Momentum Transfer and Mechanical Operations Lab

Flow through Pipes, Bends and Fittings & Hydrodynamic Visualization of Microfluidic Two Phase Flow

21st October, 2024

Team: MTMO 2

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Abstract with Graphics

In this experiment, we examined fluid dynamics in straight pipes, bends (figure 1), and microchannels to understand the impact of various factors on pressure drop and frictional losses. The experiment was divided into two parts.

The first part aimed to determine the pressure drop and friction factor for water flow through pipes of different diameters and to study the relationship between Darcy's friction factor and Reynolds number. Data from various flow rates allows us to plot the friction factor against the Reynolds number, revealing insights into laminar and turbulent flow regimes and the impact of pipe roughness on pressure drop.

The second part focused on observing and analyzing flow patterns in a microfluidic channel with two immiscible fluids, PEG600 and Na_2SO_4. This portion highlighted different flow regimes, such as slug flow and stratified flow, based on variations in flow

rate. These microchannel flow behaviors are significant in applications involving two-phase flow, such as in chemical reactors, heat exchangers, and biomedical devices. The flow observations provided a microscopic understanding of fluid interactions influenced by surface tension and pressure gradients, which are essential for optimising fluidic device design.

Our findings provide insights into fluid behaviour in pipes and microchannels, which are crucial for designing and optimising chemical reactors, separation systems, and other related devices. The experiment underscores the importance of understanding fluid dynamics in both macro and micro scales for efficient industrial processes.

A. Flow through Straight Pipes, Bends and Fittings

Figure 1

1 Aim & Objectives

- To determine the pressure drop and the friction factor for fluid flow in given setup.
- To obtain log f vs log Re graph for the different pipes.
- Calculate entrance length (transition length) for this system.

2 Background and Motivation

In chemical engineering, efficient fluid transport through pipes and microchannels is essential for optimizing operational performance and reducing energy costs in industrial systems. When fluids move through pipes, they experience resistance due to friction with the pipe walls, which varies based on the roughness of the pipe surface and the fluid flow characteristics. This friction contributes to energy losses and can lead to fluctuations in pumping requirements, directly impacting costs. An understanding of these energy losses is critical for engineers to design systems that minimize frictional losses, thereby enhancing the efficiency and cost-effectiveness of industrial processes.

Figure 2: Structural Set-up 1 (front-side)

3 Materials and Methods

3.1 Apparatus & Materials Required

- **Materials**: Water.
- **Apparatus**: Experimental setup with different pipe connections and fittings, Pressure gauge, Flow meters, Electric motor.

Figure 3: Structural Set-up 1 (back-side)

3.2 Experimental Setup Description

The experimental setup is shown in the following figures (figures 2, 3 as first set up and figures 4, 5 as second set up), which contains two structural set-ups for which the tabulations are also provided.

- **Water Tank and Pump System**: The system is connected to an electric motor, which controls the water flow from the tank through different pipe fittings.
- **Pipe Connections and Fittings**: Various pipe fittings are installed to study the pressure differences across them.
- **Pressure Gauge**: Used to measure the inlet and outlet pressures across each fitting.
- **Flow Meters**: Installed to monitor the water flow rate through the system.

3.3 Procedure

- Connect the water tank to the electrical supply for the pump operation.
- Select a designated fitting and ensure that the pressure gauge and input valves are securely installed across this fitting.

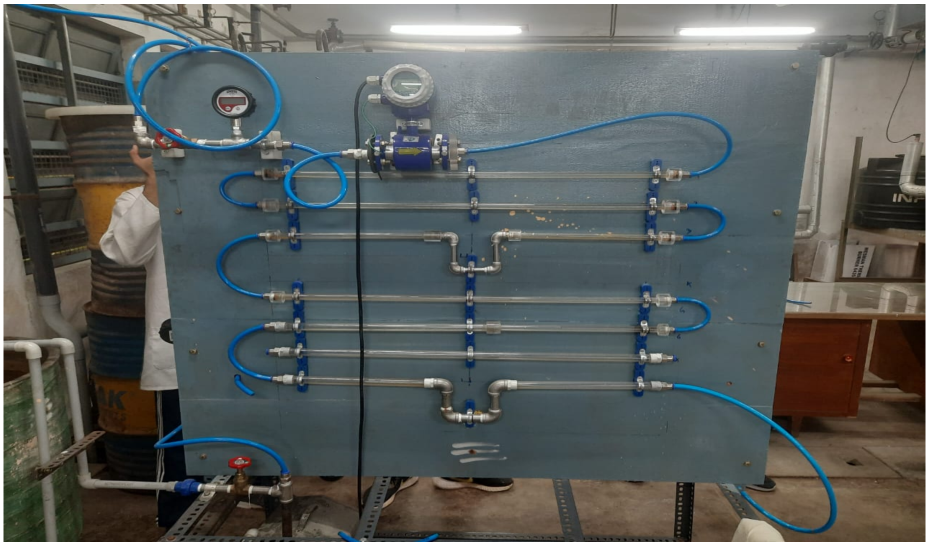


Figure 4: Structural Set-up 2 (front-side)

Figure 5: Structural Set-up 2 (back-side)

- Gradually open the inlet valve, allowing water to flow through the pipe and fitting.
- Once steady-state conditions are reached, document the volumetric flow rates along with the inlet and outlet pressure readings.
- Repeat the procedure for various valve openings (flow rates) to obtain the corresponding measurements.
- Relocate the pressure gauge to other fittings and repeat the experiment accordingly.

