Momentum Transfer and Mechanical Operations Lab

Flow in Packed Beds

26th August, 2024

Team: MTMO 2

Team Members: Aayush Bhakna (CH22B008), Rapolu Pranay Reddy (CH22B018), Deepanjhan Das (CH22B020), Atharva Sunilkumar Ghodke (CH22B035), Anmol Upadhyay (CH22B053)

Smail IDs: ch22b008@smail.iitm.ac.in, ch22b018@smail.iitm.ac.in, ch22b020@smail.iitm.ac.in, ch22b035@smail.iitm.ac.in, ch22b053@smail.iitm.ac.in

Instructors: Dr. Abhijit Deshpande, Dr. Nitin Muralidharan, Dr. Sankha Karmakar, Dr. Khushboo Suman

Department of Chemical Engineering, IIT Madras

1 Abstract with Graphics

Packed beds are extensively used in chemical engineering to enhance mass and heat transfer and facilitate chemical reactions by maximizing the contact surface area between different phases, such as liquid-gas or solid-gas interactions.

This experiment explores the dynamics of fluid flow through a packed bed column, which is a cylindrical apparatus filled with packing material to increase the surface area available for transfer processes. The packing can be random, like Raschig rings, or structured to optimize specific operations.

In the experiment, fluid dynamics were analyzed under various flow rates to study pressure drops and the effects of different packing materials. Data collected during the experiment were systematically analyzed to determine key parameters such as the Reynolds number and friction factor.

Additionally, error analysis was conducted to understand the precision and reliability of the measurements, accounting for factors like packing uniformity and flow irregularities.

The experiment's findings underscore the importance of packed beds (schematic of the column is shown in the figure 1) in operations such as absorption, adsorption, distillation,

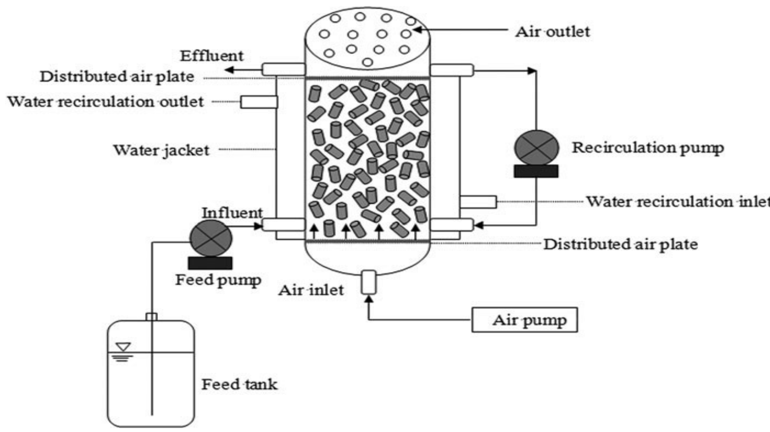


Figure 1: Schematic of the Packed Bed Column

and extraction, where efficient mass and heat transfer are critical. By evaluating the relationship between flow rates, packing type, and pressure drop, the study provides insights into optimizing packed bed design and operation for various industrial applications.

2 Aim

- Analyse the relation between pressure drop and flow rates for the different types of packing.
- Examine the hysteresis effect in the pressure drop curve for increasing flow rates and decreasing flow rates.
- Determine the validity of the Ergun equation by comparison of theoretical and practical values.

3 Background and Motivation

The movement of fluids through porous materials is a fundamental aspect of chemical engineering, influencing various processes such as oil extraction, soil remediation, and heat and mass transfer in packed beds. In these systems, understanding the behavior of fluid flow is crucial for optimizing design and operation.

Packed beds (column details is shown in figure 2), which consist of solid particles arranged in a specific configuration, are widely used in industrial applications such as reactors, distillation columns, and scrubbers. The complexity of fluid flow within these beds arises from the intricate network of channels and pores formed by the packing material. This complexity makes it challenging to predict flow behavior, particularly when compared to open tubes where flow patterns are more straightforward.

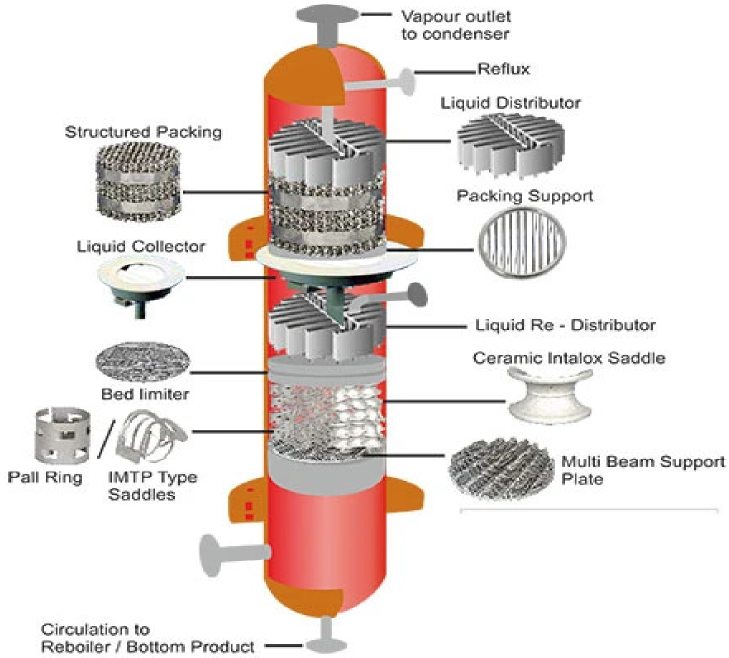


Figure 2: Schematic Details of the Packed Bed Column

The Reynolds number, a dimensionless parameter that describes the flow regime (laminar or turbulent), is often used to characterize fluid flow. However, applying the Reynolds number to packed beds is more complex due to the non-uniform flow patterns caused by the presence of solid packing material. This material introduces resistance to fluid flow, quantified by a permeability coefficient, making it more difficult for fluids to pass through the bed compared to an open tube.

