# Momentum Transfer and Mechanical Operations Lab

## Flow in Fluidized Beds

19th August, 2024

**Team:** MTMO 2

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# 1 Abstract with Graphics

In this experiment, the aim is to explore the phenomenon of fluidization in both water and air-fed beds, focusing on the determination of minimum fluidization velocities and the analysis of bed porosities, bed heights, and pressure drops. The experiment was designed to achieve fluidization, observe the behaviour of the fluidized beds at different superficial velocities, and compare the experimental results with theoretical predictions.

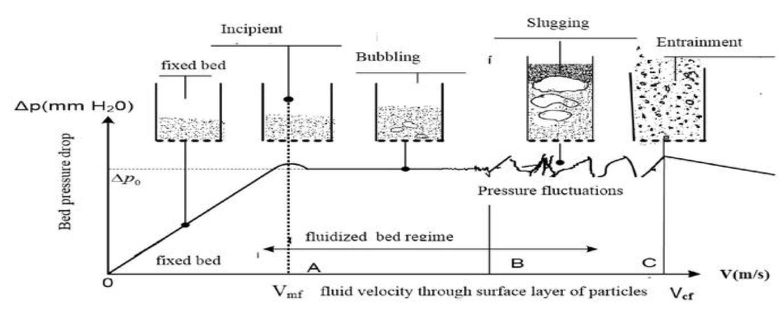
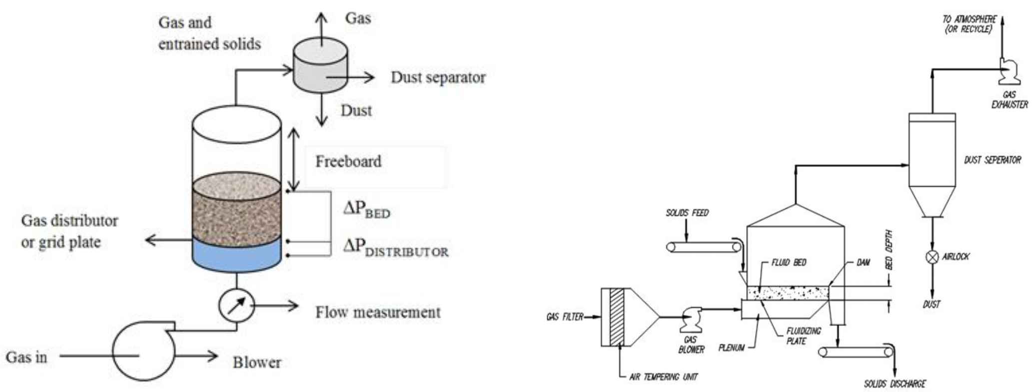



Figure 1: Fluidized bed with liquid as fluid

The procedure involved setting up a fluidized column with an inlet for fluid flow at the bottom and an outlet at the top. The column was filled with particles, and the fluid flow rate was gradually increased until the bed was fluidized, as indicated by a constant pressure drop. The experiment was repeated with both water and air, and the volumetric flow rate, pressure difference, and bed height were recorded at various stages of fluidization.

The data collected was used to calculate the superficial velocity and bed porosity. The results showed that the bed height increased with an increase in fluid velocity due to bed expansion. The minimum fluidization velocity was higher for air than for water, which was attributed to the density difference between the two fluids. The pressure difference increased linearly until the bed started moving, after which there was little change. Entrainment (figure 1) was observed at higher water velocities, leading to a decrease in pressure difference.




(a) Fluidized bed with Air Column (b) Schematic Representation

Figure 2: Typical schematic for fluidized bed with air column

The experiment provided insights into the fluid mechanics of fluidized beds and highlighted the importance of fluid properties and flow rates in achieving and maintaining fluidization. The results were compared with theoretical predictions, providing insights into the fluidization process and confirming the fundamental principles of fluid mechanics in fluidized beds. Despite minor sources of error, such as inaccuracies in flow rate measurement, the experiment successfully demonstrated the dynamics of fluidized beds and their dependence on fluid properties and flow conditions.

# 2 Aim

- Achieve fluidization for both water and air-fed beds and determine minimum fluidization velocities for both systems.

- Determine the effect of superficial velocity on bed porosities, bed heights, and pressure drops for both cases.
- Compare the minimum fluidization velocities obtained from experiments and theory (using the correlations).

