Image Analysis to Study Draining in Mini-Channels

Bachelor Thesis Project Report

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IIT KHARAGPUR

CERTIFICATE

The thesis entitled ***"Image Analysis to Study Draining in Mini-Channels"*** is being submitted by ***Mr. Soumyadeep Mukherjee, Roll No. 11CH30022,*** to the Department of Chemical Engineering, IIT Kharagpur for the fulfillment of the requirements of the Degree, Bachelor of Technology in Chemical Engineering from Indian Institute of Technology, Kharagpur. This document is a record of the bona fide work carried out by him under my supervision and guidance.

This thesis is, in my opinion, worthy of the standard for which it is submitted.

Prof. Gargi Das	Prof. S Ray
Professor	Professor
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Abstract

Liquid draining is encountered in almost every industry, where emptying of pipes and vessels or draining forms an integral part. Mini-channels are commonly used in biomedical applications where draining or infusion of fluids from/into the body form an essential part. In the present study, experiments need to be performed for draining characteristics of water and surfactant solution of 1000ppm, 2000ppm and 3000ppm in glass tubes of 2mm and 4mm diameter for partially open. Image Analysis on video recording to track the interface level and study the draining is the main objective of this thesis.

Introduction

Liquid draining is a very common phenomenon with applications in every industry. However, draining in mini-channels is a relatively new area of research with no experimental data to validate models developed for draining in micro-channels. This project aims to develop a model for draining in partially open mini-channels used extensively in bio-medical applications. This model then is validated using experimental data obtained by tracking the liquid-air interface as liquid flows using image analysis techniques on video feed. The video feed records draining in mini-channel tubes at multiple inclinations and different number of needles attached to partially open the tube.

Literature Review

Draining in micro-channels is a relatively new research with most research being done on tubes with diameters greater than 10 mm. In order to understand the working theory of drainage in mini-channels and in order to study it, the existing research was first reviewed. An extensive review was done on the three major papers which were relevant to so that a novel approach could be taken.

C.Clanet's Clepsydrae, from Galilei to Torricelli (2000) deals with free fall of solid particle and fluid particle across a stream. Both these limits are brought together in the problem of draining in a vertical tube of given diameter and hole of known diameter. This article models the draining in a vertical tube using Galileo's equations for solid particle and Torricelli's equation as water level decreases in the vertical tube.

A differential equation is modeled using this and its solutions are compared to experimental measurements conducted at different Diameters of the tube and hole through which liquid exits.

The experiment measures the liquid level as a function of time for different values of diameter of exit hole and tube diameter. The article also develops a model for a function that maps liquid level to ratio of tube diameter and diameter of exit hole as a transition from Galilei's regime to Torricelli's regime when a cylindrical vessel of diameter discharges through thin wall hole of known diameter.

However, this article works completely in the non-capillary but it gives a proper insight about the problem in its primitive form and also helps to design an experimental setup.

Zukoski's Influence of viscosity, surface tension, and inclination angle on motion of long bubbles in closed tubes (1966) aims to study the motion of bubbles in closed tubes with respect to viscosity, surface tension and inclination angle. This article describes different techniques for measurement of velocity of bubbles in a vertical tube.

First technique consisted of a tube, closed at one end, was filled with the desired fluid, and the open end was then placed under the surface of the same fluid in a beaker. The inclination of the tube was fixed and the bubble was formed by moving the beaker to expose the open end of the tube to the air. The time required for the bubble to move a measured distance along the tube was then determined and was used to calculate the velocity.

The second technique was used for the investigation of bubbles or drops of liquids moving through other liquids. A vertical tube closed at the lower end was completely filled with the two fluids in the equilibrium condition, i.e. the lighter on top, and with the bubble or droplet column considerably shorter than the primary column. The tube was then closed and suddenly placed at the desired inclination with the heavy fluid at the higher end, and the subsequent motion of the heavy droplet was observed.

Stop watches were used to determine the time required for the bubbles to move a fixed distance. Time measurements were also made with photocells used to trigger an electronic counter.

The experimental studies of the motion of long bubbles in tubes led to a better understanding of the influence of surface tension and viscosity on bubble propagation in vertical tubes. Moreover, the influence of tube inclination angle has been described in this article. This paper though irrelevant for mini-channels gives an insight into the experimental techniques used for studying the velocities and also gives an approach to the study of the influence of surface tension, viscosity and inclination angle on flow of liquid in vertical tubes.