In packed beds, fluids can exhibit different flow regimes depending on the gas-to-liquid ratio and other factors. These regimes include bubbly flow, where gas bubbles are dispersed within the liquid phase; trickle flow, resembling stable laminar flow; pulse flow, characterized by high mixing and alternating regions of gas and liquid; and spray flow, dominated by turbulent gas flow with entrained liquid droplets.

One of the most widely used empirical correlations for describing fluid flow in packed beds is the Ergun equation. This equation accounts for both viscous and inertial effects, providing a means to calculate the pressure drop across the bed for different flow conditions. The Ergun equation is essential for designing and analyzing packed bed systems, as it helps predict how fluids will behave under various operating conditions.

This experiment aims to deepen the understanding of fluid flow in packed beds by analyzing the relationship between pressure drop and flow rate for different types of packing materials, examining the hysteresis effect in pressure drop curves, and validating the applicability of the Ergun equation in different flow regimes.

Ergun Equation:

$$\frac{-\Delta P}{\Delta L} = 150\left(\frac{\mu v_{sf}}{\phi_s^2 d_p^2}\right)\frac{(1-\epsilon)^2}{\epsilon^3} + 1.75\left(\frac{\rho v_{sf}^2}{\phi_s d_p}\right)\frac{(1-\epsilon)}{\epsilon^3} \tag{1}$$

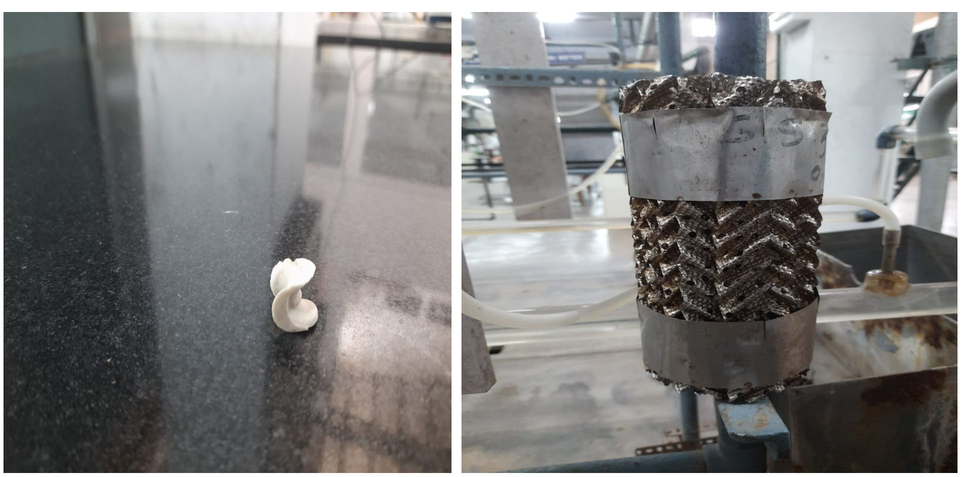
Here, ΔP is the pressure drop across the packed bed (Pa)
L is the height of the bed (m)
μ is the fluid viscosity (Pa·s)
ϵ is the void fraction or porosity (dimensionless)
d_p is the diameter of the solid particles (m)
ρ is the density of the fluid (kg/m^3)
ϕ_s is the sphericity of the packing material used
v_{sf} is the fluid superficial velocity (m/s).

4 Materials and Methods

4.1 Apparatus & Materials Required

Apparatus: Packed bed apparatus, 2L beaker, Stopwatch, 50mL measuring tube, Vernier callipers, Weighing machine, Scale ruler.

Materials: 3 types of Packed bed materials used which are Raschig Rings (figure 4), Berl Saddle (figure 3a), Structured Packing Material (figure 3b).



(a) Berl Saddle (b) Structured Packing

Figure 3: Packing Materials

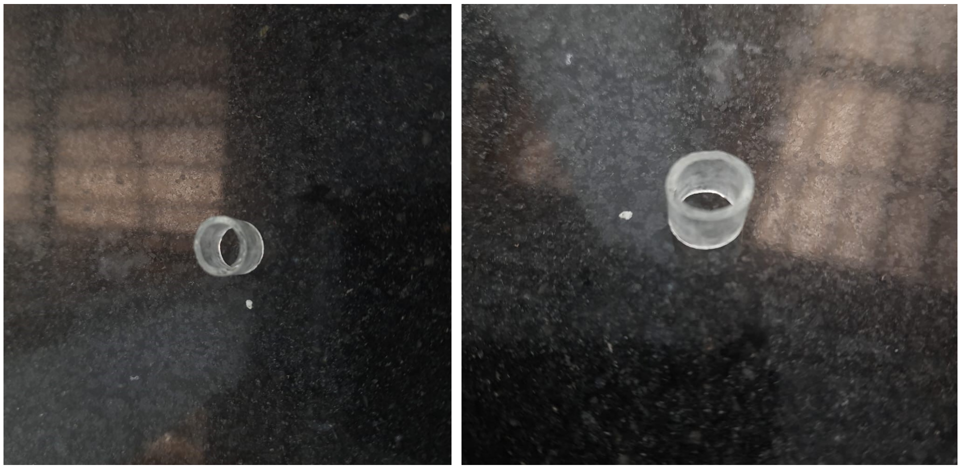


Figure 4: Raschig Ring

4.2 Experimental Setup Description

The experimental setup is shown in figure 5, which consists of three parts, (shown in figures 6, 7a & 7b) which are the three sub-parts of the experiment.

