Momentum Transfer and Mechanical Operations Lab

Stokes Law - Particle Sedimentation Studies

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Team: MTMO 2

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1 Abstract with Schematics

In this experiment, we investigated the settling behaviour of calcium carbonate ($CaCO_3$) particles in water under various conditions. The primary objectives were to determine the influence of height and concentration on settling behaviour, calculate the terminal velocity and average particle diameter, and plot the interface velocity against concentration from the height versus time data. We prepared four different concentrations of $CaCO_3$-water mixtures (5%, 10%, 15%, and 20% by weight of $CaCO_3$ in 1200 mL of water) and observed their settling in a sedimentation column. The settling time was recorded using a stopwatch, and the interface height was measured at various time intervals. The terminal velocity and average particle diameter were calculated using Stokes's law, and the settling velocity was determined from the interface velocity formula.

The results were plotted against concentration,the inverse relationship between concentration and settling velocity was confirmed, the free and hindered settling zones were identified. The study also found that the volume of the mixture had a significant impact on settling velocity, with larger volumes resulting in slower settling rates. The experiment also explored the effect of volume on settling velocity at a constant concentration of

5%. The results indicated that the settling velocity was highest when the concentration was 5% and the water volume was 1200 mL. Error analysis was conducted, considering instrument error and practical challenges such as determining the precise interface level and time-lag issues.

1.1 Schematics

Preparation of CaCO3 - Water mixtures

- Mix 5%, 10%, 15%, and 20% by weight of $CaCO_3$ in 1200 mL of water.
- Stir it well to ensure even dispersion.

Setting up the Sedimentation column

- Pour mixture into columns.
- Record initial height.

Collecting the data

- Start stopwatch.
- Measure interface height at regular intervals.
- Record time when the interface reaches certain heights.

Repeating for different Concentrations

- Use the other three columns and repeat steps for 10%, 15%, and 20% mixtures.
- Collect the data by using stopwatch.

$$\Downarrow$$

Performing it again for 4 columns with different diameters

$$\Downarrow$$

Then comes the calculations, conclusive remarks and error analysis parts done in the report with the experimental observations.

2 Aim

- Determine the effect of height and concentration on settling behaviour.
- Identify the settling zones (free and hindered).
- Determine the terminal velocity and the average particle diameter.
- Determine the settling velocity and plot interface velocity to concentration from height vs time plot.

3 Background and Motivation

Sedimentation is a key process in both natural and industrial applications, crucial for operations like water treatment and mineral processing. Understanding sedimentation behavior is essential for Chemical Engineers, as it directly impacts the design of equipment like settlers and clarifiers.

Stokes's Law offers a theoretical basis for predicting the settling velocity of particles in a fluid, linking it to factors like particle size, fluid viscosity, and density differences.

This study aims to experimentally validate Stokes's Law by examining the sedimentation of calcium carbonate ($CaCO_3$) particles. By exploring how variables such as concentration and height affect settling behavior, the experiment seeks to enhance the practical understanding of sedimentation, providing valuable insights for optimizing related industrial processes.

The net drag force (F_d) on a spherical particle moving in a fluid with $Re < 1$ is given by

$$F_d = 6\pi(\eta)(r)(u_t) \tag{1}$$

where, r = radius of sphere, η = dynamic viscosity of fluid & u_t = velocity of particle in fluid.

$CaCO_3$ is sparingly soluble in water. It forms a milky-white suspension that settles down slowly over time. There are 3 zones formed during sedimentation: free settling zone (also known as discrete settling zone), hindered settling zone, and compression zone, explained using the diagram below (figure 1):

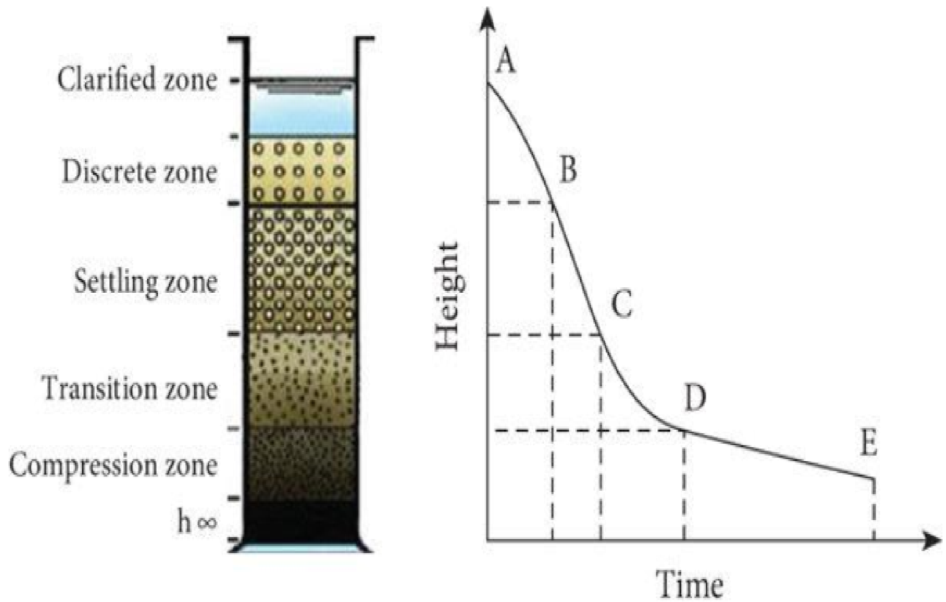


Figure 1: Stages of Particle Sedimentation

4 Materials and Methods

4.1 Apparatus Required

Metre Scale, Sedimentation columns, Beaker, Stopwatch, Rubber cork, Stirrer.

4.2 Materials Used

$CaCO_3$, Distilled water.

4.3 Experimental Setup Description

The experimental setup is shown in figure 2, which consists of two parts, (2a) & (2b) are the two sub-parts of the experiment.

Sedimentation Columns:

(a) 4 Columns of similar size (b) 4 Columns of different sizes

Figure 2: Setup for Particle Sedimentation Studies

- Four transparent sedimentation columns, each with a scale to measure sediment height.

Materials:

- *Calcium Carbonate ($CaCO_3$) Powder*: Used to prepare 5%, 10%, 15%, and 20% (w/w) mixtures.
- *Water*: Each $CaCO_3$-water mixture was made using 1200 mL water.

Beaker:

- A single beaker used to sequentially prepare each $CaCO_3$-water mixture.

Mixing Equipment:

- A stirring rod to evenly disperse $CaCO_3$ in water within the beaker.