C.Clanet and G.Searby's on the glug-glug of the bottle (2003) presents an experimental study of emptying of an ideal vertical bottle under gravity. This reduces the problem to a closed top draining through a thin walled hole on axis of cylinder. It focusses on the oscillatory emptying of the cylinder referred to as glug-glug.

The experimental setup allows the liquid to flow out of the tube as the CCD camera records the trajectory of the upper interface, while the pressure sensor informs on the pressure fluctuations in the upper gas volume. In other words, the CCD camera provides information on the time scale of liquid draining and the pressure sensor focuses on the oscillation time i.e. glug-glug. The experiment is carried varying the Physical Characteristics and geometric Properties independently to study the effect of each on the draining in the vertical tube.

This article gives a better insight into the experimental setup as it introduces to a camera to record the interface level and also shows an approach towards developing a model. However, all experiments and results are for diameters of tube >=10 mm.

Theoretical Model for Partially Open Top Draining

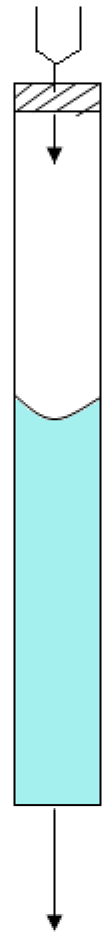


Figure 1 :

Partially open top as shown in Figure 1 draining is ensured by piercing the rubber cork by which the tube is closed at the top using a hypodermic needle. Continuous flow of air is allowed into the tube from top. Unlike the closed tube draining here the liquid draining is full bore draining. This draining is faster than closed top draining.

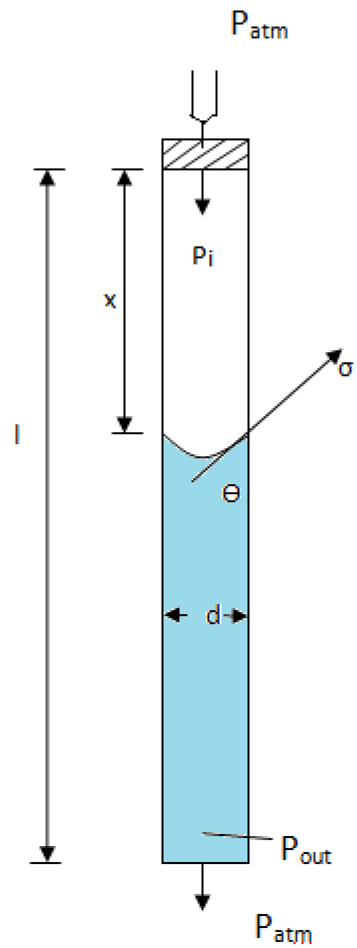


Figure 2

Active forces:

Forces as shown in Figure 2 which are acting downward facilitate draining and which acts upward retards draining.

1. Weight of liquid acting downwards= F_w
2. Surface Tension acting upwards= F_s
3. Friction acting upwards=$\Delta P_f \frac{\pi}{4} d^2$
4. Discharge loss at the needle exit
5. Discharge loss at the tube exit

1. F_w= $\rho g\ (l\text{-}x)\ \frac{\pi}{4} d^2$

2. F_s= $\pi d\sigma\cos\theta$

3. Frictional force= $\Delta P_f \frac{\pi}{4} d^2$

Where ΔP_f =Pressure drop due to friction

$\Delta P_f = f\,\frac{(l-x)}{d} \times \frac{1}{2}\rho u^2$

$\Delta P_f = f\,\frac{(l-x)}{d} \times \frac{1}{2}\rho \left(\frac{dx}{dt}\right)^2$

where f=Darcy friction factor

for Re<4000 f=64/Re

Re>4000 then f should be predicted from Colebrook equation

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D_{\mathrm{h}}} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right)$$

Where ε=roughness,

D_h=Hydraulic diameter

Glass surface is considered to be smooth so ε=0

1 Discharge Losses from the tube

= $\Delta P_d \frac{\pi}{4} d^2$

=$\frac{\pi}{4} d^2 \times \frac{1}{2}\rho \left(\frac{dx}{dt}\right)^2 \times \frac{1}{C_d^2}$

Where C_d=discharge coefficient which depends on Reynolds number and β.