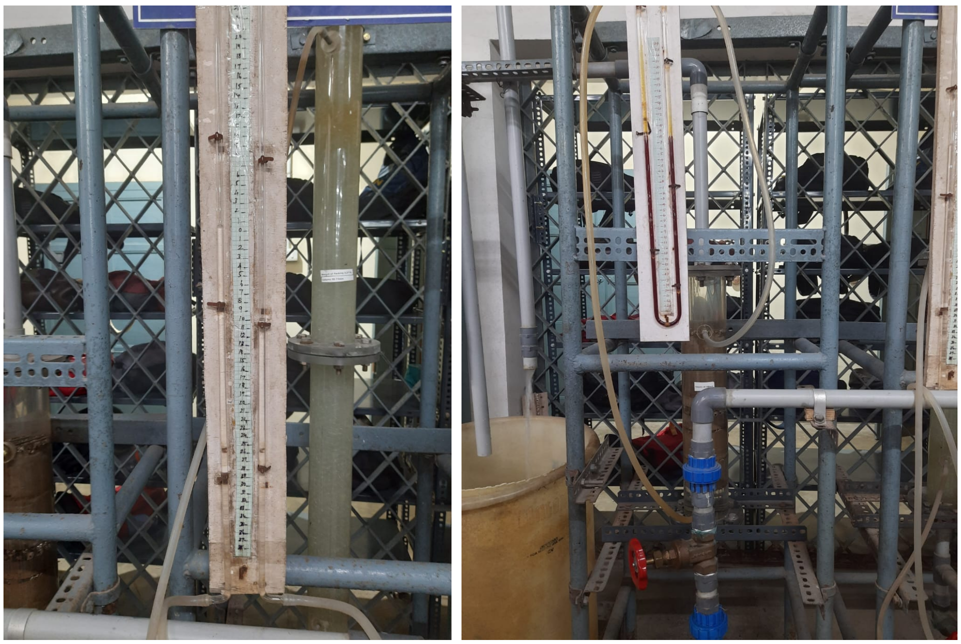
Figure 5: The Complete set-up for the Packed Bed Columns

- **Packed Bed Apparatus:**
  - A vertical column is used to hold the packing material during the experiment. The column is equipped with ports to attach probes for measuring pressure drop using a manometer.
- **Packing Materials:**
  - Samples of Raschig rings and Berl saddles are used as the packing materials. The amount of packing material added to the column is carefully noted.

Figure 6: Set up with Raschig Ring

- **Flow System:**
  - Water is used as the fluid flowing through the packed bed. A 2L beaker is placed at the outlet to collect the water, allowing for the calculation of flow rate. The time required to fill the beaker is measured with a stopwatch.
- **Measurement Devices:**
  - **Manometer:** Probes are attached across the packed bed to measure the pressure drop as water flows through the column.
  - **Stopwatch:** Used to measure the time it takes to fill water in a beaker, enabling flow rate calculations.

- **50 mL Measuring Tube:** Utilized during the volume-displacement method to measure the change in water volume when the packing material is added.
- **Weight Measure:** A weighing machine is used to measure the mass of the packing material samples.
- **Scale Ruler:** Employed for general measurements during the setup and experiment.



(a) Set-up with Berl Saddle (b) Set-up with Structured Packing

Figure 7: Set-up with Saddle and Structured Material

4.3 Procedure

- Begin by inspecting for any water leaks or faults in the lines by running water through the packed beds.
- Fill the packed beds with water to a level that ensures there is no flooding, maintaining a 100% water fill.
- Measure the height difference in the manometer to determine the pressure drop. Gradually increase the pressure for each reading.
- Extract a specific volume of water using a measuring cylinder and record the time required to reach that volume.

- Repeat the above steps to obtain 10-12 readings of pressure difference, along with the corresponding volume and time measurements.
- Conduct the same procedures using different packing materials.

4.3.1 Procedure for Determining the Density of Packing Materials:

- Obtain a sample of the packing material and measure its weight using a precision weighing machine.
- Fill a measuring cylinder with water, then add the sample of the packing material, and note the change in water volume.
- Repeat the steps above for various packing materials.
- Calculate the density of each packing material using the recorded mass and volume data.

5 Observation Tables

The tabulations include the observed data from each of the sub-experiments and are tabulated in both the following tables (tables 1, 2 & 3):

Δp ($cm\ CCl_4$)	ΔV (mL)	ΔT (s)
5.1	660	9.81
10.9	820	7.59
17.4	740	5.74
24.3	960	5.81
29.0	720	3.86
35.5	680	3.28
41.2	760	3.38
35.2	540	2.55
29.2	680	3.38
23.1	760	4.74
17.2	700	5.12
11.3	700	6.10
7.2	560	6.77
2.3	440	11.13

Table 1: Tabulation for Berl Saddle as Packing Material

Δp ($cm\ CCl_4$)	ΔV (mL)	ΔT (s)
2.0	440	10.0
4.0	660	10.0
5.7	840	10.0
7.5	1000	10.0
9.4	640	5.38
11.3	700	5.38
17.1	920	6.06
24.6	880	4.84
32.1	940	4.35
39.6	700	2.90
45.4	840	3.04
41.4	660	2.71
36.0	780	3.30
32.2	620	2.76
26.7	640	3.16
22.6	780	4.34
15.3	700	4.85
9.5	960	8.36
4.0	660	10.06

Table 2: Tabulation for Raschig Ring as Packing Material

6 Results & Calculations

6.1 Right Column | Berl Saddles

Column Height (H) = 1.259 m
Column Diameter (D) = 0.073 m
Column cross-section area (A) = 0.004185 m^2
Column Volume (V_{BED}) = 0.005269 m^3

Volume of void in column (V_{VOID}) = 0.003780 m^3
Porosity (ϵ) = V_{VOID}/V_{BED} = 0.7173

Density of packing material (ρ_p) = 2220.00 kg/m^3

Δp ($cm\ CCl_4$)	ΔV_1 (mL)	ΔV_2 (mL)	ΔT_1 (s)	ΔT_2 (s)
2.0	1120	-	3.59	-
3.9	760	-	1.75	-
6.0	780	-	1.53	-
8.0	1100	-	1.84	-
9.3	1480	-	2.02	-
10.0	840	980	1.09	1.41
10.9	880	760	1.40	1.06
10.0	1280	1040	1.69	1.39
9.2	900	980	1.20	1.38
8.0	1200	880	2.05	1.51
6.1	920	960	1.78	1.76
4.3	800	-	1.77	-
3.0	820	-	2.28	-
2.0	580	-	2.01	-

