$$	Density of Particle	ρ_s	kg/m^3	2,650
	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$$	Mean Diameter	d	m	0.000162
$$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$$	Ar	415.43		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.31	0.02822
Babu, Shah and Talwalker	0.53	0.04829
Vaid and Sen Gupta	0.47	0.04264
Bin	0.29	0.02661

200 to 300 microns

Archimedes Number (Ar)

$$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$$

Reynolds Number at minimum fluidization (Remf)

$$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$$

$$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$$

Parameters	Symbols	Unit	Value
Density of Particle	ρ_s	kg/m^3	2,650
Density of Fluid	ρ_f	kg/m^3	1.22
Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Acceleration of Gravity	g	m/s^2	9.81
Mean Diameter	d	m	0.000239
Ar	1,336.13		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.98	0.06070
Babu, Shah and Talwalker	1.67	0.10292
Vaid and Sen Gupta	1.47	0.09102
Bin	0.93	0.05731

300 to 355 microns

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$	Density of Particle	ρ_s	kg/m^3	2,650
	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$	Mean Diameter	d	m	0.000319
$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$	Ar	3,167.49		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	2.27	0.10530
Babu, Shah and Talwalker	3.80	0.17581
Vaid and Sen Gupta	3.37	0.15586
Bin	2.15	0.09970

125 to 200 microns (5s)

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
	Density of Particle	ρ_s	kg/m^3	2,650
$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$	Mean Diameter	d	m	0.000162
$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$	Ar	415.33		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.31	0.02822
Babu, Shah and Talwalker	0.53	0.04828
Vaid and Sen Gupta	0.47	0.04263
Bin	0.29	0.02660

125 to 200 microns (20s)

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
$$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$$	Density of Particle	ρ_s	kg/m^3	2,650
	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$$	Mean Diameter	d	m	0.000168
$$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$$	Ar	460.95		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.34	0.03023
Babu, Shah and Talwalker	0.59	0.05170
Vaid and Sen Gupta	0.52	0.04565
Bin	0.32	0.02850

125 to 200 microns (30s)

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$	Density of Particle	ρ_s	kg/m^3	2,650
	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$	Mean Diameter	d	m	0.000160
$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$	Ar	399.02		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.30	0.02748
Babu, Shah and Talwalker	0.51	0.04703
Vaid and Sen Gupta	0.45	0.04153
Bin	0.28	0.02591

200 to 300 microns (10s)

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
	Density of Particle	ρ_s	kg/m^3	2,650
$Ar = \frac{(\rho_s - \rho_f)gd^3\rho_f}{\mu^2}$	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$Re_{mf} = \frac{u_{mf}\rho_f d}{\mu}$	Mean Diameter	d	m	0.000235
$u_{mf} = \frac{Re_{mf}\mu}{\rho_f d}$	Ar	1,267.85		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.93	0.05867
Babu, Shah and Talwalker	1.58	0.09954
Vaid and Sen Gupta	1.40	0.08802
Bin	0.88	0.05539

200 to 300 microns (20s)

Archimedes Number (Ar)	Parameters	Symbols	Unit	Value
$$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$$	Density of Particle	ρ_s	kg/m^3	2,650
	Density of Fluid	ρ_f	kg/m^3	1.22
	Viscocity of Fluid	μ	$Pa.\ s$	0.000018
Reynolds Number at minimum fluidization (Remf)	Acceleration of Gravity	g	m/s^2	9.81
$$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$$	Mean Diameter	d	m	0.000237
$$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$$	Ar	1,296.56		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.95	0.05953
Babu, Shah and Talwalker	1.62	0.10097
Vaid and Sen Gupta	1.43	0.08929
Bin	0.90	0.05620

200 to 300 microns (30s)

Archimedes Number (Ar)

$$Ar = \frac{(\rho_s - \rho_f) g d^3 \rho_f}{\mu^2}$$

Reynolds Number at minimum fluidization (Remf)

$$Re_{mf} = \frac{u_{mf} \rho_f d}{\mu}$$

$$u_{mf} = \frac{Re_{mf} \mu}{\rho_f d}$$

Parameters	Symbols	Unit	Value
Density of Particle	ρ_s	kg/m^3	2,650
Density of Fluid	ρ_f	kg/m^3	1.22
Viscosity of Fluid	μ	$Pa.\ s$	0.000018
Acceleration of Gravity	g	m/s^2	9.81
Mean Diameter	d	m	0.000237
Ar	1,309.24		

Author	Reynolds Number at minimum fluidization	Minimum Fluidization Velocity
		m/s
Bourgeis and Grenier	0.96	0.05991
Babu, Shah and Talwalker	1.63	0.10160
Vaid and Sen Gupta	1.45	0.08985
Bin	0.91	0.05656