Filling Process:

- The prepared $CaCO_3$-water mixture is directly poured into the sedimentation columns.

Timing Device:

- A stopwatch to measure the settling time of the sediment in each column.

Cleaning Equipment:

- A water source to rinse the beaker and sedimentation columns between different mixture preparations.

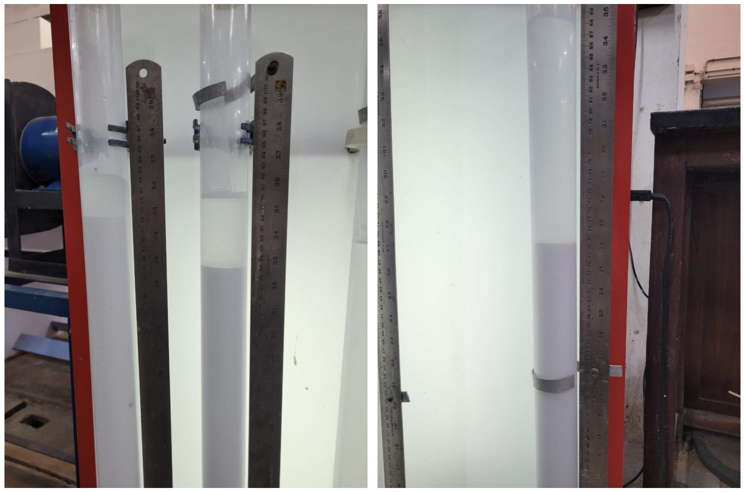


Figure 3: Scales used to observe the lower meniscus of the sedimentation ring of the solution

4.4 Procedure

- Prepare four different concentrations of 5%, 10%, 15%, and 20% $CaCO_3$ solutions in 1200 mL water each. Stir each mixture well until the powder is evenly dispersed.
- Fill a sedimentation column with water up to the marked level. The column should have a transparent wall and a scale to measure the height of the sediment.
- Pour the solutions one by one in 4 different sedimentation columns and wait till the solution forms a ring.
- Start the stopwatch when the ring touches a certain reading and note down the time for each reading thereafter.
- Next, take the 5% $CaCO_3$ solution and pour it down into 4 columns of different diameters. Start the stopwatch and record the time every 1 cm of settling.
- Once enough records have been observed, drain the columns and rinse them with water.

5 Calculations & Tabulations

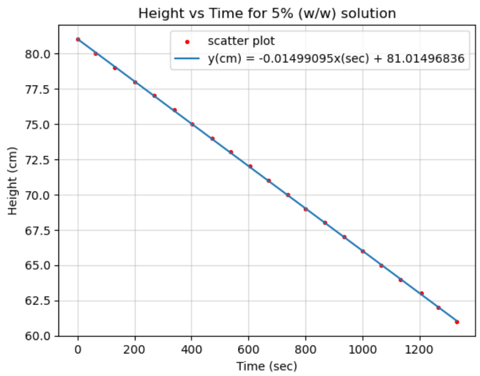
The following two tables (table 1 & 2) contain the observation made during the experiment.

5.1 Observation Tables

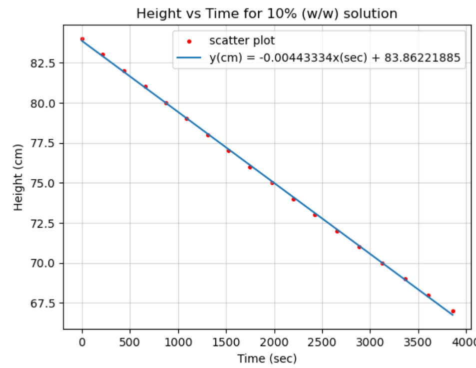
Experiment Part A : Column Diameter = 42.50 mm							
20 % (w/w)		15 % (w/w)		10 % (w/w)		5 % (w/w)	
Height	Time	Height	Time	Height	Time	Height	Time
91	00:00.00	87	00:00.00	84	00:00.00	81	00:00.00
90	24:41.75	86	14:27.53	83	03:35.36	80	01:01.63
89	48:21.55	85	29:10.11	82	07:16.76	79	02:10.32
88	1:10:20.02	84	44:11.84	81	10:56.14	78	03:20.02
87	1:34:19.46	83	59:22.86	80	14:35.73	77	04:28.15
-	-	82	1:14:40.44	79	18:08.11	76	05:38.69
-	-	81	1:27:42.41	78	21:50.79	75	06:42.71
-	-	80	1:41:02.01	77	25:26.70	74	07:51.39
-	-	-	-	76	29:08.00	73	08:57.78
-	-	-	-	75	32:55.57	72	10:04.35
-	-	-	-	74	36:42.24	71	11:10.46
-	-	-	-	73	40:25.58	70	12:16.74
-	-	-	-	72	44:17.33	69	13:19.74
-	-	-	-	71	48:07.59	68	14:29.22
-	-	-	-	70	52:01.42	67	15:34.75
-	-	-	-	69	56:01.25	66	16:41.91
-	-	-	-	68	1:00:05.01	65	17:46.59
-	-	-	-	67	1:04:18.30	64	18:52.34
-	-	-	-	-	-	63	20:06.12
-	-	-	-	-	-	62	21:06.10
-	-	-	-	-	-	61	22:10.41

Table 1: Tabulation of sedimentation in different conc of $CaCO_3$

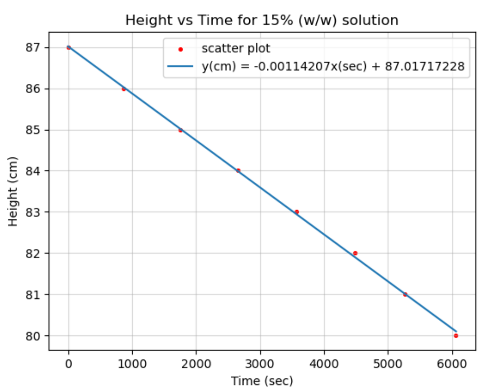
5.2 Plots corresponding to Exp - Part A (Table 1)



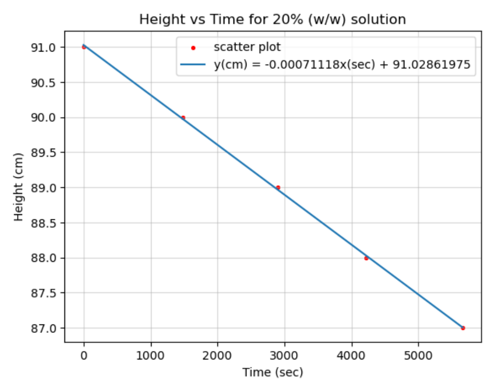
(a) With 5% $CaCO_3$ Solution. The instantaneous velocity comes out to be = 0.01499095 cm/s