4 Observation Tables

The tabulations include the observed data from each of the sub-parts of the first experiment and are tabulated in the following tables (tables 1 & 2):

Q (L/Hr)	P_{in}(PSI)	P_{out}(PSI)	ΔP
118	3.1	1.8	1.3
143	5.8	3.3	2.5
166	6.5	4.0	2.5
198	10.2	6.2	4.0
225	13.0	7.6	5.4
253	16.2	9.4	6.8
278	22.0	12.9	9.1
309	24.5	14.3	10.2

Table 1: Corresponding to Structural Set-up 1 (figures 2 & 3)

Q (L/Hr)	P_{in}(PSI)	P_{out}(PSI)	ΔP
190	8.2	5.0	3.2
218	13.7	8.2	5.5
267	17.5	10.4	7.1
291	21.7	12.9	8.8
317	25.2	14.7	10.5
341	30.1	17.6	12.5
365	33.6	19.7	13.9
386	37.1	21.7	15.4
391	39.7	23.2	16.5
400	39.5	23.0	16.5

Table 2: Corresponding to Structural Set-up 2 (figures 4 & 5)

Notations used: Q = Volumetric flow rate (Liter per hour), P_{in} & P_{out} = inlet and outlet pressure respectively (in PSI), ΔP = pressure difference between inlet and outlet.

5 Theory & Calculations

Assuming that the fluid is incompressible, that the volumetric velocity remains constant throughout the system and that the system is in steady state when taking measurements, the equation for pressure drop (ΔP) becomes :

$$\Delta P = f_D \cdot \frac{\rho v^2}{2} \frac{L}{D} + \rho g H \tag{1}$$

$$v = \frac{Q}{A} = \frac{4Q}{\pi D^2} \tag{2}$$

Here, f_D is Darcy's friction factor, ρ is Density of liquid (Water), η is the viscosity, v is speed of fluid, Q is Volumetric flow rate, D is diameter of pipe, L is length of the pipe and H is drop in height.

For calculating Darcy's friction factor (f_D), we will be using the following equations :

$$Reynold's\ Number\ :\ Re = \frac{\rho v D}{\eta} \tag{3}$$

$$Laminar\ Flow\ :\ f_D = 64 \cdot Re^{-1} \tag{4}$$

$$Turbulent\ Flow\ :\ f_D = 0.3164 \cdot Re^{-1/4} \tag{5}$$

5.1 Hydrodynamic Entry Length

The hydrodynamic entry length (L_h) is the distance from the entry point to the point where velocity profile is fully developed. It can be calculated using the following equations:

$$Laminar\ Flow\ :\ L_h = 0.05 \cdot Re \cdot D \tag{6}$$

$$Turbulent\ Flow\ :\ L_h = 1.359 \cdot Re^{1/4} \cdot D \tag{7}$$

5.2 Loss Coefficient

The Loss Coefficient (K) refers to the expansion and contraction loss which occurs due to sudden change in pipe diameter. It can be calculated using the following expression :

$$K_{SE} = \left[1 - \left(\frac{D_{new}}{D_{old}}\right)^2\right]^2 \tag{8}$$

5.3 Results

The resulting plots are given in the following figures (figures 6, 7 & 8);

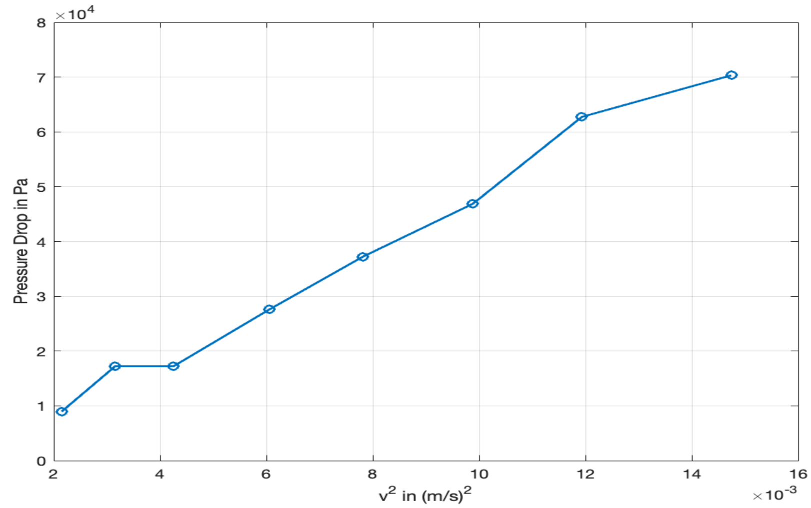


Figure 6: Setup 1 - Pressure Drop against Velocity Squared

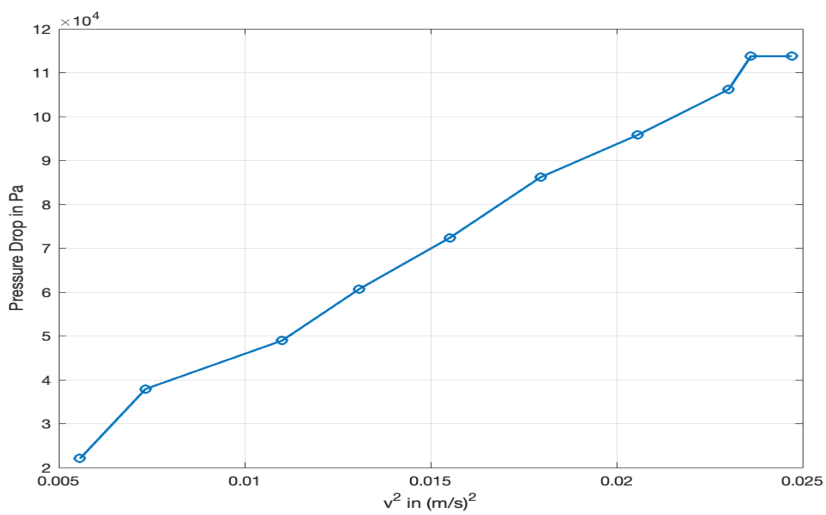


Figure 7: Setup 2 - Pressure Drop against Velocity Squared

6 Conclusions and Remarks

- The Reynold's Number (Re) comes out to be larger than 1000 throughout the experiment. As such, using the Blasius Equation for turbulent flow is preferred.
- The friction factor (f_D) decreases as Volumetric Flow Rate (Q) increases.
- The pressure drop (ΔP) increases as Volumetric Flow Rate (Q) increases and ap-