# 3 Background and Motivation

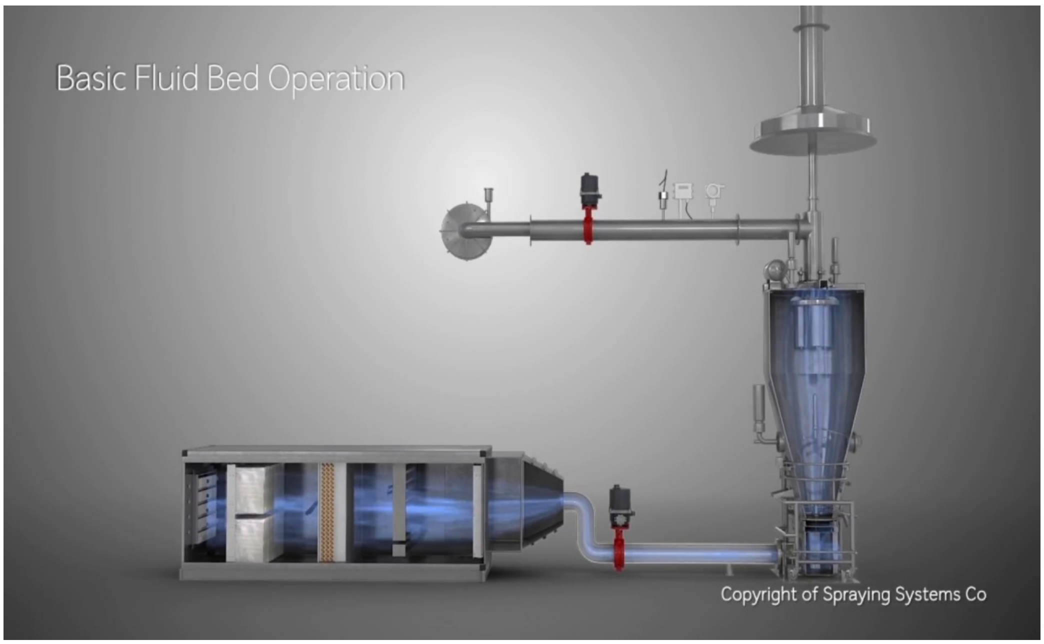



Figure 3: Fluidized Beds

## 3.1 Background

Fluidized beds are crucial in chemical engineering, used in processes like catalytic cracking, combustion, and heat and mass transfer. Fluidization occurs when a fluid flows upward through solid particles, causing them to behave like a fluid. Key concepts include:

- **Minimum Fluidization Velocity ($V_f$):** The fluid velocity at which particles begin to fluidize.
- **Superficial Velocity ($V_{sf}$):** The hypothetical velocity assuming only the fluid is present in a given cross-sectional area.
- **Porosity ($\epsilon$):** The ratio of void space between particles to the total bed volume, indicating particle packing.

### 3.2 Motivation

Fluidized beds offer advantages like better heat and mass transfer and reduced pressure drop compared to fixed beds. This experiment aims to:

- Understand fluidization concepts.
- Determine minimum fluidization velocity and porosity.
- Observe fluidized bed behavior at different fluid velocities.
- Compare experimental and theoretical $U_{mf}$ values.

This will enhance our understanding of fluidized beds and their industrial applications.

## 4 Materials and Methods

### 4.1 Apparatus & Materials Required

**Apparatus:** Fluidized bed, Manometer, Flow regulator, Stopwatch, Beaker, Metre Scale.

**Materials:** Glass beads and sand grains as materials for the fluidized beds.

(a) Liquid column with glass beads (b) Air column with sand grains

Figure 4: Setup for Flow study in Fluidized beds

## 4.2 Experimental Setup Description

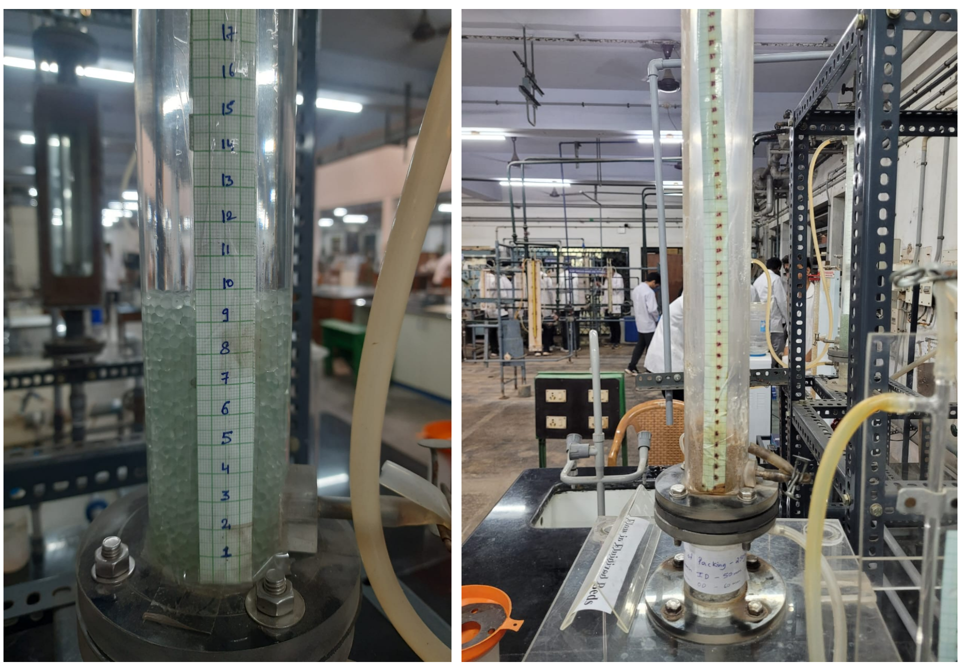
The experimental setup is shown in figure 4, which consists of two parts, ( 4a) & ( 4b) are the two sub-parts of the experiment.

**Fluidized Column:**

- A vertical column is used for both water and air fluidization experiments. It has an inlet at the bottom for fluid flow and an outlet at the top. The column is transparent, allowing for easy observation of the particles during the fluidization process.

**Supply System:**

- **Water Fluidization:** The water supply is connected directly to the column's inlet. There is no need for a pressure regulator in this setup. The flow rate of water is adjusted directly to achieve the desired fluidization of the bed.
- **Air Fluidization:** The air supply system includes a pressure regulator and a flow control valve to precisely control the airflow rate. A rotameter and manometer are connected to monitor the flow rate and pressure within the system.



(a) Glass Beads (b) Sand Grains

Figure 5: Types of Bed Particles used

**Bed Particles:**

- **Water Fluidization:** Glass beads (figure 5a) are used as the bed particles. The column is filled with these beads to the desired height before fluidization.
- **Air Fluidization:** Sand grains (figure 5b) is used as the only type of particle for the air fluidization experiment. The column is filled with sand to the desired height.

**Flow Control:**

- **Water Fluidization:** The water flow rate is gradually increased until the bed of glass beads is fluidized. The process focuses on observing particle behavior and bed height during fluidization.
- **Air Fluidization:** The air flow rate (figure 6) is gradually increased in small steps using the control valve until the sand bed is fluidized. The airflow is carefully monitored to ensure the particles remain fluidized.