(b) With 10% $CaCO_3$ Solution. The instantaneous velocity comes out to be = 0.00443334 cm/s



(c) With 15% $CaCO_3$ Solution. The instantaneous velocity comes out to be = 0.00114207 cm/s



(d) With 20% $CaCO_3$ Solution. The instantaneous velocity comes out to be = 0.00071118 cm/s

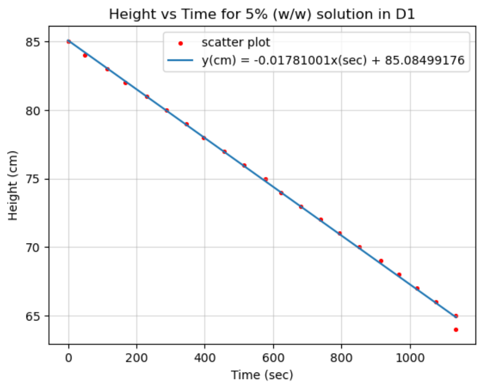
Figure 4: Instantaneous velocity becomes constant as linear regression is performed. This is because it's believed that there is a linear relationship between the independent and the dependent variables of concern and theoretically it comes under the settling region.

In the **result** section these instantaneous velocity values are used as practical terminal/settling velocity values obtained from the experimental observations. If we have performed polynomial regression then other than linear, the theoretical improvement won't be much thoroughly implying the system to be in settling region. Now it's completely on the calculation part which will specify which kind of settling between free and hindered.

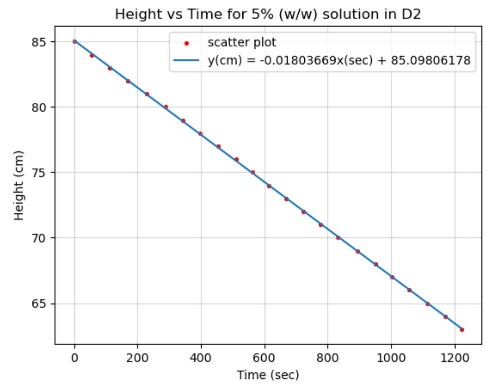
Experiment Part B : $CaCO_3$ concentration = 5 % (w/w)							
D_1 = 22.30 mm		D_2 = 17.88 mm		D_3 = 11.70 mm		D_4 = 5.80 mm	
Height	Time	Height	Time	Height	Time	Height	Time
85	00:49.21	85	00:00.00	85	00:00	90	00:00.00
84	01:53.99	84	00:56.18	84	01:26	89	00:49.47
83	02:47.71	83	01:53.23	83	02:50	88	01:45.57
82	03:50.25	82	02:49.38	82	04:14	87	02:37.21
81	04:48.35	81	03:48.04	81	05:39	86	03:26.93
80	05:45.99	80	04:48.04	80	07:03	85	04:16.19
79	06:37.33	79	05:41:80	79	08:28	84	05:11.45
78	07:36.49	78	06:37.98	78	09:53	83	06:11.76
77	08:35.07	77	07:35.09	77	11:16	82	07:03.98
76	09:37.09	76	08:30.57	76	12:38	81	07:55.69
75	10:21.85	75	09:23.79	75	14:02	80	08:45.36
74	11:21.53	74	10:14.24	74	15:27	79	09:37.07
73	12:17.28	73	11:08.98	73	16:54	78	10:32.01
72	13:14.96	72	12:03.27	72	18:16	77	11:26.73
71	14:11.48	71	12:57.17	71	19:36	76	12:18.99
70	15:13.56	70	13:51.17	70	20:58	75	13:09.45
69	16:08.43	69	14:53.82	69	22:23	74	14:07.61
68	17:00.93	68	15:50.66	68	23:45	73	14:54.99
67	17:56.14	67	16:43.18	67	25:07	72	15:46.91
66	18:52.67	66	17:37.03	66	26:30	71	16:38.79
65	19:54.91	65	18:34.47	65	27:54	70	17:28.82
-	-	64	19:30.11	-	-	69	18:15:92
-	-	63	20:23.53	-	-	68	19:12.59

Table 2: Tabulation of sedimentation in columns of different diameters

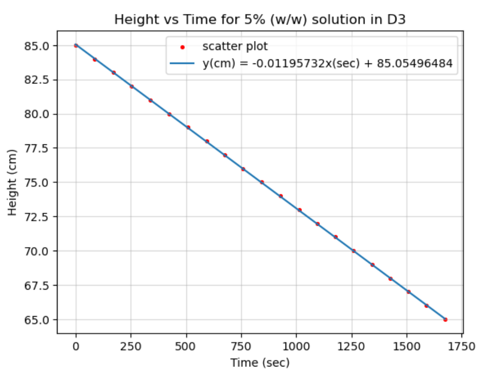
5.3 Plots corresponding to Exp - Part B (Table 2)



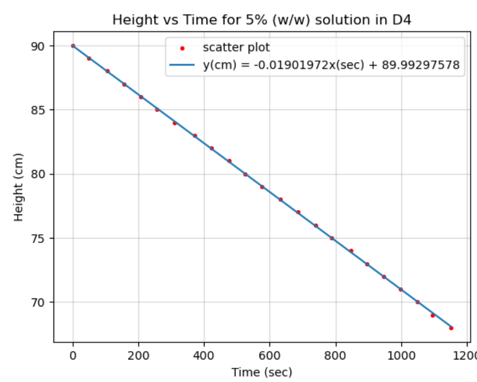
(a) With 5% $CaCO_3$ Solution in D1 column. The instantaneous velocity comes out to be = 0.01781001 cm/s



(b) With 5% $CaCO_3$ Solution in D2 column. The instantaneous velocity comes out to be = 0.01803669 cm/s



(c) With 5% $CaCO_3$ Solution in D3 column. The instantaneous velocity comes out to be = 0.01195732 cm/s



(d) With 5% $CaCO_3$ Solution in D4 column. The instantaneous velocity comes out to be = 0.01901972 cm/s

Figure 5: Instantaneous velocity becomes constant as linear regression is performed. This is because it's believed that there is a linear relationship between the independent and the dependent variables of concern and theoretically it comes under the settling region.