Table 3: Tabulation for Structured Packing Material

Nominal diameter of Berl Saddle (D_p) = 0.009267 m
Thickness of Berl Saddle (d_h) = 0.5 mm (appx)
Surface Area per Volume of Berl Saddle = $2/d_h$ (appx)

Value of Sphericity :

$$\phi_s = \frac{(6/D_p)}{2/d_h} = 0.1619 \tag{2}$$

Value of Superficial velocity :

$$v_{sf} = \frac{Q\ (Volumetric\ Flow\ Rate)}{A\ (Cross\ Sectional\ Area)} \tag{3}$$

6.1.1 Calculating Error in Pressure Drop

Using Ergen's equation:

$$\frac{\Delta p}{H} = \frac{150\mu(1-\epsilon)^2}{{\phi_s}^2 {D_p}^2 \epsilon^3} \cdot v_{sf} + \frac{1.75\rho(1-\epsilon)}{\phi_s D_p \epsilon^3} \cdot {v_{sf}}^2 \tag{4}$$

After putting the values in this equation, we can calculate the theoretical value of pressure drop. After that, error% is:

$$err\% = \frac{(\Delta\hat{p} - \Delta p)}{\Delta\hat{p}} \cdot 100\% \tag{5}$$

This gives us the following results (table 4 & figures 8, 9):

v_{sf} (m/s)	Δp (Pa)	$\Delta\hat{p}$ (Pa)	$err\%$
0.0161	795.5	522.1	52.4
0.0258	1700.2	1120.0	51.8
0.0308	2714.0	1508.6	79.9
0.0395	3790.3	2317.0	63.6
0.0446	4523.4	2869.6	57.6
0.0495	5537.3	3465.0	59.8
0.0537	6426.3	4010.1	60.3
0.0506	5490.5	3599.5	52.5
0.0481	4554.6	3283.6	38.7
0.0383	3603.1	2198.2	63.9
0.0327	2682.8	1668.0	60.8
0.0274	1762.6	1238.9	42.3
0.0198	1123.0	723.6	55.2
0.0094	358.8	236.7	51.6

Table 4: Case : Water + Ceramic Berl Saddles

6.1.2 Calculating Sphericity of Berl Saddle

Let us assume that we cannot calculate the sphericity of Berl Saddle at the moment. Then we put use the observed pressure drop into the Ergen's equation and get the values

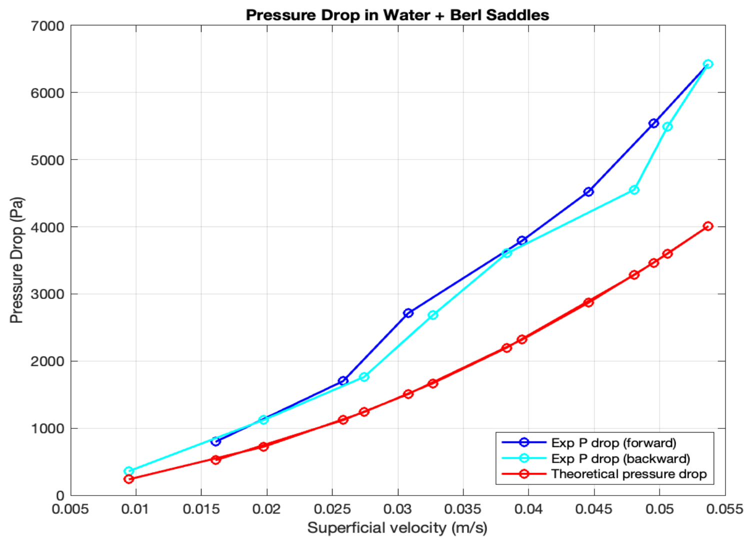


Figure 8: The pressure drop vs superficial velocity for Right Column

of ϕ_s. Then we can simply mean the results to get one final value.

$$\bar{\phi_s} = \frac{1}{n}\sum(\hat{\phi_s}) = 0.1158 \tag{6}$$

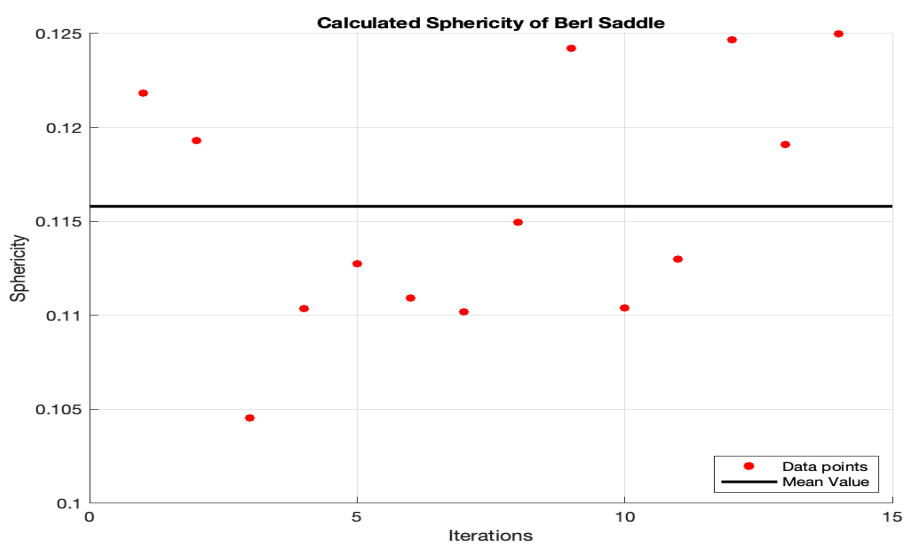


Figure 9: Sphericity Calculation for Berl Saddle

6.2 Middle Column | Raschig Rings

Column Height (H) = 1.259 m
Column Diameter (D) = 0.073 m
Column cross-section area (A) = 0.004185 m^2
Column Volume (V_{BED}) = 0.005269 m^3