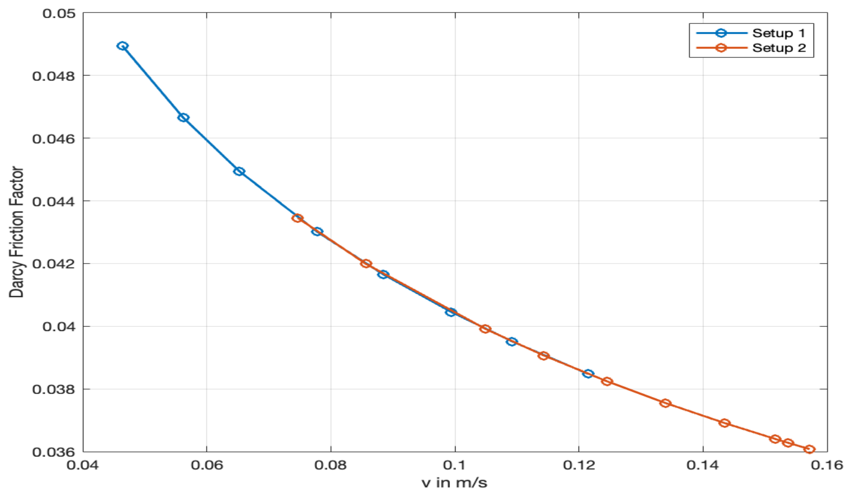


Figure 8: Theoretical Darcy Friction Factor against Velocity

proximately follows the Darcy's equation for pressure drop.

7 Error Analysis (Sources of Error)

- **Inaccurate Pressure Gauge Readings**: Calibration errors, or lag in response time can lead to incorrect inlet and outlet pressure measurements.
- **Leakage at Joints**: Small leaks at joints or fittings can affect the pressure difference, leading to inaccurate measurements of flow resistance.

8 Precautions

- Ensure all tubing, fittings, and pressure gauges are securely connected and free from leaks to prevent inaccurate measurements and potential safety hazards.
- Avoid exceeding the maximum pressure rating of the tubes to prevent potential rupture or damage to the experimental setup.
- Remove any trapped air from the system before starting to ensure accurate pressure drop measurements. Bubbles can affect the fluid's flow dynamics and pressure readings.
- Keep the fluid temperature stable throughout the experiment, as temperature fluctuations can affect fluid viscosity, leading to inconsistent Reynolds number and friction factor calculations.

B. Microfluidic Two Phase Flow

1 Aim

- Record slug flow and stratified flow conditions (pics/videos).
- Plot set flow-rate versus actual flow-rate for both flow types.
- Discuss the possibility of fluid friction at the walls in such micro channels from flow visualizations using the setup.

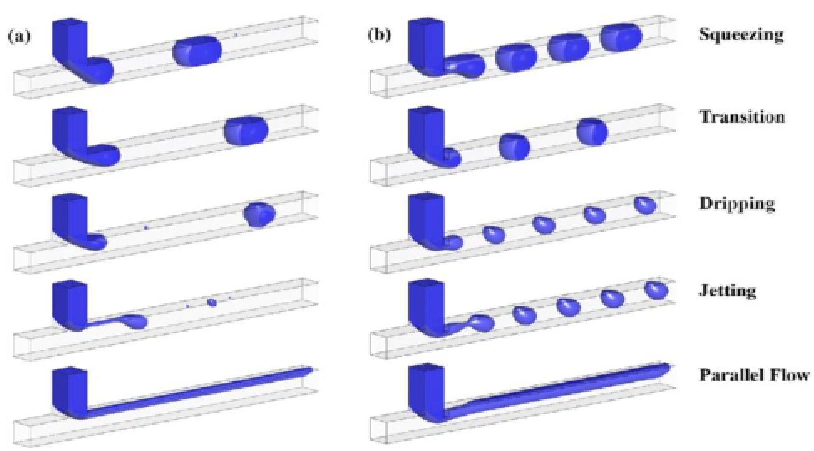


Figure 9: Micro-fluidics: Flow regimes in micro-channels

2 Background and Motivation

As fluid transport systems advance, especially at the microscale, the study of fluid dynamics in microchannels becomes increasingly relevant. Microfluidic systems offer enhanced control over reaction conditions, making them valuable in applications like chemical reactors and biological assays. However, the distinct flow regimes that arise in microchannels (figure 9), such as slug flow and stratified flow, present unique challenges in visualizing and controlling hydrodynamic behavior.

By examining flow characteristics in both conventional and microfluidic channels, engineers can gain insights into pressure drop, friction factors, and flow behaviors that inform the design of more efficient, reliable, and versatile fluid transport systems.

3 Materials and Methods

3.1 Apparatus & Materials Required

- **Materials**: Polyethylene glycol (PEG600), Sodium sulfate (Na_2SO_4), Coomassie Brilliant Blue G20 dye.
- **Apparatus**: Silicon tube, T-junction, Syringes, Injectors, Stopwatch.

3.2 Experimental Setup Description

The experimental setup which includes micro-infusion pumps (figure 11) for the fluids to flow through the channels, is shown in the following figure 10.