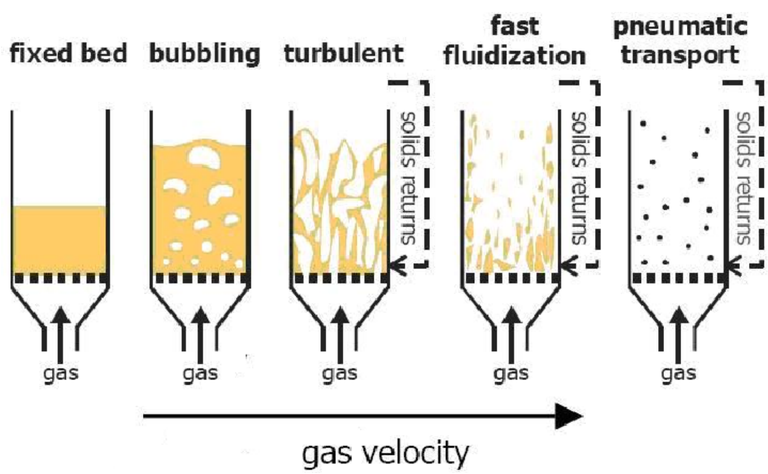



Figure 6: Effect of gas flow rate

**Measurement Devices:**

- **Water Fluidization:** A manometer (figure 7a) is used to measure the pressure difference across the bed of glass beads. Observations are made to focus on the particle behavior and the height of the bed during fluidization.
- **Air Fluidization:** Both a manometer (figure 7b) and a rota-meter (figure 7c) are used in this setup. The manometer measures the pressure difference across the sand bed, while the rota-meter records the volume flow rate at different heights during the experiment.

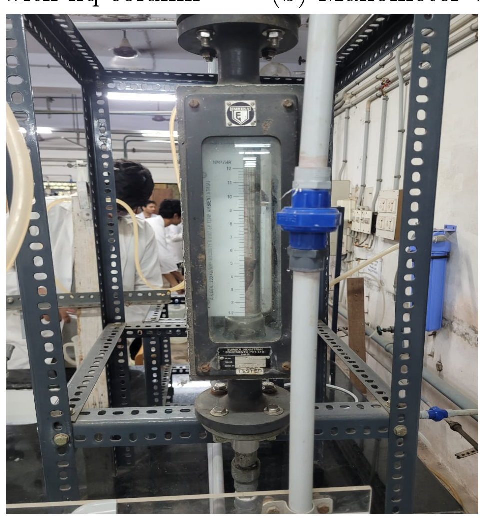
## 4.3 Procedure

- Set up the fluidized column, ensuring that it has an inlet for fluid flow at the bottom and an outlet at the top.

- Assemble the air supply system, incorporating a pressure regulator and a flow control valve to manage the airflow rate precisely.

(a) Manometer with liq column

(b) Manometer with air column



(c) Rotameter used with air column

Figure 7: Apparatus used for various measurements

- Fill the column with the glass beads to the predetermined height. Activate the water supply and adjust the flow rate using the control valve.
- Incrementally increase the water flow rate, carefully monitoring the manometer readings, until the bed reaches fluidization and the pressure drop remains constant.
- Collect a fixed volume of water from the outlet at each incremental level and record the time required to reach each level.
- Continue to gradually increase the water flow rate into the column, observing the behavior of the particles within the bed.
- Measure the pressure differential and volume flow rate at various heights up to the maximum level, beyond which the particles do not lift further.
- Gradually decrease the water flow rate, allowing the particles to settle back into the bed.
- Turn off the water supply and disconnect the equipment. And repeat the experiment using air, with sand as the bed particles.

# 5 Observation Tables

The tabulations include the observed data from each of the sub-experiments and are tabulated in both the following tables (table 1 & 2):

| $\Delta p$ $(cmHg)$ | H (cm) | $F$ $(Nm^3/Hr)$ |
|---|---|---|
| 2.7 | 4.1 | 2.4 |
| 3.7 | 4.5* | 3.8 |
| 4.4 | 5.0 | 4.2 |
| 4.3 | 5.5 | 4.8 |
| 4.3 | 6.5 | 5.4 |
| 4.3 | 5.2 | 4.8 |
| 4.3 | 4.5 | 4.2 |
| 4.3 | 4.4 | 3.6 |
| 3.2 | 4.3 | 2.6 |
| 2.4 | 4.1 | 2.0 |

Table 1: Tabulation of the case : Air + Sand Grains

| $\Delta p$ ($cm\ CCl_4$) | H (cm) | $V_1$ (mL) | $T_1$ (s) | $V_2$ (mL) | $T_2$ (s) | $V_3$ (mL) | $T_3$ (s) |
|---|---|---|---|---|---|---|---|
| 1.1 | 10.0 | 300 | 18.03 | 280 | 16.71 | 190 | 11.33 |
| 3.4 | 10.0 | 300 | 9.00 | 340 | 10.01 | 320 | 9.90 |
| 6.1 | 10.0 | 330 | 6.56 | 310 | 6.59 | 300 | 6.26 |
| 11.1 | 10.0 | 420 | 6.31 | 420 | 5.85 | 420 | 5.81 |
| 18.1 | 10.0 | 390 | 4.52 | 390 | 4.53 | 420 | 4.98 |
| 19.4 | 10.4 | 550 | 5.77 | 500 | 5.35 | 500 | 5.42 |
| 19.4 | 11.0 | 510 | 4.73 | 510 | 4.71 | 510 | 4.72 |
| 19.4 | 11.5 | 460 | 3.69 | 500 | 4.17 | 450 | 3.66 |
| 18.8 | 12.0 | 470 | 3.51 | 470 | 3.39 | 510 | 3.51 |
| 18.7 | 13.0 | 600 | 3.76 | 630 | 3.87 | - | - |
| 18.3 | 13.5 | 620 | 3.41 | 600 | 3.54 | 610 | 3.46 |
| 18.3 | 13.0 | 600 | 3.54 | 600 | 3.50 | - | - |
| 18.8 | 12.0 | 580 | 4.00 | 600 | 4.20 | - | - |
| 19.1 | 11.5 | 500 | 3.91 | 500 | 3.87 | - | - |
| 19.1 | 10.5 | 470 | 4.50 | 490 | 4.81 | - | - |
| 19.5 | 10.0 | 380 | 3.85 | 390 | 4.24 | - | - |
| 18.6 | 10.0 | 380 | 4.54 | 400 | 4.85 | - | - |
| 15.1 | 10.0 | 300 | 4.17 | 300 | 4.24 | - | - |
| 11.0 | 10.0 | 200 | 3.14 | 230 | 3.77 | - | - |
| 4.3 | 10.0 | 200 | 6.18 | 210 | 6.89 | 210 | 6.79 |