Volume of void in column (V_{VOID}) = 0.00424 m^3
Porosity (ϵ) = V_{VOID}/V_{BED} = 0.8046

Density of packing material (ρ_p) = 2933.33 kg/m^3
Nominal diameter of Raschig Ring (D_p) = 0.007256 m
Thickness of Raschig Ring (d_h) = 0.5 mm (appx)
Surface Area per Volume of Raschig Ring = $2/d_h$ (appx)

Value of Sphericity :

$$\phi_s = \frac{(6/D_p)}{2/d_h} = 0.2067 \tag{7}$$

Value of Superficial velocity :

$$v_{sf} = \frac{Q\ (Volumetric\ Flow\ Rate)}{A\ (Cross\ Sectional\ Area)} \tag{8}$$

6.2.1 Calculating Error in Pressure Drop

Using Ergen's equation:

$$\frac{\Delta p}{H} = \frac{150\mu(1-\epsilon)^2}{{\phi_s}^2 {D_p}^2 \epsilon^3} \cdot v_{sf} + \frac{1.75\rho(1-\epsilon)}{\phi_s D_p \epsilon^3} \cdot {v_{sf}}^2 \tag{9}$$

After putting the values in this equation, we can calculate the theoretical value of pressure drop. After that, error% is:

$$err\% = \frac{(\Delta\hat{p} - \Delta p)}{\Delta\hat{p}} \cdot 100\% \tag{10}$$

This gives us the following results (table 5 & figures 10, 11):

6.2.2 Calculating Sphericity of Raschig Ring

Let us assume that we cannot calculate the sphericity of Raschig Ring at the moment. Then we put use the observed pressure drop into the Ergen's equation and get the values of ϕ_s. Then we can simply mean the results to get one final value.

$$\bar{\phi_s} = \frac{1}{n}\sum(\hat{\phi_s}) = 0.1318 \tag{11}$$

v_{sf} (m/s)	Δp (Pa)	$\Delta\hat{p}$ (Pa)	$err\%$
0.0105	195.4	112.1	74.2
0.0158	390.7	213.7	82.9
0.0201	556.8	319.3	74.4
0.0239	732.6	430.2	70.3
0.0284	918.2	582.3	57.7
0.0311	1103.8	682.4	61.8
0.0363	1670.3	899.3	85.7
0.0434	2402.9	1247.9	92.6
0.0516	3135.5	1715.0	82.8
0.0577	3868.1	2106.7	83.6
0.0660	4434.6	2713.9	63.4
0.0582	4053.6	2142.1	89.2
0.0565	3516.4	2025.9	73.6
0.0537	3145.2	1842.9	70.7
0.0484	2608.0	1521.4	71.4
0.0429	2207.5	1221.7	80.7
0.0345	1494.5	821.2	82.0
0.0274	927.9	547.3	69.5
0.0157	390.7	211.6	84.7

Table 5: Case : Water + Plastic Raschig Rings

6.3 Left Column | Structured Packing (Mellapak 250)

Column Height (H) = 0.595 m
Column Diameter (D) = 0.100 m
Column cross-section area (A) = 0.004185 m^2
Column Volume (V_{BED}) = 0.005269 m^3

Volume of void in column (V_{VOID}) = 0.00424 m^3
Porosity (ϵ) = V_{VOID}/V_{BED} = 0.9260

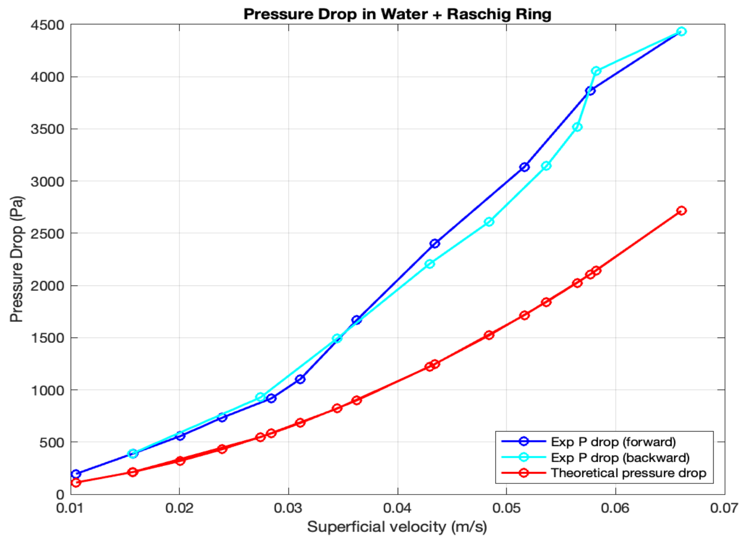


Figure 10: The pressure drop vs superficial velocity for Middle Column

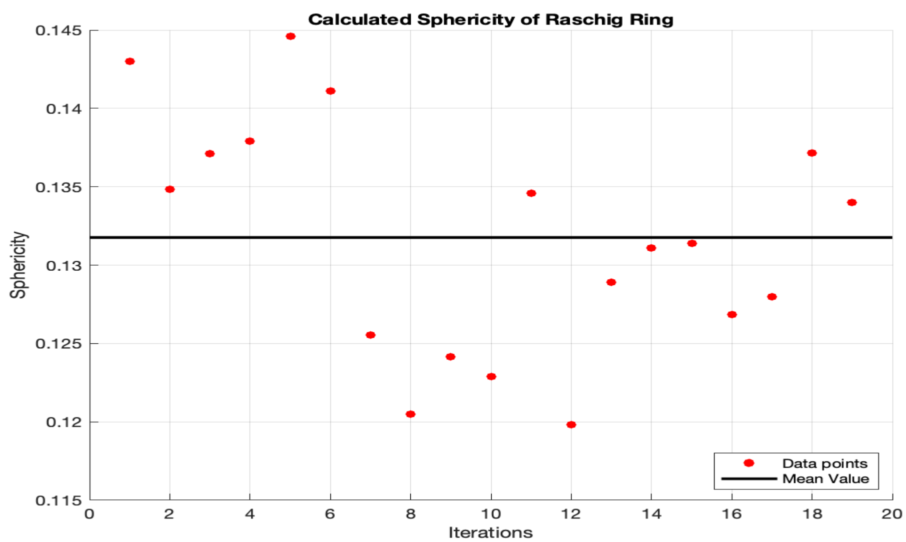


Figure 11: Sphericity Calculation for Raschig Rings

Value of Superficial velocity :

$$v_{sf} = \frac{Q\ (Volumetric\ Flow\ Rate)}{A\ (Cross\ Sectional\ Area)} \tag{12}$$