6 Results & Calculations

Density values considered for calculation (external condition : 30°C temperature):
$\rho_p(CaCO_3) = 2.71\ g/cm^3$ & ρ (water) $= 0.997\ g/cm^3$

For free-settling regime, according to Stokes's law,

$$u_t(\text{theoretical}) = u_p(\text{practical}) \tag{2}$$

$$u_p = \frac{gD_p^2}{18\eta}(\rho_p - \rho) \tag{3}$$

For hindered-settling regime, according to Stokes's law,

$$u_p = u_t \cdot \epsilon^{4.5} \tag{4}$$

$$u_p = \frac{gD_p^2}{18\eta}(\rho_p - \rho)\epsilon^{4.5} \tag{5}$$

$$\text{where, } \epsilon = 1 - \frac{Hm_s}{hV_H\rho_p} \tag{6}$$

here, ϵ = volumetric fluid fraction, H = total height of the solution, m_s = mass of the solute used, h = height of the interface, V_H = total volume of the solution.

6.1 Assuming D_p is known and determining settling regime

For this case, we will be assuming that the average particle diameter is a known value. In the literature, it has been given that the D_p of $CaCO_3$ in water is in a range of 0.2 to 30 μm. As such, we will take the mean of that range and assume that -

$$D_p = 15.1\mu m \tag{7}$$

This gives us the following results (table 3):

Conc	D	u_p	N_{Re}	n	$\hat{u_p}$	Regime
5	42.50	0.01499	0.0028	25.66	0.02406	Hindered Stokes
10	42.50	0.00443	0.0008	39.35	0.02167	Hindered Stokes
15	42.50	0.00114	0.0002	47.21	0.01975	Hindered Stokes
20	42.50	0.00071	0.0001	39.95	0.01774	Hindered Stokes
5	22.30	0.01781	0.0034	17.44	0.0240	Hindered Stokes
5	17.88	0.01804	0.0034	16.66	0.0240	Hindered Stokes
5	11.70	0.01196	0.0023	34.61	0.0240	Hindered Stokes
5	5.80	0.01902	0.0036	15.41	0.0241	Hindered Stokes

Table 3: Regime of given Sedimentation Case

6.2 Assuming hindered settling regime and calculating D_p

For this case, we will be assuming that the sedimentation occurs in the Hindered-settling Stokes Regime. This means that -

$$u_t = u_p \cdot \epsilon^{-4.5} \tag{8}$$

$$D_p = \left(\frac{18\eta \cdot u_t}{g(\rho_p - \rho)}\right)^{0.5} \tag{9}$$

This gives us the following results (table 4):

Conc	D	u_p	ϵ	$\hat{u_t}$	D_p
5	42.50	0.01499	0.9771	0.0166	11.92
10	42.50	0.00443	0.9546	0.0055	6.83
15	42.50	0.00114	0.9352	0.0015	3.63
20	42.50	0.00071	0.9599	0.0011	3.02
5	22.30	0.01781	0.9767	0.0198	13.00
5	17.88	0.01804	0.9763	0.0201	13.10
5	11.70	0.01196	0.9767	0.0133	10.66
5	5.80	0.01902	0.9778	0.0210	13.40

Table 4: D_p of $CaCO_3$ particle in given sedimentation case

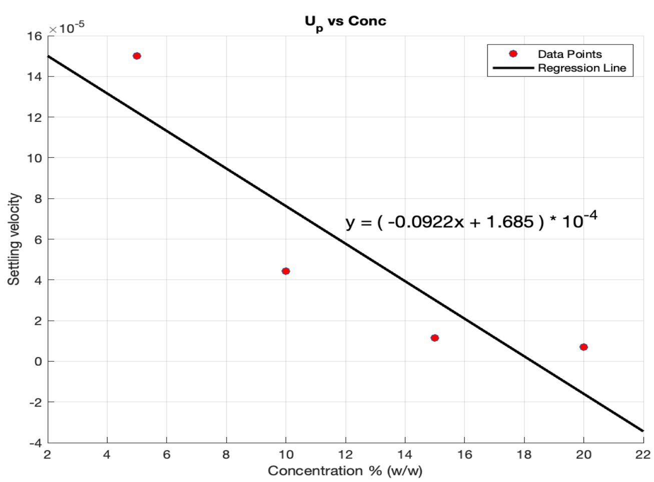
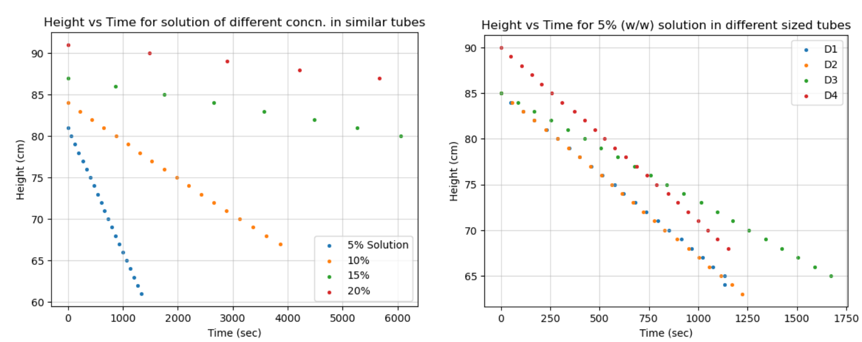


Figure 6: Interphase velocity vs Concentration observations

7 Conclusion and Remarks

- To begin with, we need to identify all of the assumptions made throughout this report. It has been assumed that $CaCO_3$ is completely insoluble in water, making $\Delta V_{MIX} = 0$. We have also considered no agglomerates have been formed by $CaCO_3$ for simpler calculations.
- Considering that the particle diameter of $CaCO_3$ is less than $30\mu m$, we can safely assume that $N_{Re} < 1$ and that the particle-fluid interactions to lie under Stokes Regime.
- From the very high values of n in the relation $u_p = u_t \cdot \epsilon^n$, it can be concluded that our system lies in the Hindered-settling region, instead of the Free-settling region.
- It is observed that the speed of the descending interface decreases (slightly) as the depth increases. This means that relation between sedimentation speed and height of interface is of the nature - $u_p \propto h^{-n}$.
- It is to be noted however, that the values of u_p come out be only slightly decreasing, making it difficult to not take it as a constant value (refer to figure 7).
- All the values of D_p calculated using the observed u_p values lie in the range defined by the literature (0.2 to 30 μm). This means that our experimental values are decent enough to be used for further calculations or remarks.