Table 2: Tabulation of the case : Water + Glass Beads

For each tabulation in case of fluidized bed where the fluid is liquid water (table 2), in order to calculate the volumetric flow rate volume of liquid is observed twice or thrice separately to obtain more accurate value for the same.

# 6 Results & Calculations

## 6.1 CASE : Air + Sand Grains

In this case, the $D_p$ of sand grains is about 0.5 mm, which is much smaller than the diameter of column ($D = 50$ mm). As the value of $D_p/D = 0.01$ is very close to zero,

$$Porosity\ :\ \epsilon = 0.34\ (appx) \tag{1}$$

However, it is noted, that the fluid used in manometer is unknown. This means that the value of density of manometer fluid ($\rho_m$) is unknown. To find this value, we can equate the theoretical pressure difference in a fluidized bed to the pressure difference shown in a manometer. So -

$$\Delta p = gh(1-\epsilon)(\rho_p - \rho) + g(H-h)\rho \tag{2}$$

$$\Delta p = gh_m\rho_m \tag{3}$$

Here, $H$ is the total height of column, $h$ is the height of fluidized bed and $h_m$ is the height difference in manometer.
Now, after equating the above two equations and calculating the value of $\rho_m$, we get the following results -

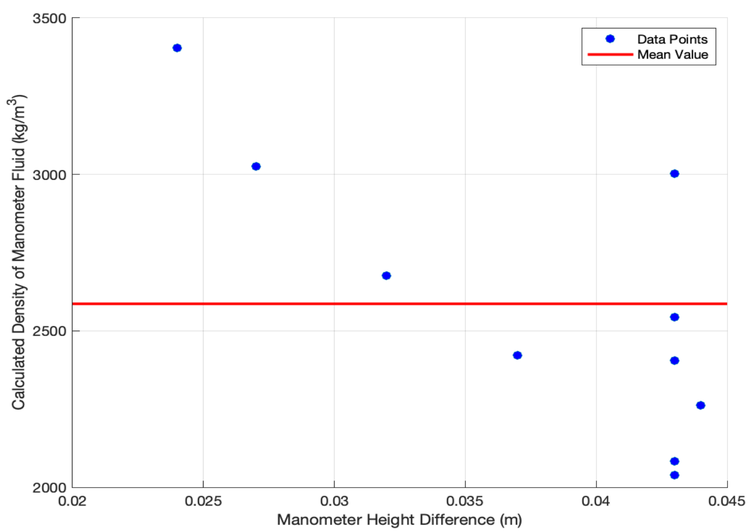


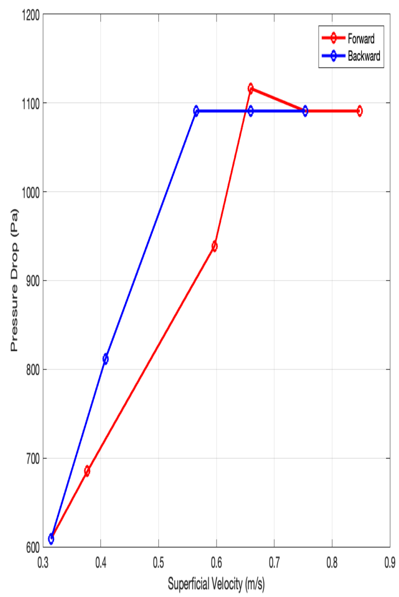

Figure 8: Density of the fluid used in manometer in case of Air column experiment

From this graph(figure 8), we get the final result as -

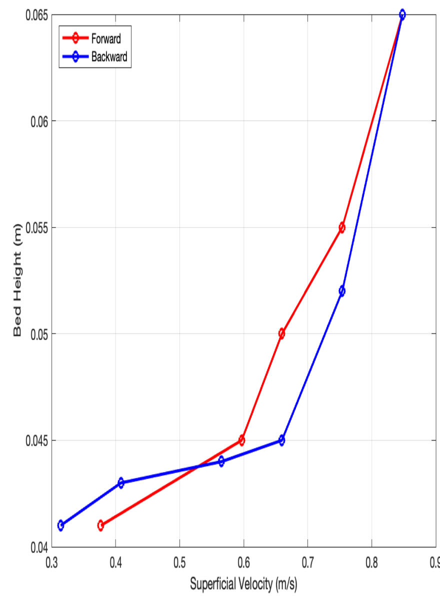
$$\rho_m = 2586.4\ kg/m^3 \tag{4}$$

$$V_f = 0.6125\ m/s \tag{5}$$

The other graphs which show the values of $\Delta p$ and $h$ in respect to change in superficial velocity $V_{sf}$ are as follows (figure 9a & 9b) & the results are shown in table 3.




(a) Pressure drop vs $V_{sf}$




(b) Bed height vs $V_{sf}$

Figure 9: Change of superficial velocity with respect to pressure drop and bed height

## 6.2 CASE : Water + Glass Beads

In this case, the $D_p = 0.380$ cm,
Weight of the bed = 300g,
Inner and outer diameter of the column are 5cm ($C_{ID}$) & 6cm ($C_{OD}$) respectively,
$\rho_{\text{water}} = 0.99567 g/cm^3$ @30°C Density of each bead is calculated from the average value of the observed data of volume of some amount of glass beads ($\rho_p = m_p/V_p$).