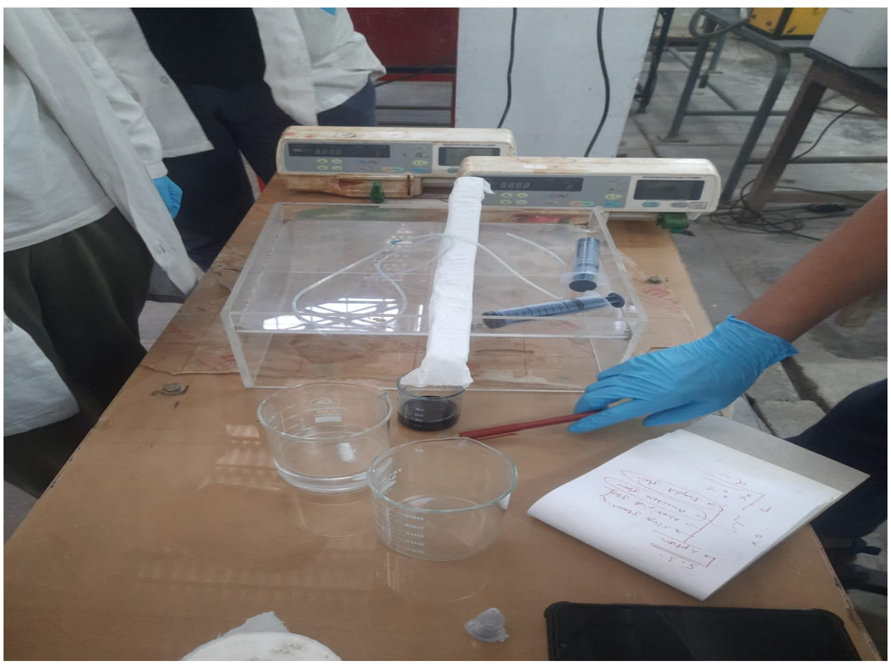


Figure 10: Complete Experimental Set Up

- **Syringe Pumps and Syringes**: Syringes filled with PEG600 and sodium sulfate are connected to syringe pumps. These pumps regulate the flow rates of the fluids through the system.
- **Multichannel and T-junction**: Syringes are connected to a multichannel system that directs both fluids into a T-junction, allowing controlled mixing of the substances.

- **Silicon Tube**: Fluids flow through a silicon tube, and the velocity of the slug formed is measured over a 65 cm tube length.
- **Stopwatch**: Used to measure the time for the system to reach steady-state conditions and to calculate slug velocity.

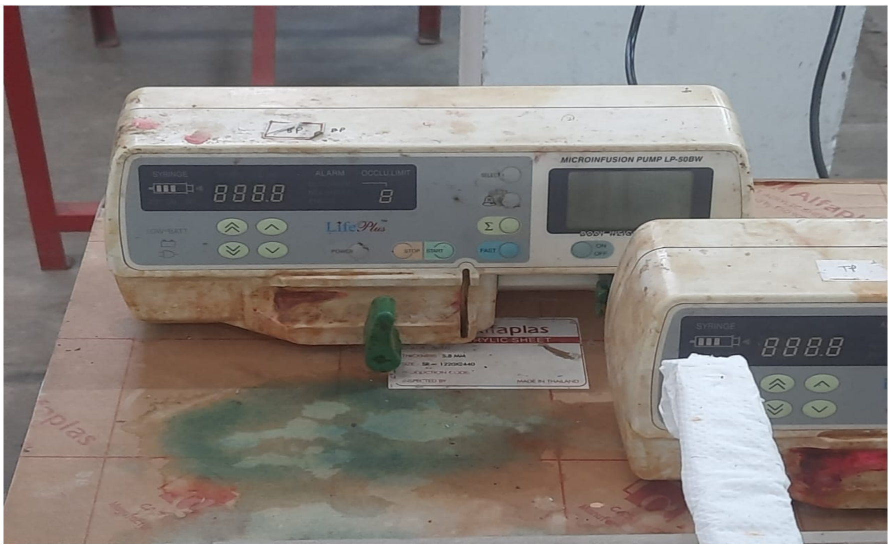


Figure 11: Micro-infusion Pump

3.3 Procedure

- Calibrate the syringe pumps and fill the syringes with PEG600 and sodium sulfate solutions.
- Securely attach the syringes to the syringe pumps.
- Connect the syringes to the multichannel system.
- Set the flow rate of each syringe to 60 mL/min, and flush the channel until fully filled with both fluids.
- Allow the fluid system to reach steady-state conditions.
- Adjust the flow rates for either phase as needed and repeat the above procedure.
- Document the time required for the system to achieve steady-state conditions.
- Determine the slug's velocity by recording the time taken for it to travel the tube length of 65 cm.

4 Observation Tables

By measuring the tube lengths we get:
L_α = 20.0 cm, L_β = 20.0 cm, $L_{\alpha\beta}$ = 65.0 cm.
D (diameter of all the tubes are same) = 1 mm.

The tabulations include the observed data from the second experiment and are tabulated in the following table (table 3):

Q_α (mL/Hr)	Q_β (mL/Hr)	$Q_{\alpha\beta}$ (mL/Hr)	τ_α (sec)	τ_β (sec)	$\tau_{\alpha\beta}$ (sec)	$SS.time$ (sec)	Flow
4.0	4.0	8.0	141.372	141.372	229.729	161.73	Slug
3.0	3.0	6.0	188.496	188.496	306.305	360.44	Slug
2.5	4.0	6.5	226.195	141.372	282.743	210.82	Slug
4.0	2.5	6.5	141.372	226.195	282.743	195.76	Slug
10.0	10.0	20.0	56.549	56.549	91.891	77.81	Stratified
30.0	20.0	50.0	18.849	28.274	36.757	31.38	Stratified
20.0	30.0	50.0	28.274	18.849	36.757	37.09	Stratified
25.0	45.0	70.0	22.619	12.566	26.255	26.57	Stratified

Table 3: Two-Phase Flow through Microchannels

Notations used: Q_α & Q_β = Volumetric flow rates of fluid in α & β phase, $Q_{\alpha\beta}$ signifies the volumetric flow rate of the two-phase mixture along the longer tube τ_i = residence time for i-th phase, $SS.time$ = Steady State time (in sec), and flow signifies the flow characteristics.

Here α phase signifies to 10% PEG-water (by weight) solution whereas β phase signifies to the salt 15% Na_2SO_4-water solution (by weight).

5 Results & Calculations

During experiment the volumetric flow rate of each of the phases was controlled and the steady state time was observed. From the values of the lengths and the diameter of the tubes the τ or the residence time is calculated by the following relation:

$$\tau = \frac{\text{Volume}}{\text{Volumetric Flow Rate}} \tag{9}$$

And by plotting the volumetric flow rate (Q) values the ranges of the fluid flow characteristics can also be observed which is given by the following plot (figure 12).