(a) Exp A - Different concentrated solutions in similar types of columns

(b) Exp B - Same 5% concentrated solution in different types of columns

Figure 7: Comparative analysis for different sedimentation columns in eac sub-parts of the experiment

8 Error Analysis

Least Count of wooden length scale $\equiv \Delta h = 1$ mm
Least Count of stopwatch $\equiv \Delta t = 0.01$ sec
Least Count of vernier caliper $\equiv \Delta D = 0.02$ mm
Least Count of weighting scale $\equiv \Delta m_s = 0.01$ g

$$\frac{\Delta u_p}{u_p} = \frac{\Delta h}{h} + \frac{\Delta t}{t} \tag{10}$$

$$\frac{\Delta \epsilon}{\epsilon} = \frac{\Delta h}{h} + \frac{\Delta m_s}{m_s} + 2 \cdot \frac{\Delta D}{D} \tag{11}$$

$$\frac{\Delta D_p}{D_p} = 0.5 \cdot \frac{\Delta u_p}{u_p} + 2.25 \cdot \frac{\Delta \epsilon}{\epsilon} \tag{12}$$

8.1 Assuming D_p is known and determining settling regime

Conc	D	u_p	$\hat{u_p}$	Error %
5	42.50	0.0150	0.0241	37.7
10	42.50	0.0044	0.0217	79.5
15	42.50	0.0011	0.0198	94.2
20	42.50	0.0007	0.0177	96.0
5	22.30	0.01781	0.0240	25.8
5	17.88	0.01804	0.0240	24.7
5	11.70	0.01196	0.0240	50.2
5	5.80	0.01902	0.0241	21.2

Table 5: Percentage error in sedimentation speed of $CaCO_3$

9 Precautions

- Accurately weigh the $CaCO_3$ powder for each concentration to prevent discrepancies in the experimental results.
- Utilize precise measuring instruments for determining water volumes to maintain consistency across all solutions.

- Thoroughly mix the $CaCO_3$ solutions to ensure the even dispersion of particles, as incomplete mixing may result in inconsistent settling behavior.
- Ensure that sedimentation columns are impeccably clean and devoid of any residual contaminants. Any remaining particles could adversely affect the settling behavior of the new solutions.
- Verify that the sedimentation columns are correctly calibrated and that the measurement scale is clearly visible. Misalignment or erroneous readings may lead to inaccuracies in recording sediment heights.
- Position the sedimentation columns on a stable, vibration-free surface to avoid any external disturbances that could disrupt the settling process during the experiment.

10 Thought Question / Open-Ended

Q. How will you perform your particle sedimentation experiment if we replace the water with cornstarch-water mixture? Explain what equations and expressions will you consider adding to your Stoke's Law for enabling such a change? (Explanations should relate to the experiment you performed in the lab)

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 and suspended media is done by referring from two scholarly articles mentioned in the **references** section & from this study we as a team have come up with this possible answer)

Challenges with the new mixture:

- The cornstarch-water mixture is a classic example of a **non-Newtonian** fluid, specifically a **shear-thickening** fluid. This means that its viscosity increases when a force is applied (not constant) and it depends on the shear rate.
- Cornstarch particles do not dissolve in water; instead, they form a suspension. The fluid becomes more viscous as the shear rate increases, which means the sedimentation process will be slower than in a Newtonian fluid.

Experimental Concerns: With this mixture we need to incorporate some changes in our procedure to conduct the experiment, which are as follows:

- As the concentration of the mixture affects the viscosity and shear-thickening behavior, while preparing the mixture we need to give special care as well as the shear history as how this mixture is handled.

- It may exhibit more complex behaviour, hence we need powerful cameras to keep a track of the process. The settling process may be slower and more variable. Hence it needs to be monitored for a longer time.
- Given the non-linear nature of the sedimentation in a non-Newtonian fluid, we may need to conduct several trials with varying cornstarch concentrations and particle sizes to understand the full range of behaviors.

Mathematical Changes: In order to handle the shear effect on the sedimentation of this non-Newtonian fluid, some more variables need to be incorporated in the Stokes's formula used in case of $CaCO_3$-water mixture (eq 3, 4, 5).

- **For free-settling regime**, for non-Newtonian fluid,

$$u_p = \frac{gD_p^2}{18\eta_{eff}(\hat{\gamma})}(\rho_p - \rho) \tag{13}$$

- **For hindered-settling regime**, for non-Newtonian fluid,

$$u_p = \Big(\frac{gD_p^2}{18\eta_{eff}(\hat{\gamma})}(\rho_p - \rho)\Big)\epsilon^{4.5} \tag{14}$$

  where, $\eta_{eff}(\hat{\gamma})$ is the effective viscosity, which is a function of the shear rate $\hat{\gamma}$. The shear rate $\hat{\gamma}$ near a settling particle can be approximated as

$$\hat{\gamma} \equiv \frac{u_p}{D_p} \tag{15}$$

  So the effective viscosity $\eta_{eff}(\hat{\gamma})$ will change with the particle's velocity, making the equation implicit. We may need to solve it iteratively or use a power-law model for viscosity.

11 Acknowledgements

We as a group contributed our respective parts into completing the above report on Stokes's Law - Particle Sedimentation Studies.

In terms of specifications, Rapolu Paranay Reddy helped with "Apparatus & Materials"; "Experimental Setup Description" for 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, we wrote as per our understanding. Therefore no such transcript is provided in the **Appendix** section.