Now, the volumetric flow rate is calculated as:

$$F = V/T \tag{6}$$

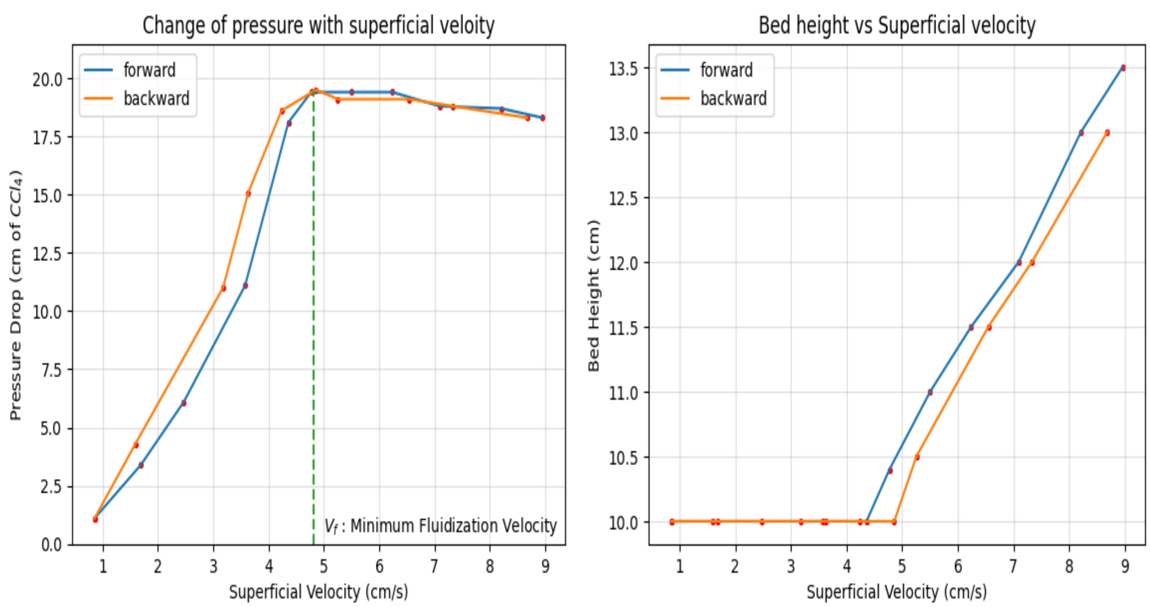
where V is the amount of volume flown in T unit time.

Calculation of superficial velocity follows:

$$V_{sf} = \frac{F}{\pi\ (C_{OD}/2)^2} \tag{7}$$

| $F$ $(m^3/s)$ | $V_{sf}$ $(m/s)$ | $\hat{\Delta p}$ $(Pa)$ | $\rho_m$ |
|---|---|---|---|
| 0.0007 | 0.377 | 801.52 | 3026.1 |
| 0.0012 | 0.597 | 879.05 | 2421.8 |
| 0.0013 | 0.660 | 975.96 | 2261.0 |
| 0.0015 | 0.754 | 1072.91 | 2543.4 |
| 0.0017 | 0.848 | 1266.73 | 3002.8 |
| 0.0015 | 0.754 | 1014.72 | 2405.5 |
| 0.0013 | 0.660 | 879.05 | 2083.9 |
| 0.0011 | 0.565 | 859.67 | 2037.9 |
| 0.0008 | 0.408 | 840.28 | 2676.7 |
| 0.0006 | 0.314 | 801.52 | 3404.3 |

Table 3: Results of the case : Air + Sand Grains




(a) Pressure drop vs $V_{sf}$

(b) Bed height vs $V_{sf}$

Figure 10: Change of superficial velocity with respect to pressure drop and bed height

Then the number of bed particles are calculated by the ratio of mass of the bed to the mass of one bed particle. Which is roughly coming out to be 4227 (refer to the **coded scripts** in GitHub for detailed calculations).

At the end, the porosity of the bed is calculated by the following formula (eq 8):

$$\epsilon = 1 - \frac{\text{Volume occupied by bed particles}}{\text{Total volume of the bed}} \tag{8}$$

The results are shown in the following graphs (figure 10a & 10b) and also the tabulation of the corresponding calcualted data are in the table 4.

| $F$ $(cm^3/s)$ | $V_{sf}$ $(cm/s)$ | $\epsilon$ |
|---|---|---|
| 16.722 | 0.852 | 0.381 |
| 33.207 | 1.691 | 0.381 |
| 48.423 | 2.466 | 0.381 |
| 70.215 | 3.576 | 0.381 |
| 85.571 | 4.358 | 0.381 |
| 93.676 | 4.771 | 0.405 |
| 108.051 | 5.503 | 0.438 |
| 122.505 | 6.239 | 0.462 |
| 139.282 | 7.094 | 0.485 |
| 161.183 | 8.209 | 0.524 |
| 175.870 | 8.957 | 0.542 |
| 170.460 | 8.681 | 0.524 |
| 143.929 | 7.330 | 0.485 |
| 128.538 | 6.546 | 0.462 |
| 103.158 | 5.254 | 0.411 |
| 95.341 | 4.856 | 0.381 |
| 83.087 | 4.232 | 0.381 |
| 71.349 | 3.633 | 0.381 |
| 62.351 | 3.176 | 0.381 |
| 31.256 | 1.592 | 0.381 |

Table 4: Results of the case : Water + Glass Beads

# 7 Conclusions and Remarks

- Height ($h$) of the fluidized bed initially remains constant with increase in superficial velocity ($V_{sf}$). However, once the fluidization velocity ($V_f$) is reached, the height starts to increase in a linear fashion.