6.3.1 Plotting Pressure Drop

The result is shown in figure 12:

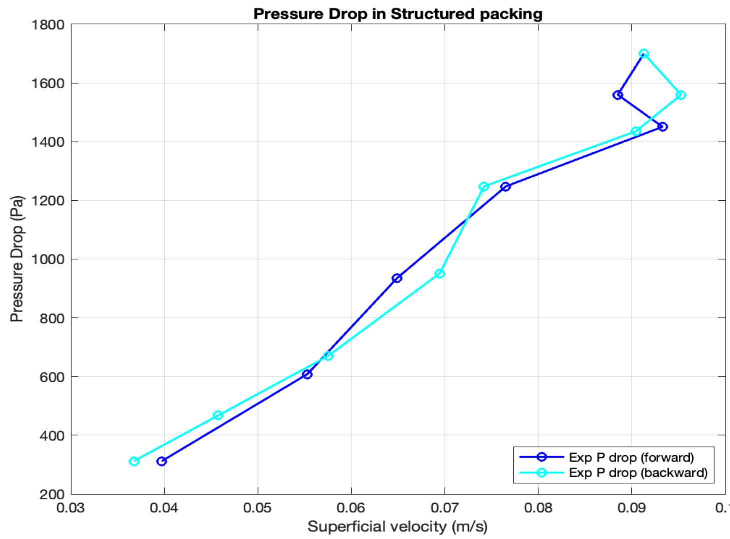


Figure 12: The pressure drop vs superficial velocity for Left Column

7 Conclusions and Remarks

- The pressure drop (Δp) across the bed / column increases with a rise in the value of superficial velocity (v_{sf}).
- The values obtained while the process was in forward are very similar to the values obtained while process was in backwards.
- The porosity of the left column is the highest, and causes the superficial velocity to be higher as well.
- However, the contact surface area is low in case of the structured packing (left column), causing pressure drop to be lower as well.

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 $\equiv \Delta m_p = 0.1$ 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

8.1 Sources of Error

- We must compute superficial velocity from volumetric flow rate using the cross-sectional area of the smaller pipe through which we acquire water, even when the trends of other parameters remain unchanged.
- Mistakes brought on by an imprecise measurement of the volumetric flow rate (a very high least count while measuring volume)
- Mistakes brought on by spilled water during sample collection for estimates of volumetric flow rate at higher flow rates.

9 Precautions

- Prior to commencing the experiment, conduct a comprehensive inspection of all equipment, including packed beds, manometers, and measuring cylinders, to identify any damage, leaks, or malfunctions. Verify that all connections are secure and ensure the system is free from leaks.
- Calibrate all measurement instruments, such as manometers and flow meters, to guarantee the accuracy of the readings. Calibration should be carried out regularly and documented accordingly.
- Consistently monitor and maintain the water temperature throughout the experiment, as fluctuations in temperature can affect the density and viscosity of the water, which may, in turn, impact the pressure drop and flow rate.
- Apply pressure gradually and consistently during the experiment to avoid abrupt increases that could result in inaccurate readings or potential damage to the equipment.
- Ensure that the packing materials are clean and devoid of any contaminants or dust, as impurities could alter the flow dynamics and pressure drop. Use packing materials of uniform size and shape to facilitate accurate comparisons.
- Conduct measurements under stable environmental conditions (such as temperature and humidity) to minimize variability and ensure the reliability of the results.

10 Thought Question / Open-Ended

Q. If you replace water in your packed 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 your experiment? How will your final conclusions change? Use relevant expressions to explain.

A. First we need to understand the challenges and the key differences of these two mixtures that we will face while performing our experiment (**Note**. The study with the *'non-Newtonian fluids'*, *'Lattice Boltzmann investigation on fluid flows'* and *'Flow of non-Newtonial fluid throgh packed beds'* is done by referring from some scholarly articles mentioned in the **references** section & from this study we as a team have come up with this possible answer)

Effects of Replacing Water with Candle Wax:

- **Nature of the Fluid and Temperature Effects:** Candle wax, at temperatures just above its melting point, behaves as a non-Newtonian fluid. Unlike water, melted candle wax exhibits a viscosity that changes with the applied shear rate. The non-Newtonian behavior of the wax would result in a more complex flow pattern through the packed bed.
- **Fluid Properties and Flow Dynamics:** When operating at the melt temperature of wax, several fluid properties become critical:
  - **Viscosity:** The viscosity of melted wax is significantly higher than that of water, leading to increased resistance to flow. Higher viscosity would result in a greater pressure drop across the packed bed. Given the higher viscosity (μ) of melted wax, the first term of the Ergun equation (eq 1) would increase substantially, leading to a significant pressure drop.
  - **Density and Buoyancy Effects:** The density of wax is also different from that of water, which affects the buoyancy forces acting on the particles within the packed bed. This could potentially alter the distribution of the wax within the packed bed and affect the overall fluid dynamics.
- **Temperature Control:** More stringent temperature control mechanisms would be necessary to maintain consistent wax properties throughout the experiment, given the sensitivity of wax viscosity to temperature changes.
- **Error and Uncertainty Analysis:** The experimental error analysis must incorporate the additional uncertainties due to temperature fluctuations, phase changes, and non-Newtonian behavior, which would likely result in a broader confidence interval for any measurements of flow parameters.