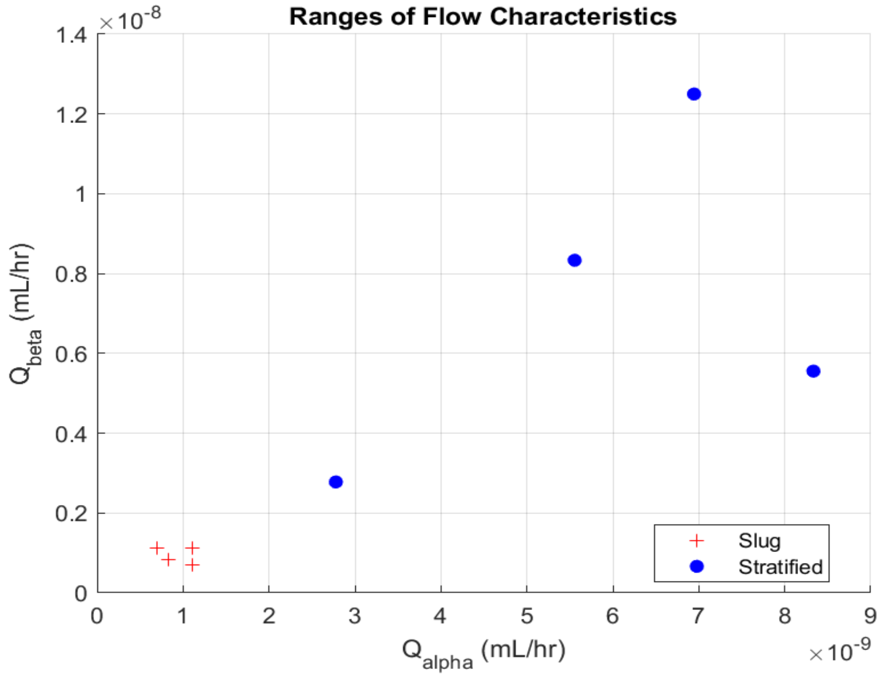


Figure 12: Flow Characteristics

The wall friction differs for different flow rates and that cause these two different fluid characteristics.

- **Formation of Slug Flow**: Slug flow occurs when large bubbles (or slugs) of low density fluid become trapped between segments of higher density fluid.
- In micro-channels, wall friction affects the movement of these slugs by resisting the fluid's motion and potentially causing periodic acceleration and deceleration of the fluid.
- This friction also impacts the size and speed of the slugs, as the wall interactions resist the motion of both the fluid and the trapped bubbles.
- **Stratified Flow**: In stratified flow, the two phases flow in separate layers. Wall friction impacts this flow pattern by influencing the interface stability between the two phases.
- In horizontal micro-channels, gravity has less effect due to the small dimensions, so wall friction and surface tension forces become more prominent.

- These forces contribute to the maintenance of the interface, allowing the higher density fluid to wet the channel walls while the lower density fluid flows above it.

6 Conclusions and Remarks

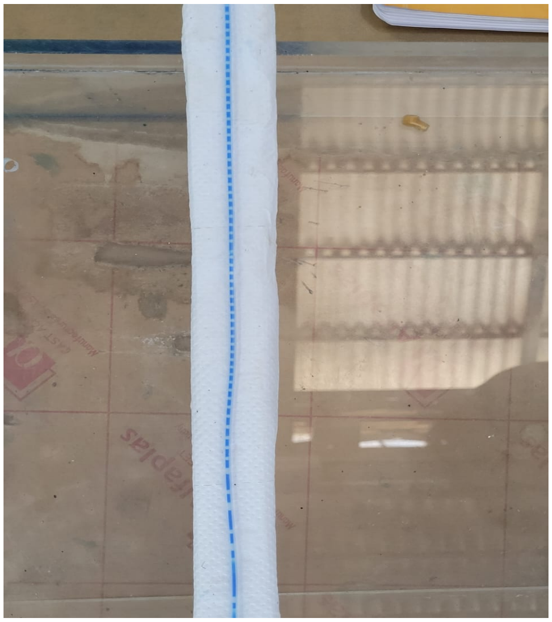
- Few photos have been taken while observing the two-phase fluid flow characteristics through the micro-channels and are provided in the following set of figures.
- Slug flows are shown in figures 13a, 13b, 13c & 13d whereas stratified flows are shown in figures 14a, 14b, 14c & 14d.
- The plot in figure 12 shows that **Slug** flow only happens in lower region where the volumetric flow rates of the both the fluids are less (roughly lesser than 9-10 mL/Hr).
- Whereas the **Stratified** flow happens in a larger region where the flow rates are comparatively high.
- With even more data a standard binary-classification can be performed on this set to classify both the regions on the 2D axis.
- Also to talk on the fluid friction at walls, due to the small scale of micro-channels, the surface area-to-volume ratio is high, which enhances the effect of wall interactions.
- This friction, or wall shear stress, influences the velocity distribution across the channel and affects the stability and behavior of the flow. Higher fluid-wall friction in micro-channels can cause increased energy dissipation and resistance to flow, altering the dynamics of both phases (liquid and gas) as they move through the channel.

7 Error Analysis

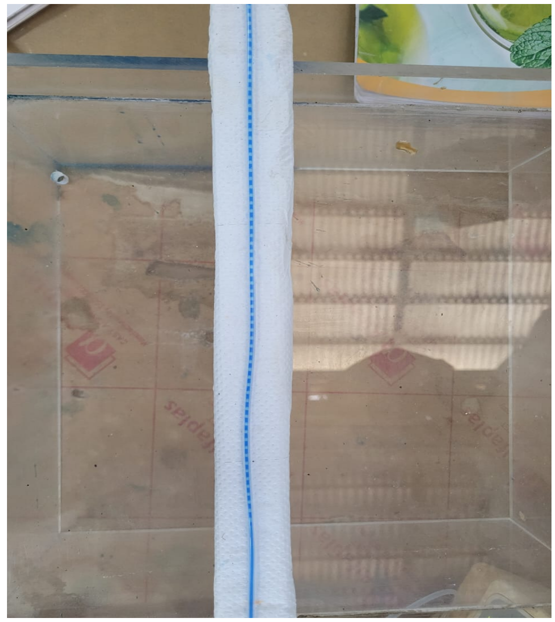
Error in Timer $\equiv \Delta t = 5$ sec $= 0.0833$ min (human calibration)
Least Count of Vernier Calliper $\equiv 0.01\ mm$
Least Count of Main Scale = 1 mm

7.1 Sources of Error

- **Timing with Stopwatch**: Manual timing introduces human reaction time delays, affecting accuracy when measuring flow duration.