- The Pressure Drop ($\Delta p$) in column increases with increase in superficial velocity ($V_{sf}$). However, once $V_f$ is reached, it stops increases and stabilizes to a constant value.

- The minimun fluidization velocity ($V_f$) of air comes out to be much greater than the value for water. (AIR = 0.6125 m/s and WATER = 0.0481 m/s)

- The porosity in the case of water and glass beads increases with increase in $V_{sf}$. It reaches a maximum value of about 0.542 and a minimum value of 0.381, which is in agreement with literature data.

# 8 Error Analysis

Least Count of scale $\equiv \Delta h = 1$ mm
Least Count of stopwatch $\equiv \Delta t = 0.01$ sec
Least Count of weighting scale $\equiv \Delta m_p = 0.01$ g
Least Count of Volume beaker (small) $\equiv \Delta V_p = 0.1$ mL
Least Count of Volume beaker (large) $\equiv \Delta V = 10$ mL

$$\frac{\Delta \rho_p}{\rho_p} = \frac{\Delta m_p}{m_p} + \frac{\Delta V_p}{V_p} \tag{9}$$

$$Air \ : \ \frac{\Delta V_{sf}}{V_{sf}} = \frac{\Delta Q}{Q} \tag{10}$$

$$Water \ : \ \frac{\Delta V_{sf}}{V_{sf}} = \frac{\Delta V}{V} + \frac{\Delta t}{t} \tag{11}$$

$$Water \ : \ \frac{\Delta \epsilon}{\epsilon} = \frac{\Delta h}{h} + \frac{\Delta \rho_p}{\rho_p} + \frac{\Delta h_m}{h_m} \tag{12}$$

# 9 Precautions

- Thoroughly inspect all equipment, including the fluidized column, air supply system, and water supply, for any signs of damage or leaks before initiating the experiment. Ensure that all connections are properly secured.

- Gradually increase the air and water flow rates to avoid abrupt changes in the bed's behavior, which could result in spillage, equipment damage, or inaccurate data collection.
- Calibrate the flow control valves, pressure sensors, and manometer to ensure accurate measurements before commencing the experiment.
- Maintain flow rates within safe limits to prevent particles from being expelled from the column, thereby ensuring precise fluidization observations and minimizing material loss.
- Slowly decrease the flow rate before shutting off the water or air supply to prevent sudden pressure fluctuations.

# 10 Thought Question / Open-Ended

**Q.** If you replace water in your fluidized bed with candle's wax and operate the device at melt temperatures. How will the combined effect of temperature and nature of wax at the melt temperature affect fluidization? How will your final conclusions change? Use relevant expressions to explain.

**A.** Paraffin wax at its melting point (about 57 celcius) is a non-Newtonian fluid and exhibits different properties than water, particularly in terms of viscosity and density. These changes, combined with the effects of temperature, will significantly impact the fluidization behavior.

**Change in the fluid properties**, such as viscosity & density should be kept under consideration,

- Melted candle wax typically has a much higher viscosity than water. The viscosity of the wax will also change with temperature, which affects the drag forces acting on particles in the fluidized bed.
- The density of liquid wax (900 $kg/m^3$) is generally lower than that of water. This reduced density affects the buoyant force on the particles in the bed, altering the minimum fluidization velocity.

**Temperature Effects**, such as

- **Temperature Dependency of Viscosity:** As temperature increases, the viscosity of the wax decreases. This is significant because the lower the viscosity, the easier it is for particles to become suspended, or fluidized, in the liquid wax.

- **Thermal Expansion:** Both the wax and the bed particles may undergo thermal expansion, which can affect bed porosity and packing density. This can change the minimum fluidization velocity and the overall behavior of the fluidized bed.

**Mathematical modifications in case of liquid wax:**

The viscosity $\mu$ of wax is strongly temperature-dependent. As temperature increases, viscosity decreases, which in turn reduces $V_f$ . The modified expression considering the viscosity as a function of temperature T would be:

$$V_f(T) = \frac{D_p^2(\rho_p - \rho_f(T))g}{18\mu(T)} \tag{13}$$

If the wax is more viscous than water at the melt temperature, we will need a higher fluid velocity to achieve fluidization. The viscosity at the operating temperature will critically determine this value.

Due to the non-Newtonian nature and the higher viscosity of liquid wax, fluidization might not be as uniform as in water. The bed may exhibit more channeling or formation of clusters, depending on the specific properties of the wax and particle interactions. This necessitates modifications in bed design or operation to ensure uniform fluidization.

## 11 Acknowledgements

We as a group contributed our respective parts into completing the above report on Flow in Fluidized Beds.

In terms of specifications, Rapolu Paranay Reddy helped with "Apparatus & Materials"; "Experimental Setup Description" part of the report. Atharva Sunilkumar Ghodke contributed in "Procedure" & "Precaution" parts. Anomol Upadhyay delivered the content for "Aim (Objective)"; "Background & Motivation". Lakkireddy Vishnu Vardhan Reddy wrote the "Abstract", and rest of the parts are done & organized by Deepanjhan Das (general editor) & Aayush Bhakna (proof reader).

And regarding AI transcript for the open-ended thought question asked, we didn't use ChatGpt for our thought question. It was more confusing and so we after discussing the scenario and after reading some related papers, we wrote as per our understanding. Therefore no such transcript is provided in the **Appendix** section.