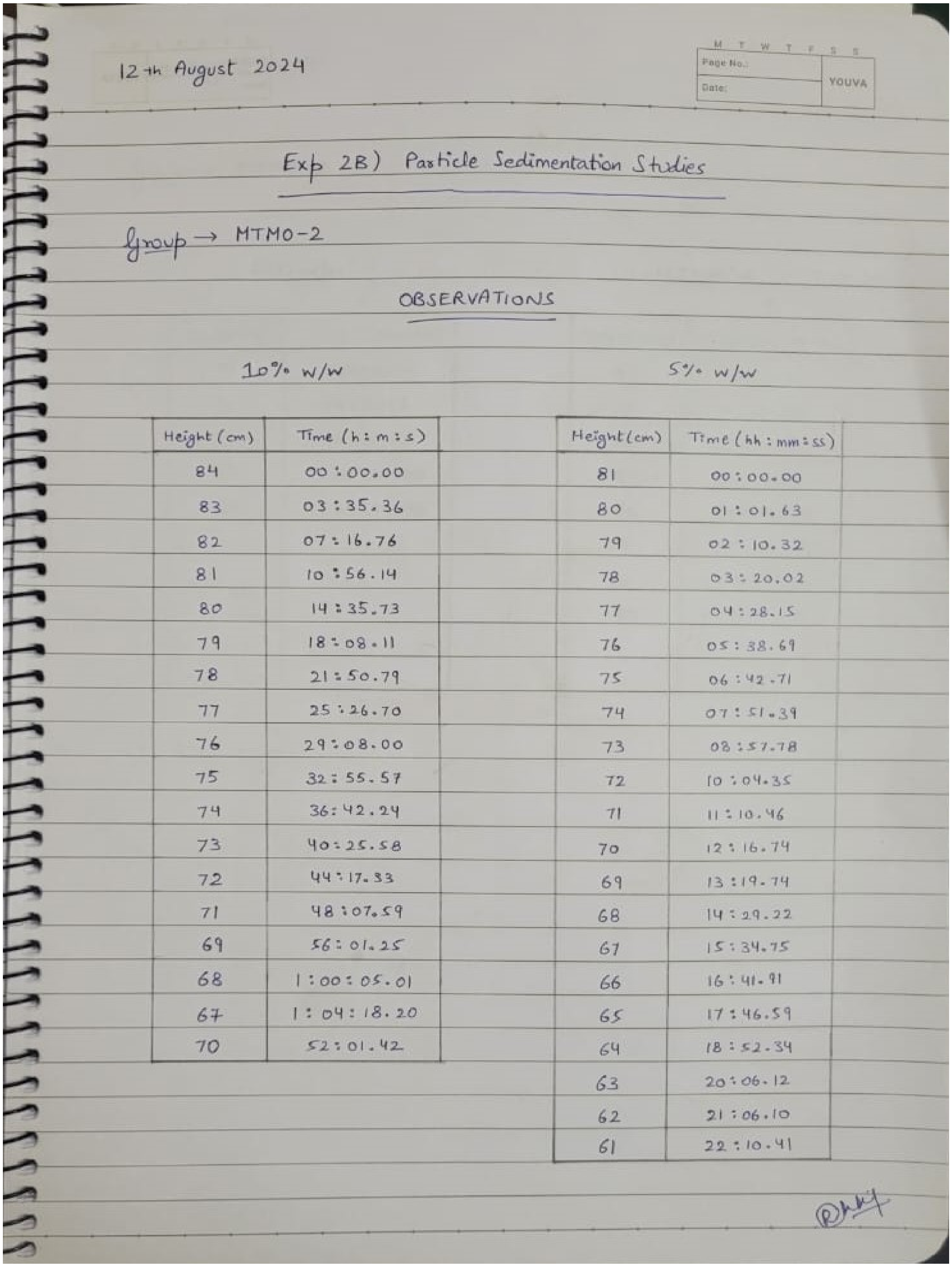
References

- Fox and McDonald's Introduction to Fluid Mechanics, 8th edition
- CH2015 : Fluid and Particle Mechanics course notes
- Study on Stokes's Regime: https://en.wikipedia.org/wiki/Stokes%27_law
- Study on Particle Sedimentation: https://en.wikipedia.org/wiki/Sedimentation
- Study on Sedimentation in Non-newtonian fluids: https://www.researchgate.net/publication/335023062_Newtonian_and_Non-Newtonian_sediment_fluid_flow_hydrodynamic_runoff_model
- Analysis of suspension sedimentation in fluids with rheological shear-thinning properties and thixotropic effects: https://www.sciencedirect.com/science/article/pii/S0032591016309032?ref=pdf_download&fr=RR-2&rr=8b5380498b449373

Appendix

Lab Data: All the experimental observations with each of the 4 liquid columns in each of sub-parts of the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures 8, 9, 10, 11).

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_2B. 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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Exp 2B) Particle Sedimentation Studies