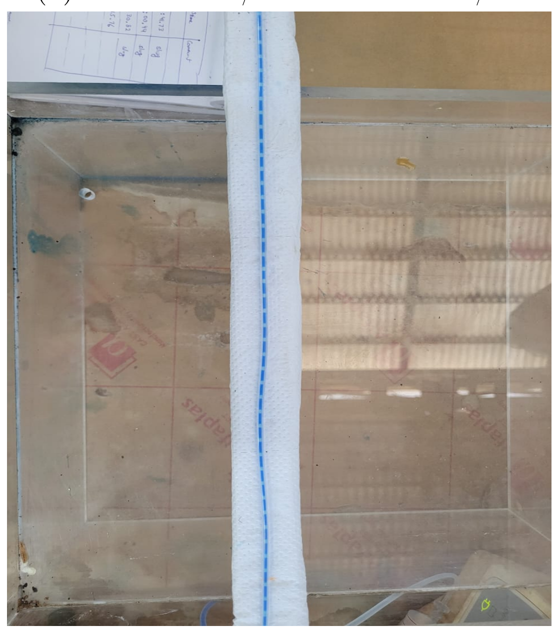


(a) PEG - 4 mL/Hr & Salt - 4 mL/Hr



(b) PEG - 3 mL/Hr & Salt - 3 mL/Hr

(c) PEG - 2.5 mL/Hr & Salt - 4 mL/Hr

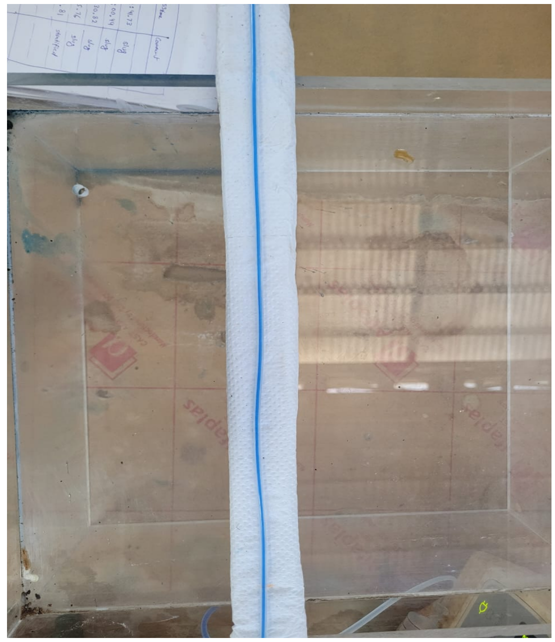


(d) PEG - 4 mL/Hr & Salt - 2.5 mL/Hr

Figure 13: Micro-fluidics: Slug Flows

- **Micro-infusion Pump Flow Rate**: Flow rate stability is crucial, and minor fluctuations or calibration errors in the pump can lead to inconsistent flow rates.

(a) PEG - 10 mL/Hr & Salt - 10 mL/Hr



(b) PEG - 30 mL/Hr & Salt - 20 mL/Hr

(c) PEG - 20 mL/Hr & Salt - 30 mL/Hr

(d) PEG - 25 mL/Hr & Salt - 45 mL/Hr

Figure 14: Micro-fluidics: Stratified Flows

- **Unstable Flow Patterns**: At micro-scales, small perturbations can change the flow regime, introducing slugs or waves unpredictably and impacting observations.

- Variations in ambient or fluid temperature can affect viscosity and surface tension, both critical in two-phase flows, leading to altered flow behavior.
- Minor air entrapment or inconsistent distribution of phases can alter the expected flow pattern, causing deviations in measurements for slug or stratified flow types.

8 Precautions

- Ensure that all microchannels, syringes, and fittings are tightly secured to prevent leaks and spills, which can impact flow visualization and pose safety risks.
- Calibrate flow meters and syringe pumps accurately before starting the experiment to ensure that set and actual flow rates match closely.
- Keep the experimental area free from external vibrations, as microchannels are sensitive to even minor disturbances, which may alter flow patterns and result in inaccurate visualizations.
- Ensure that the channels are clean and transparent for unobstructed recording. Any residue on the channels can interfere with visual clarity, making it difficult to observe flow patterns accurately.

Thought Question / Open-Ended

Q. Can you redesign your experiment to show us how fluidic logic gates can be created? What will be their governing equations? Will friction factors matter for these?

A. To redesign the experiment for demonstrating fluidic logic gates, we can use microfluidic channels with specific configurations to mimic digital logic operations (like AND, OR, NOT). Fluidic logic gates leverage fluid flow properties (like pressure, flow rate, and path resistance) to perform logic operations without electrical power.

Experiment Redesign for Fluidic Logic Gates

1. Setup and Design:
    - **Channel Configuration**: Create micro-channels with specific junctions and branching patterns, where the inputs (fluids entering the channels) merge at points to perform logical operations.
    - **Inputs**: Use two fluid inlets to represent binary inputs (1 or 0). For example: Flowing fluid represents logic 1 and No flow represents logic 0.

- **Outputs**: The output channel measures flow presence (1) or absence (0) based on the pressure and fluid dynamics.

2. Example Gate Designs:

   - **AND Gate**: Design a configuration where both input flows are required to meet at a junction for a combined output flow, representing a logic 1 only when both inputs are 1.
   - **OR Gate**: Configure channels so that flow in either input channel produces an output, representing logic 1 if either input is 1.
   - **NOT Gate**: Use a single input channel that diverts the fluid when flow is present, creating an output in an alternate path when input flow is absent.

Governing Equations

The flow in each channel follows Bernoulli's equation and Hagen–Poiseuille's law for pressure-driven flow in microchannels, which can be expressed as:

1. **Hagen–Poiseuille's Law**:
$$Q = \frac{\Delta P \cdot \pi r^4}{8\mu L} \tag{10}$$
where Q is the volumetric flow rate, ΔP is the pressure difference across the channel, r is the channel radius, μ is the fluid viscosity, and L is the channel length.