## References

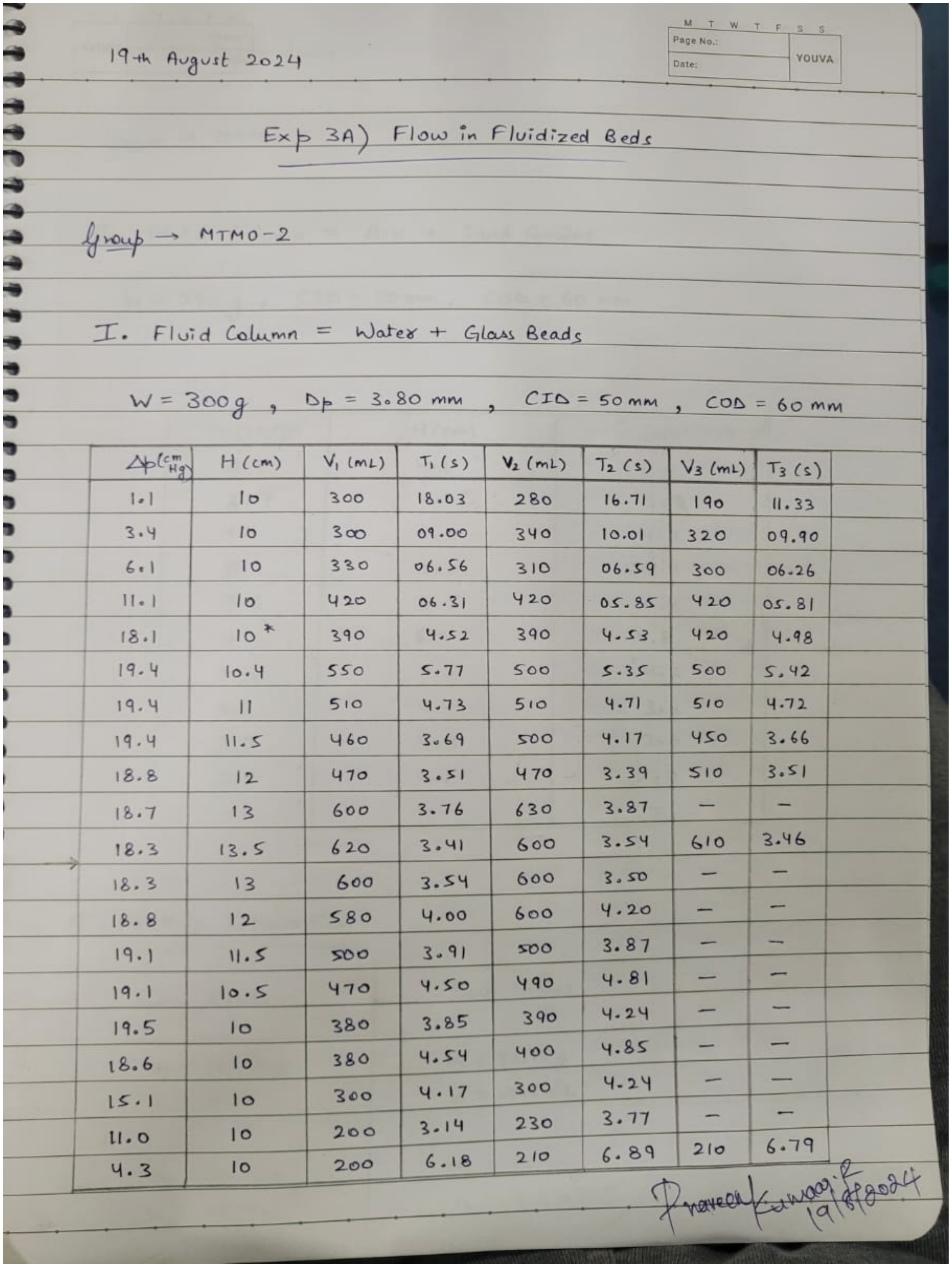
- 'Flow through Packed and Fluidized Beds' | Shankar Balasubramanian | Clarkson University

- Fox and McDonald's Introduction to Fluid Mechanics, 8th edition
- CH2015 : Fluid and Particle Mechanics course notes


# Appendix

**Lab Data:** All the experimental observations with each of the columns in each of subparts of the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures).

**Reference to all the contents:** The official GitHub repository which contains all the related data and coded scripts for calculations is also provided below: https://github.com/deep183Das/CH3510_MTMO_Lab_Group_2/tree/main/Experiment_3A. One can easily refer to all the related lab resources from this GitHub repository from where screenshots of few instances are shown in the above figures, in the "Particle Sedimentation Studies" experiment.