11 Acknowledgements

We as a group contributed our respective parts into completing the above report on Flow in Packed 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" and rest of all the parts are done & organized by Deepanjhan Das (general editor) & Aayush Bhakna (proof reader).

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.

And at last but not the least, we specially thank the respective TA for this experiment Mr. Praveen Kumar bhaiya for his kind help and to let us have a thorough understanding of the whole process and the concept. We thank all the course instructors for their effective control and high co-operation as per the need.

References

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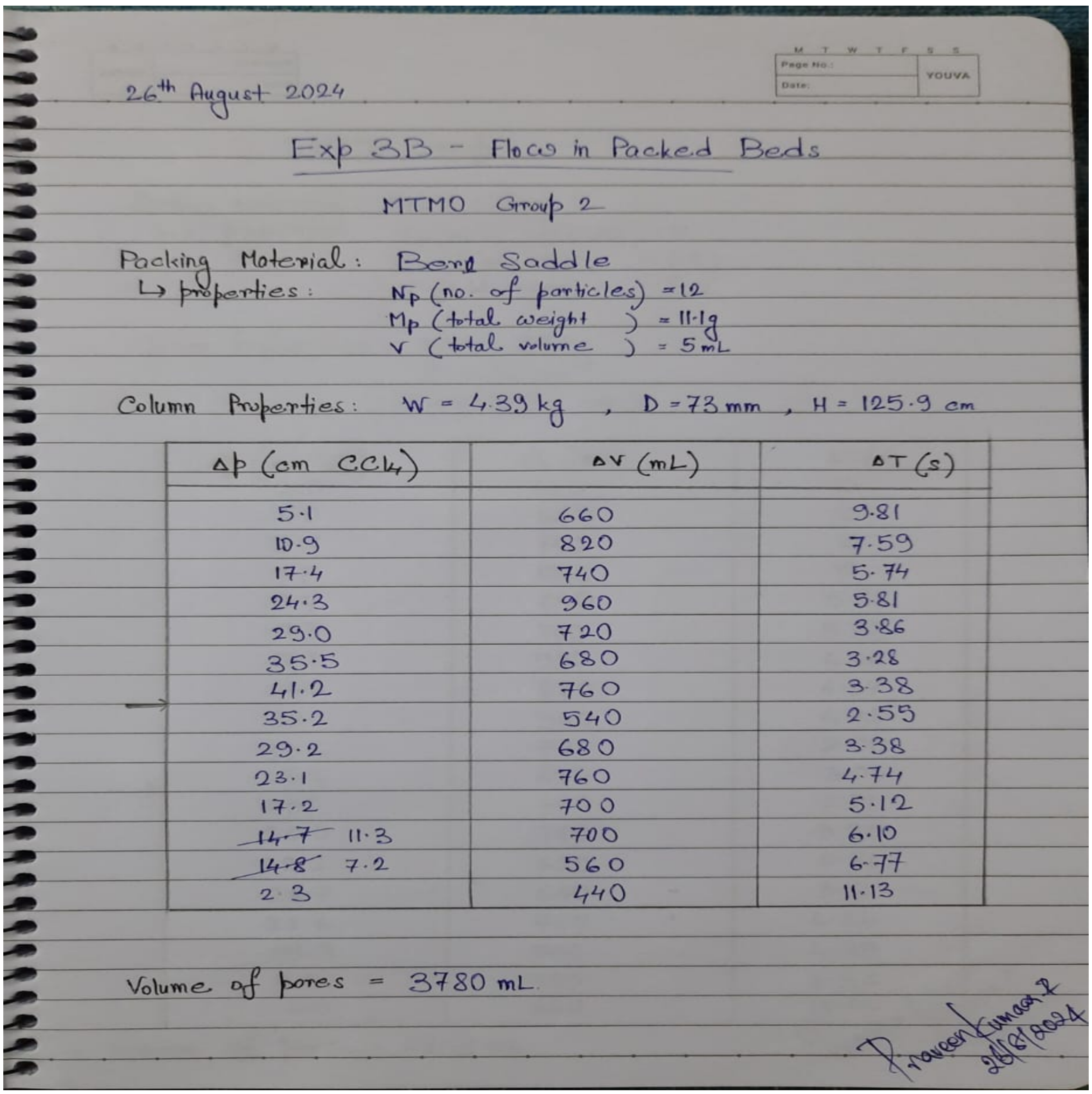
- CH2015 : Fluid and Particle Mechanics course notes
- 'Flow through Packed and Fluidized Beds' | Shankar Balasubramanian | Clarkson University [https://people.clarkson.edu/projects/subramanian/ch330/notes/Flow%20Through%20Packed%20and%20Fluidized%20Beds.pdf]
- Lattice Boltzmann investigation on fluid flows through packed beds: Interaction between fluid rheology and bed properties [https://www.sciencedirect.com/science/article/pii/S0032591020304150?ref=pdf_download&fr=RR-2&rr=8bc746546b9d9365]
- Lattice Boltzmann investigation of non-Newtonian fluid flow through a packed bed of uniform spheres [https://www.sciencedirect.com/science/article/pii/S0032591018309501]

Appendix

Lab Data: All the experimental observations with each of the columns the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures 13, 14, 15).

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_3B. 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 in this report.