2. **Continuity Equation**:
$$Q_{in} = Q_{out,1} + Q_{out,2} \tag{11}$$
Ensures flow conservation at junctions.

3. **Pressure and Flow Relationships**: At each junction, pressure drop influences flow distribution. Logic gates rely on the balance between pressure drops and flow rates through various branches.

Role of Friction Factors

Friction factors significantly impact micro-channel flow and, thus, are essential for fluidic logic gates:

- **Flow Resistance**: Friction affects how easily fluid flows through each channel, which determines if output flow (logic 1) occurs. High friction in certain branches can inhibit flow, creating a logic 0 condition.

- **Pressure Drop**: Higher friction factors result in larger pressure drops, which must be managed to ensure desired logic behavior across gates.

By carefully designing channel lengths, widths, and junctions while managing pressure drops and friction, fluidic logic gates perform reliable logic operations. This approach is applicable in micro-fluidic circuits for applications in biochemical processing and lab-on-chip devices.

Acknowledgements

We as a group contributed our respective parts into completing the above report.

In terms of specifications, Rapolu Paranay Reddy helped with "Apparatus & Materials" and "Experimental Setup Description" part of the report. Atharva Sunilkumar Ghodke contributed in "Procedure" & "Precaution" parts. Anmol Upadhyay delivered the content for "Objective" and "Background & Motivation" sections along with Lakkireddy Vishnu Vardhan Reddy helping in "Abstract" part of the report and rest of all the parts are collaboratively 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 Shivam bhaiya for this experiment 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

- Notes from the course CH5140 : Process Modelling Simulation and Analysis by Prof. Renganathan.

- Scholarly paper talking about all kinds of two-phase fluid flows through micro-channels, (addition to slug & stratified, ring, lump flows).
  https://www.sciencedirect.com/science/article/pii/S0894177702001759

- Two-phase flow and heat transfer through wavy microchannel *S. Chandrasekhar, V.R.K. Raju*
  https://www.theijes.com/papers/NHTFF-2020/Volume%20-2/10,%2059-65.pdf

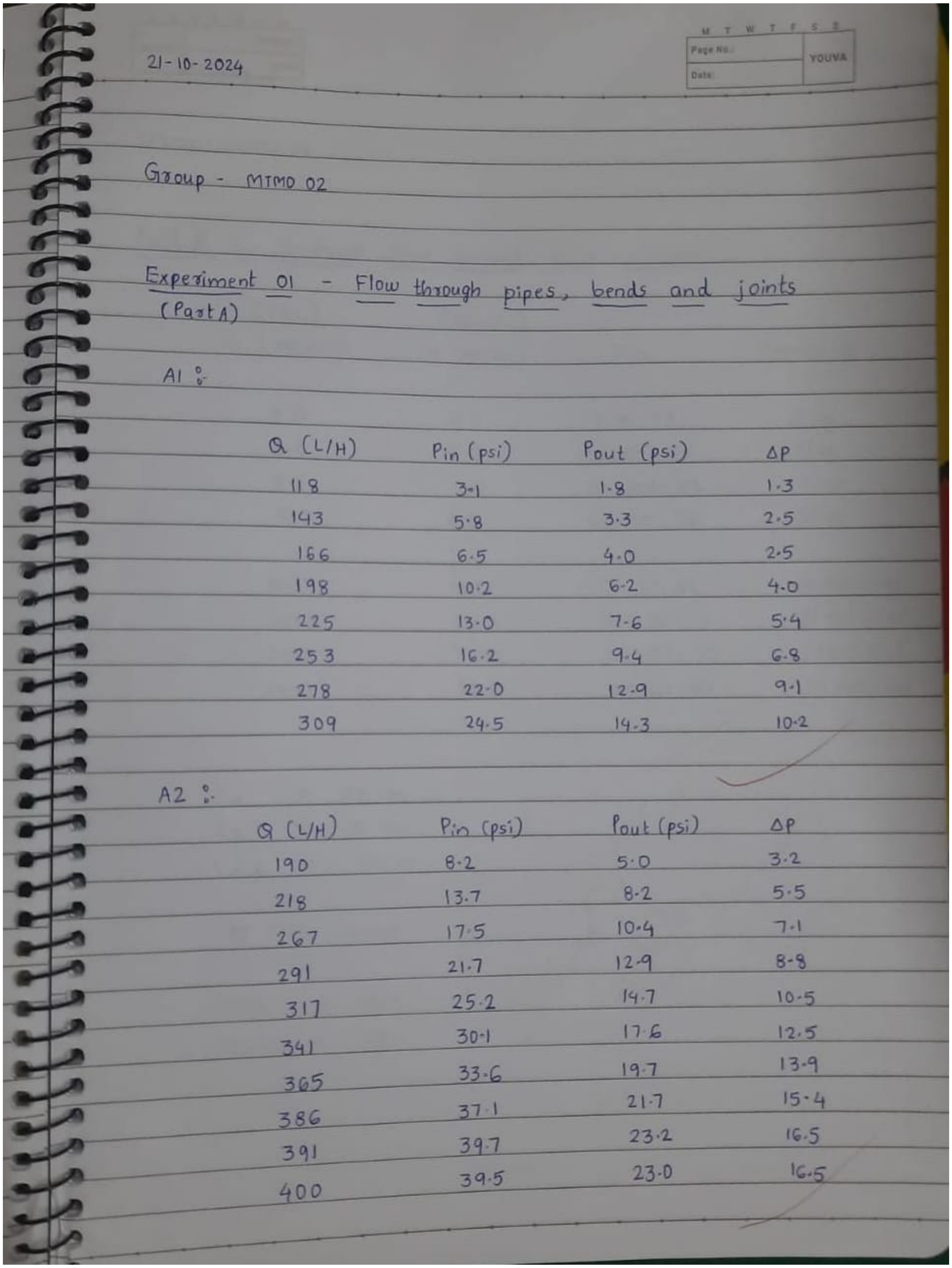
- S. Zhang, B. Kwak, and D. Floreano, "Design and manufacture of edible microfluidic logic gates," in 2023 IEEE/RAS International Conference on Soft Robotics

(RoboSoft), 2023.
https://www.researchgate.net/publication/369823770_Design_and_manufacture_of_edible_microfluidic_logic_gates#full-text

Appendix

Lab Data: All the experimental observations with each of the sub-parts of the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures 15 & 16).