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19th August 2024

Exp 3A) Flow in Fluidized Beds

Group → MTMO-2

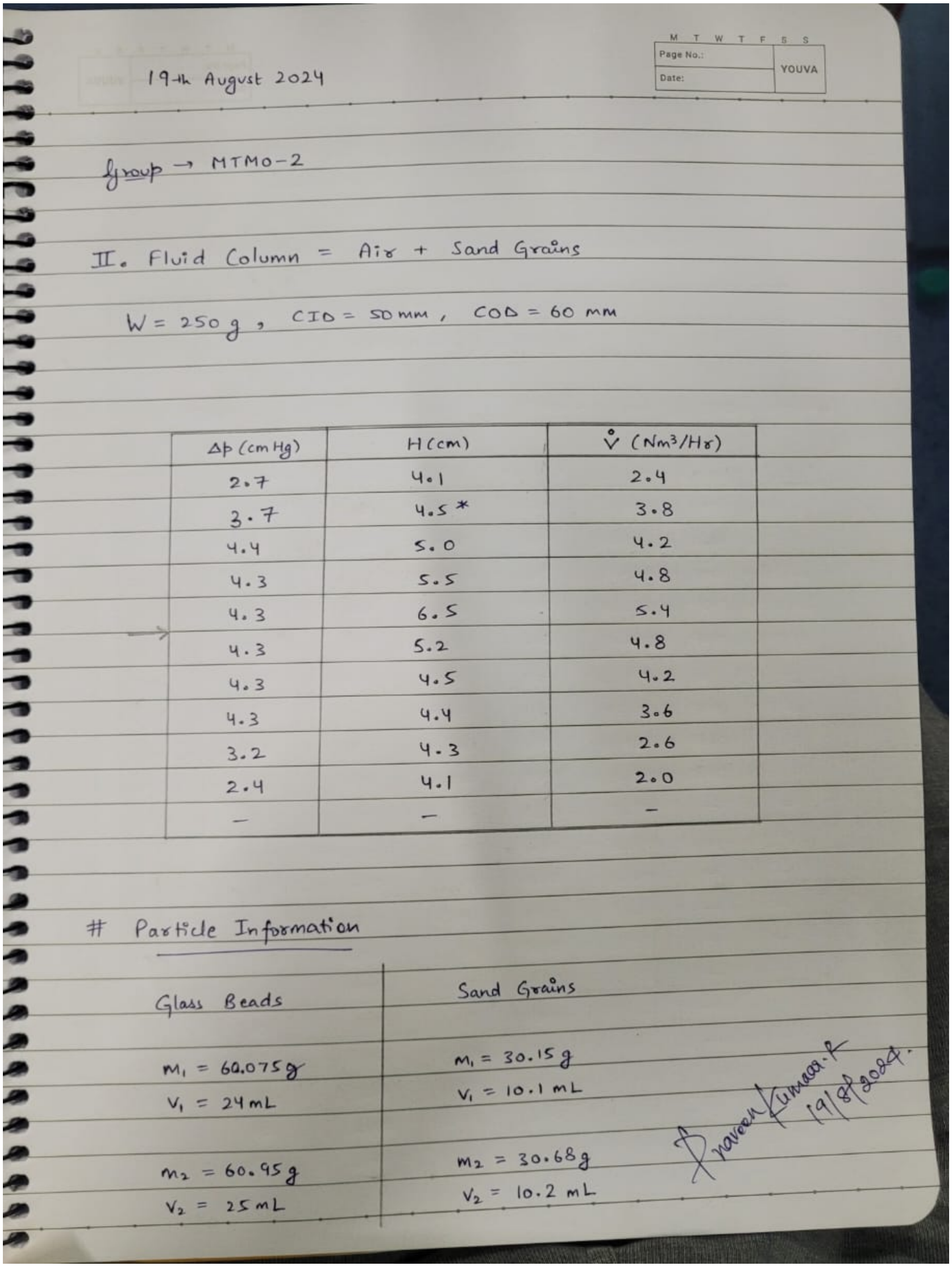
I. Fluid Column = Water + Glass Beads

W = 300g , Dp = 3.80 mm , CID = 50 mm , COD = 60 mm

| Δp (cm Hg) | H (cm) | $V_1$ (mL) | $T_1$ (s) | $V_2$ (mL) | $T_2$ (s) | $V_3$ (mL) | $T_3$ (s) |
|---|---|---|---|---|---|---|---|
| 1.1 | 10 | 300 | 18.03 | 280 | 16.71 | 190 | 11.33 |
| 3.4 | 10 | 300 | 09.00 | 340 | 10.01 | 320 | 09.90 |
| 6.1 | 10 | 330 | 06.56 | 310 | 06.59 | 300 | 06.26 |
| 11.1 | 10 | 420 | 06.31 | 420 | 05.85 | 420 | 05.81 |
| 18.1 | 10 * | 390 | 4.52 | 390 | 4.53 | 420 | 4.98 |
| 19.4 | 10.4 | 550 | 5.77 | 500 | 5.35 | 500 | 5.42 |
| 19.4 | 11 | 510 | 4.73 | 510 | 4.71 | 510 | 4.72 |
| 19.4 | 11.5 | 460 | 3.69 | 500 | 4.17 | 450 | 3.66 |
| 18.8 | 12 | 470 | 3.51 | 470 | 3.39 | 510 | 3.51 |
| 18.7 | 13 | 600 | 3.76 | 630 | 3.87 | — | — |
| 18.3 | 13.5 | 620 | 3.41 | 600 | 3.54 | 610 | 3.46 |
| 18.3 | 13 | 600 | 3.54 | 600 | 3.50 | — | — |
| 18.8 | 12 | 580 | 4.00 | 600 | 4.20 | — | — |
| 19.1 | 11.5 | 500 | 3.91 | 500 | 3.87 | — | — |
| 19.1 | 10.5 | 470 | 4.50 | 490 | 4.81 | — | — |
| 19.5 | 10 | 380 | 3.85 | 390 | 4.24 | — | — |
| 18.6 | 10 | 380 | 4.54 | 400 | 4.85 | — | — |
| 15.1 | 10 | 300 | 4.17 | 300 | 4.24 | — | — |
| 11.0 | 10 | 200 | 3.14 | 230 | 3.77 | — | — |
| 4.3 | 10 | 200 | 6.18 | 210 | 6.89 | 210 | 6.79 |

Praveen Kumar 19/8/2024

Figure 11: Data for glass beads as fluidizing beds in liquid column



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group → MTMO-2

II. Fluid Column = Air + Sand Grains

W = 250 g , CID = 50 mm , COD = 60 mm

| Δp (cm Hg) | H (cm) | $\dot{V}$ ($Nm^3/Hr$) |
|---|---|---|
| 2.7 | 4.1 | 2.4 |
| 3.7 | 4.5 * | 3.8 |
| 4.4 | 5.0 | 4.2 |
| 4.3 | 5.5 | 4.8 |
| 4.3 | 6.5 | 5.4 |
| 4.3 | 5.2 | 4.8 |
| 4.3 | 4.5 | 4.2 |
| 4.3 | 4.4 | 3.6 |
| 3.2 | 4.3 | 2.6 |
| 2.4 | 4.1 | 2.0 |
| – | – | – |

# Particle Information

| Glass Beads | Sand Grains |
|---|---|
| $m_1$ = 60.075 g | $m_1$ = 30.15 g |
| $V_1$ = 24 mL | $V_1$ = 10.1 mL |
| $m_2$ = 60.95 g | $m_2$ = 30.68 g |
| $V_2$ = 25 mL | $V_2$ = 10.2 mL |

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Figure 12: Data for sand grains as fluidizing beds in air column