Group → MTMO-2

OBSERVATIONS

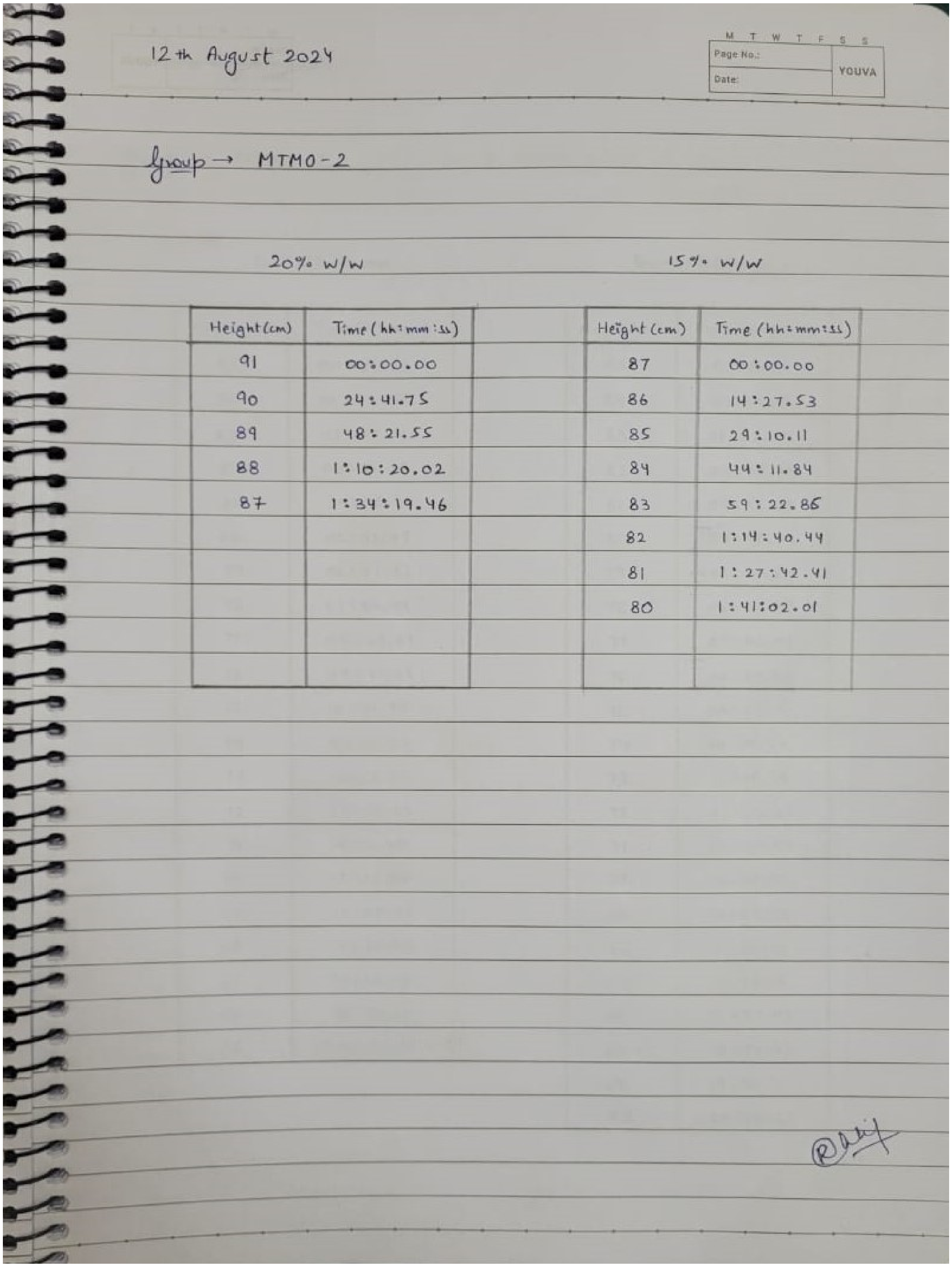
10% w/w

Height (cm)	Time (h : m : s)
84	00 : 00.00
83	03 : 35.36
82	07 : 16.76
81	10 : 56.14
80	14 : 35.73
79	18 : 08.11
78	21 : 50.79
77	25 : 26.70
76	29 : 08.00
75	32 : 55.57
74	36 : 42.24
73	40 : 25.58
72	44 : 17.33
71	48 : 07.59
69	56 : 01.25
68	1 : 00 : 05.01
67	1 : 04 : 18.20
70	52 : 01.42

5% w/w

Height (cm)	Time (hh : mm : ss)
81	00 : 00.00
80	01 : 01.63
79	02 : 10.32
78	03 : 20.02
77	04 : 28.15
76	05 : 38.69
75	06 : 42.71
74	07 : 51.39
73	08 : 57.78
72	10 : 04.35
71	11 : 10.46
70	12 : 16.74
69	13 : 19.74
68	14 : 29.22
67	15 : 34.75
66	16 : 41.91
65	17 : 46.59
64	18 : 52.34
63	20 : 06.12
62	21 : 06.10
61	22 : 10.41

Figure 8: Data for 5% & 10% conc $CaCO_3$ studied in similar types of columns



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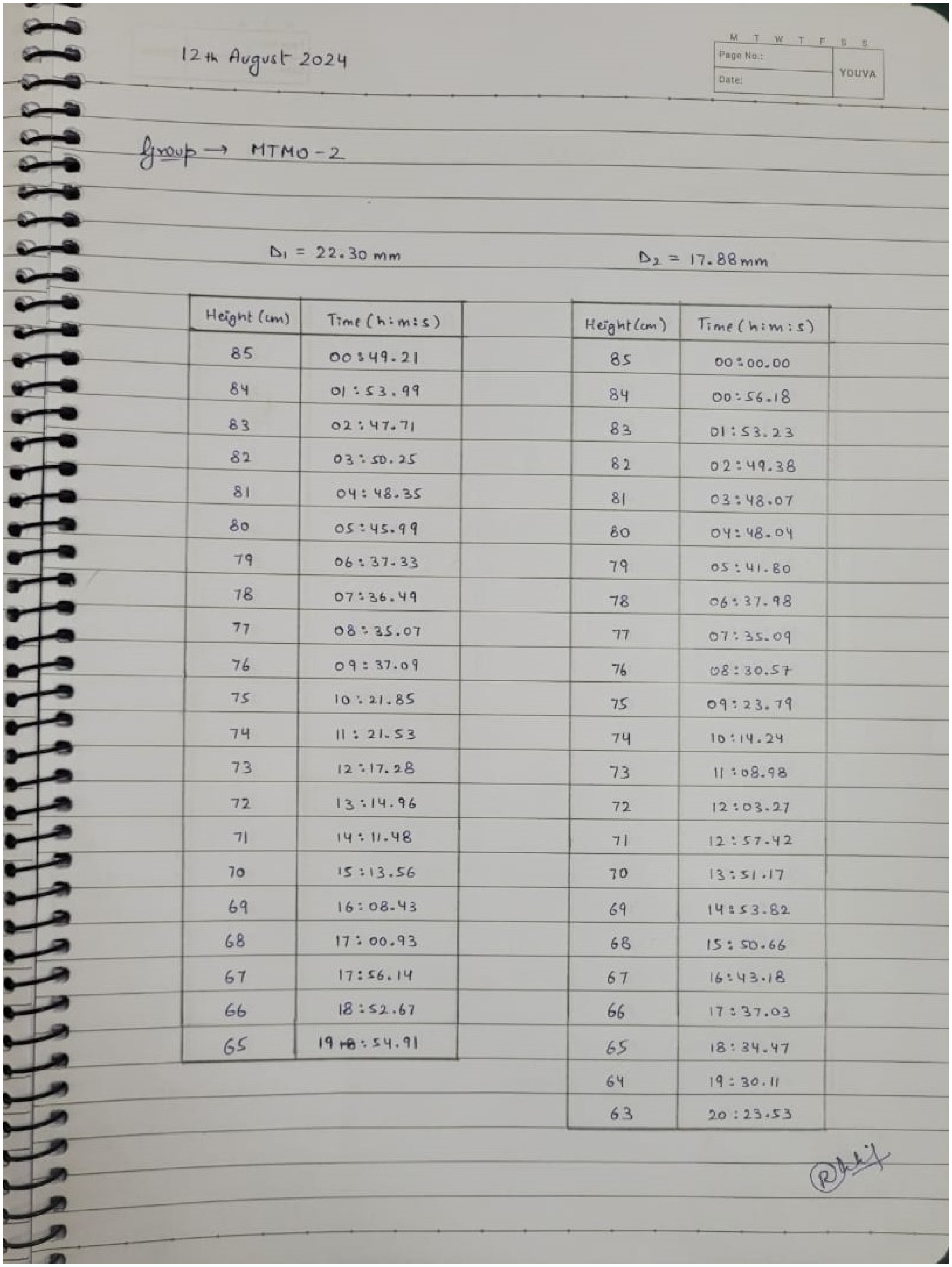
20% w/w

Height (cm)	Time (hh:mm:ss)
91	00:00.00
90	24:41.75
89	48:21.55
88	1:10:20.02
87	1:34:19.46

15% w/w

Height (cm)	Time (hh:mm:ss)
87	00:00.00
86	14:27.53
85	29:10.11
84	44:11.84
83	59:22.86
82	1:14:40.44
81	1:27:42.41
80	1:41:02.01