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_1. 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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Group - MTMO 02

Experiment 01 - Flow through pipes, bends and joints (Part A)

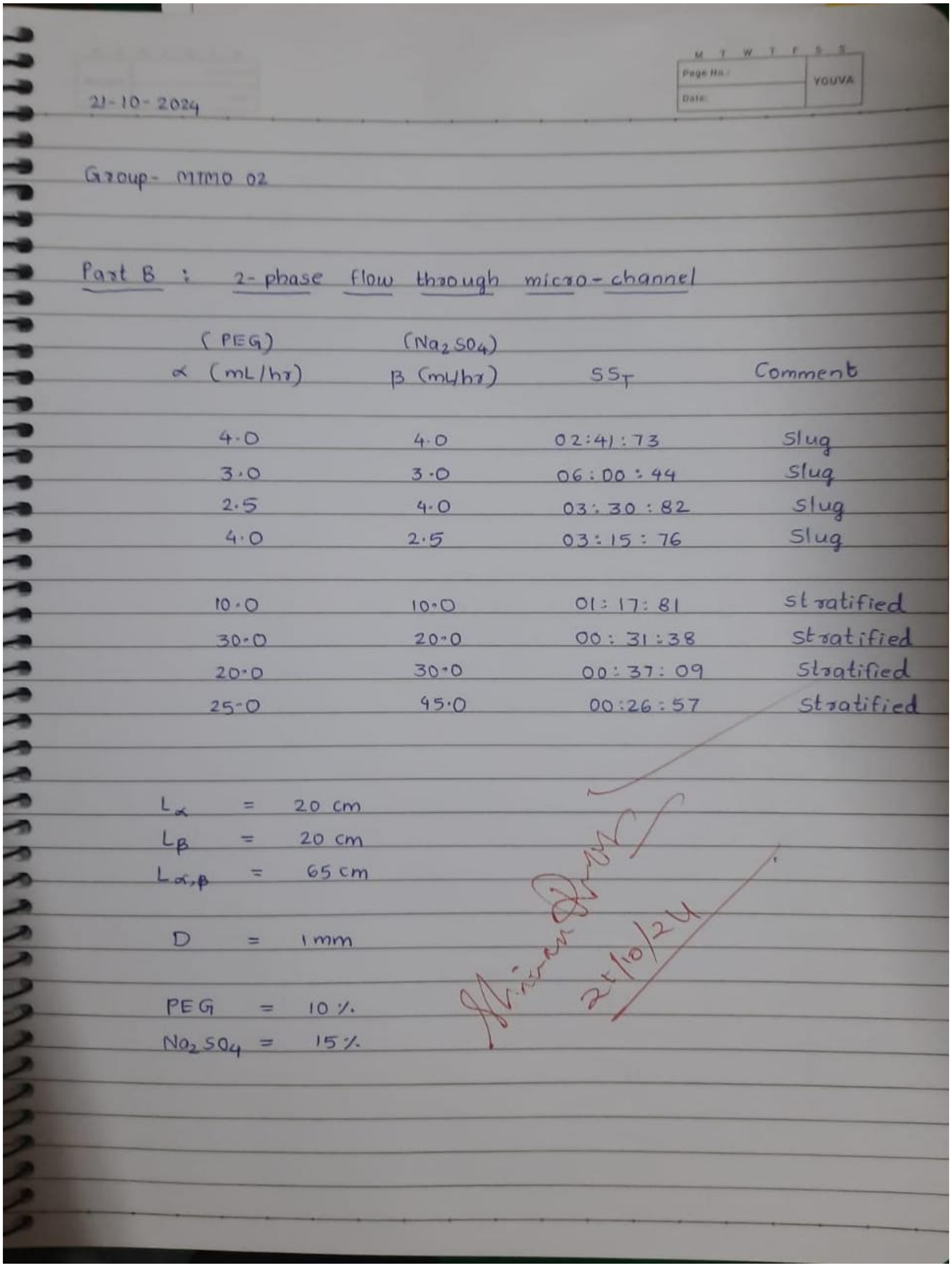
A1 :-

Q (L/H)	Pin (psi)	Pout (psi)	ΔP
118	3.1	1.8	1.3
143	5.8	3.3	2.5
166	6.5	4.0	2.5
198	10.2	6.2	4.0
225	13.0	7.6	5.4
253	16.2	9.4	6.8
278	22.0	12.9	9.1
309	24.5	14.3	10.2

A2 :-

Q (L/H)	Pin (psi)	Pout (psi)	ΔP
190	8.2	5.0	3.2
218	13.7	8.2	5.5
267	17.5	10.4	7.1
291	21.7	12.9	8.8
317	25.2	14.7	10.5
341	30.1	17.6	12.5
365	33.6	19.7	13.9
386	37.1	21.7	15.4
391	39.7	23.2	16.5
400	39.5	23.0	16.5

Figure 15: Flow through Pipes, Bends and Joints



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Group- MTMO 02

Part B : 2-phase flow through micro-channel

(PEG) α (mL/hr)	(Na_2SO_4) β (mL/hr)	SS_T	Comment
4.0	4.0	02:41:73	Slug
3.0	3.0	06:00:44	Slug
2.5	4.0	03:30:82	Slug
4.0	2.5	03:15:76	Slug
10.0	10.0	01:17:81	stratified
30.0	20.0	00:31:38	stratified
20.0	30.0	00:37:09	Stratified
25.0	45.0	00:26:57	Stratified

L_α = 20 cm

L_β = 20 cm

$L_{\alpha,\beta}$ = 65 cm

D = 1 mm

PEG = 10 %

Na_2SO_4 = 15 %

21/10/24

Figure 16: Two-Phase Flow through Microchannels