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26th August 2024

Exp 3B – Flow in Packed Beds

MTMO Group 2

Packing Material: Berl Saddle

↳ properties: N_p (no. of particles) = 12

M_p (total weight) = 11.1 g

V (total volume) = 5 mL

Column Properties: W = 4.39 kg, D = 73 mm, H = 125.9 cm

Δp (cm CCl_4)	ΔV (mL)	ΔT (s)
5.1	660	9.81
10.9	820	7.59
17.4	740	5.74
24.3	960	5.81
29.0	720	3.86
35.5	680	3.28
41.2	760	3.38
35.2	540	2.55
29.2	680	3.38
23.1	760	4.74
17.2	700	5.12
~~14.7~~ 11.3	700	6.10
~~14.8~~ 7.2	560	6.77
2.3	440	11.13

Volume of pores = 3780 mL

Praveen Kumar R 26/8/2024

Figure 13: Data for Berl Saddle as packing material

MTMO Group 2

Packing material: Raschig Ring

↳ properties: N_p (no. of particles) = 15

M_p (total mass) = 8.8 g

V (total volume) = 3 mL

Column Properties: W = 3.37 kg

D = 73 mm

H = 125.9 cm

ΔP (cm H_2O)	ΔV (mL)	ΔT (s)
2.0	440	10
4.0	660	10
5.7	840	10
7.5	1000	10
9.4	640	5.38
11.3	700	5.38
17.1	920	6.06
24.6	880	4.84
32.1	940	4.35
39.6	700	2.90
→ 45.4	840	3.04
41.5	660	2.71
36.0	780	3.30
32.2	620	2.76
26.7	640	3.16
22.6	780	4.34
15.3	700	4.85
9.5	960	8.36
4.0	660	10.06

Volume of pores = 4240 mL.

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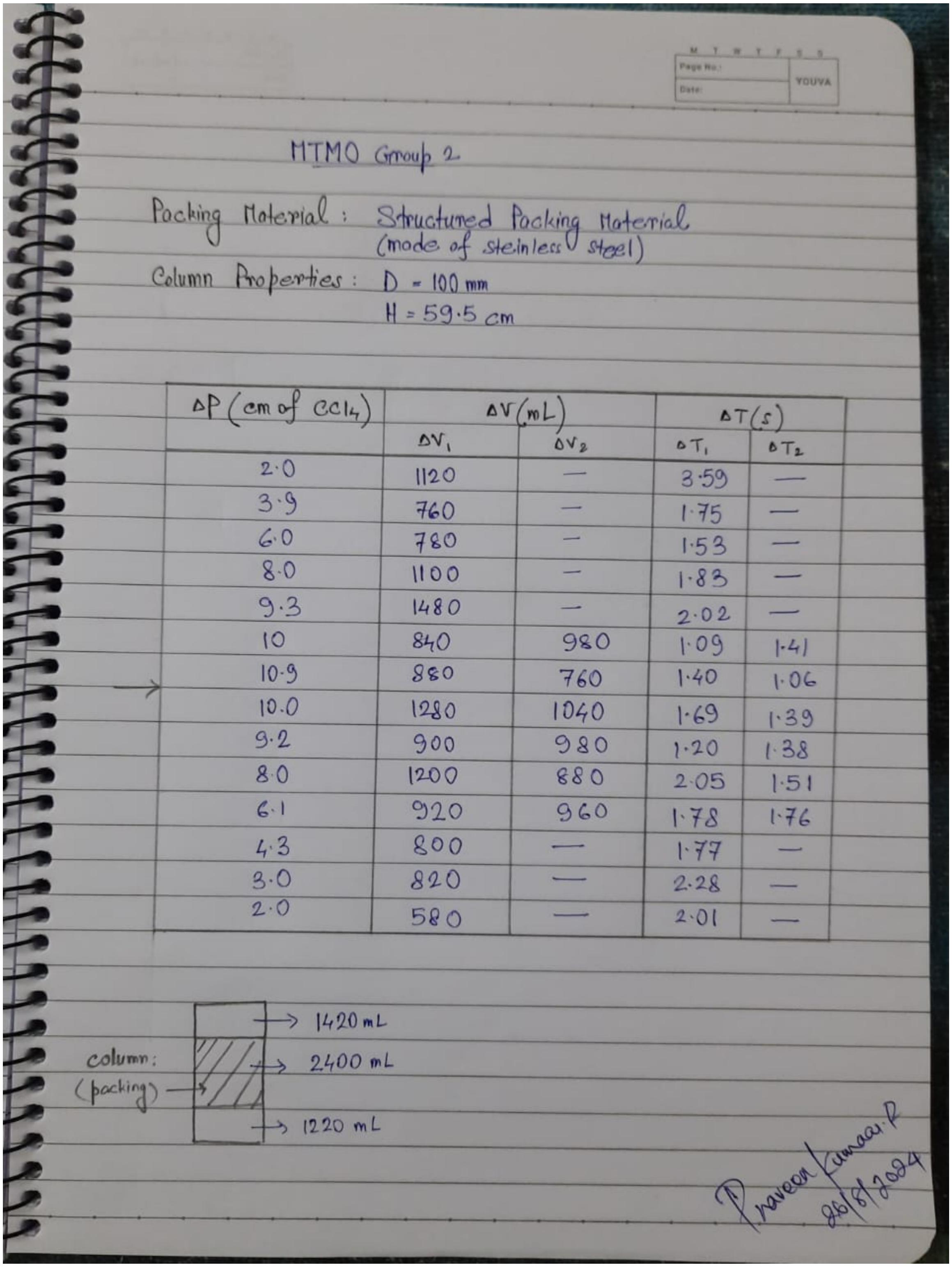
Figure 14: Data for Raschig Ring as packing material



MTMO Group 2

Packing Material : Structured Packing Material (made of stainless steel)

Column Properties : D = 100 mm
H = 59.5 cm

ΔP (cm of CCl_4)	ΔV (mL)		ΔT (s)	
	ΔV_1	ΔV_2	ΔT_1	ΔT_2
2.0	1120	—	3.59	—
3.9	760	—	1.75	—
6.0	780	—	1.53	—
8.0	1100	—	1.83	—
9.3	1480	—	2.02	—
10	840	980	1.09	1.41
10.9	880	760	1.40	1.06
10.0	1280	1040	1.69	1.39
9.2	900	980	1.20	1.38
8.0	1200	880	2.05	1.51
6.1	920	960	1.78	1.76
4.3	800	—	1.77	—
3.0	820	—	2.28	—
2.0	580	—	2.01	—

column:
(packing)
1420 mL
2400 mL
1220 mL

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Figure 15: Data for Structured packing material