Figure 9: Data for 15% & 20% conc $CaCO_3$ studied in similar types of columns



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Group → MTMO-2

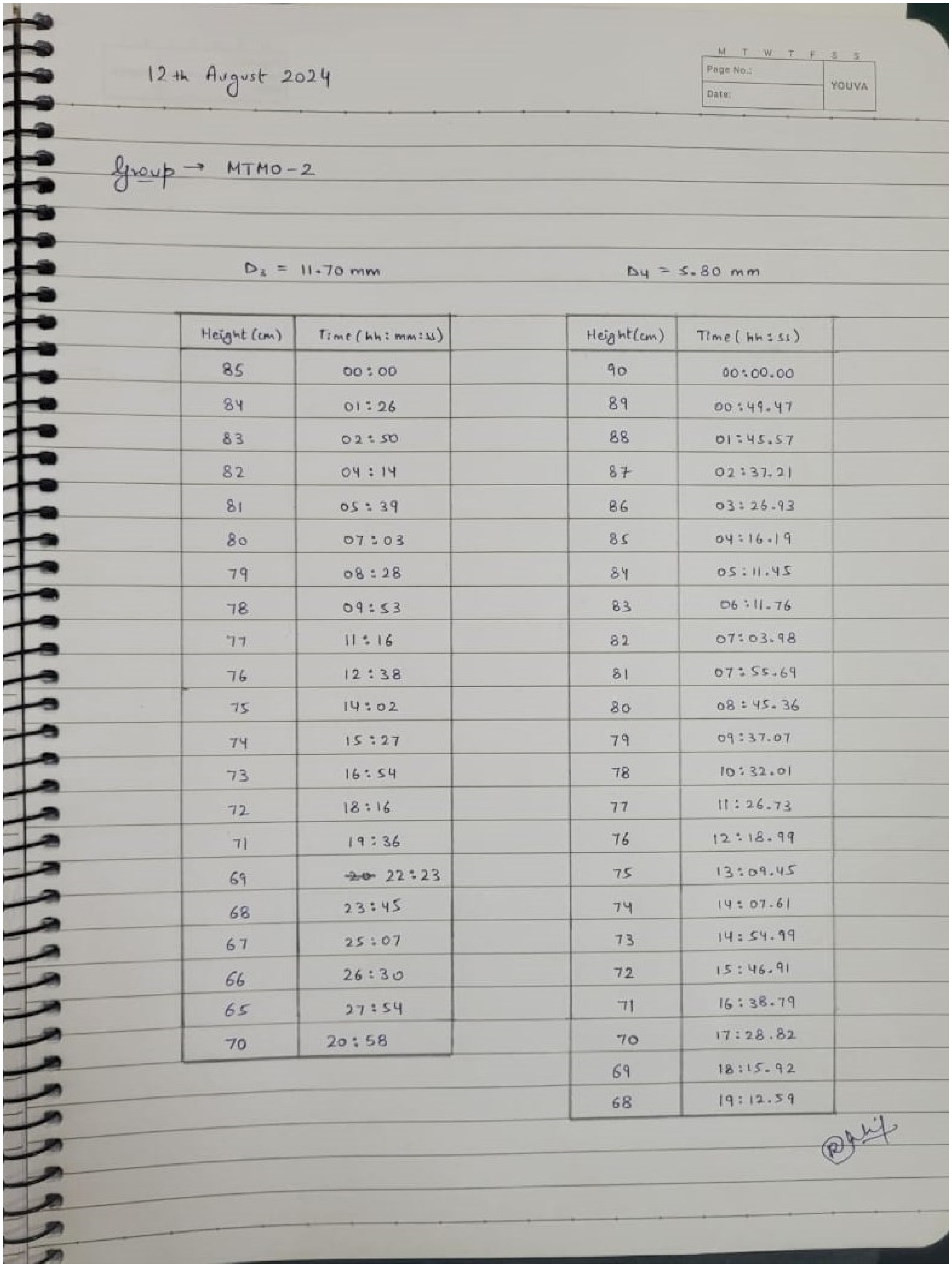
D_1 = 22.30 mm

Height (cm)	Time (h:m:s)
85	00:49.21
84	01:53.99
83	02:47.71
82	03:50.25
81	04:48.35
80	05:45.99
79	06:37.33
78	07:36.49
77	08:35.07
76	09:37.09
75	10:21.85
74	11:21.53
73	12:17.28
72	13:14.96
71	14:11.48
70	15:13.56
69	16:08.43
68	17:00.93
67	17:56.14
66	18:52.67
65	19 ~~18~~:54.91

D_2 = 17.88 mm

Height (cm)	Time (h:m:s)
85	00:00.00
84	00:56.18
83	01:53.23
82	02:49.38
81	03:48.07
80	04:48.04
79	05:41.80
78	06:37.98
77	07:35.09
76	08:30.57
75	09:23.79
74	10:14.24
73	11:08.98
72	12:03.27
71	12:57.42
70	13:51.17
69	14:53.82
68	15:50.66
67	16:43.18
66	17:37.03
65	18:34.47
64	19:30.11
63	20:23.53

Figure 10: Data for 5% conc $CaCO_3$ studied under liquid columns with diameter D_1 & D_2



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Group → MTMO-2

D_3 = 11.70 mm

Height (cm)	Time (hh : mm : ss)
85	00 : 00
84	01 : 26
83	02 : 50
82	04 : 14
81	05 : 39
80	07 : 03
79	08 : 28
78	09 : 53
77	11 : 16
76	12 : 38
75	14 : 02
74	15 : 27
73	16 : 54
72	18 : 16
71	19 : 36
69	~~20~~ 22 : 23
68	23 : 45
67	25 : 07
66	26 : 30
65	27 : 54
70	20 : 58

D_4 = 5.80 mm

Height (cm)	Time (hh : ss)
90	00 : 00.00
89	00 : 49.47
88	01 : 45.57
87	02 : 37.21
86	03 : 26.93
85	04 : 16.19
84	05 : 11.45
83	06 : 11.76
82	07 : 03.98
81	07 : 55.69
80	08 : 45.36
79	09 : 37.07
78	10 : 32.01
77	11 : 26.73
76	12 : 18.99
75	13 : 09.45
74	14 : 07.61
73	14 : 54.99
72	15 : 46.91
71	16 : 38.79
70	17 : 28.82
69	18 : 15.92
68	19 : 12.59

Figure 11: Data for 5% $CaCO_3$ studied under liquid columns with diameter D_3 & D_4