Navier Stokes Equation:

Using Navier Stokes Equation:

$$\boldsymbol{\rho}\left(\frac{\partial \mathbf{v}}{\partial \boldsymbol{t}}+\boldsymbol{v}.\nabla \boldsymbol{v}\right)= -\nabla \boldsymbol{p}+ \boldsymbol{\mu}\, \nabla^{2}\, \boldsymbol{v}+\boldsymbol{f}$$

Since, $\nabla p = 0$ *as it's partially open tube with pressure same on top and below and* $\nabla^2 v = 0$,
we get, $\boldsymbol{\rho}\left(\frac{\partial \mathbf{v}}{\partial \boldsymbol{t}}+\boldsymbol{v}.\nabla \boldsymbol{v}\right)=f$ *where f* **=** $\text{gravity} - \text{surface tension} - \text{friction} - \text{exit losses}$

$$\boldsymbol{\rho}\left(\frac{\partial \mathbf{v}}{\partial \boldsymbol{t}}\right)+\boldsymbol{v_x}\,\frac{\boldsymbol{dv_x}}{\boldsymbol{dx}}+\ \boldsymbol{v_y}\,\frac{\boldsymbol{dv_x}}{\boldsymbol{dy}}+\ \boldsymbol{v_z}\,\frac{\boldsymbol{dv_x}}{\boldsymbol{dz}}=\boldsymbol{f}$$

Since, $v_y = v_z = 0$ and $\frac{dv_x}{dx} = 0$ and multiplying by area of cross section,

$\frac{d(mv)}{dt}=\frac{d}{dt}\left[\frac{\pi}{4}d^2(l-x)\rho\frac{dx}{dt}\right]$

$$\frac{d(mv)}{dt}=\frac{\pi}{4}d^2\,\rho\left[(l-x)\frac{d^2x}{dt^2}-\left(\frac{dx}{dt}\right)^2\right]$$

$\frac{\pi}{4}d^2\rho(l-x)g-\pi\mathrm{d}\sigma\cos\theta-f\,\frac{(l-x)}{d}\times\frac{1}{2}\rho\left(\frac{dx}{dt}\right)^2\frac{\pi}{4}d^2-\frac{\pi}{4}d^2\times\frac{1}{2}\rho\left(\frac{dx}{dt}\right)^2\times\frac{1}{C_d^2}+$
$(P_i-P_{atm})\frac{\pi}{4}d^2=\frac{\pi}{4}d^2\,\rho\left[(l-x)\frac{d^2x}{dt^2}-\left(\frac{dx}{dt}\right)^2\right]$

$\frac{d^2x}{dt^2}=2g-\frac{8\sigma\cos\theta}{d\rho(l-x)}-\frac{2(P_{atm}-P_i)}{\rho(l-x)}-\left(\frac{dx}{dt}\right)^2\left[\frac{f}{d}+\frac{1}{C_d^2(l-x)}-\frac{1}{(l-x)}\right]$ (1) $\longrightarrow$

Initial conditions are

i. At t=0, x=0
ii. At t=0, $\frac{dx}{dt}=0$

P_i and P_{atm} are related assuming the process is adiabatic.

Non-choked flow of real gas through orifice for $\beta < 0.25$ is given by

$w = C_{do}A_o\rho_{air}\,\frac{2ZRT}{M}\times\left(\frac{\gamma}{\gamma-1}\right)\sqrt{\left\{\left[\frac{P_i}{P_{atm}}^{\frac{2}{\gamma}}-\frac{P_i}{P_{atm}}^{\frac{\gamma+1}{\gamma}}\right]\right\}}$ $\longrightarrow$ (2)

Where

C_{do}=Discharge coefficient of orifice

C_{do} is included to account for the discharge losses through the orifice w=Mass flow rate air through orifice

A_o=Cross sectional area of orifice

Z=Compressibility factor=1

R=Gas constant

T=Temperature in K

M=Molecular weight of air

$\gamma = 1.4\ for\ air$

Mass flow rate (w) can also be expressed as

w=Q*ρ=$\frac{d}{dt}\left[\frac{\frac{\pi}{4}d^2x(P_i-P_S)M}{RT}\right]$

Ps=vapour pressure of water(≈ 0)

$$w = \frac{\pi}{4}d^2\frac{M}{RT}\left[x\frac{dP_i}{dt} + P_i\frac{dx}{dt}\right]$$

$$x\frac{dP_i}{dt} + P_i\frac{dx}{dt} = \frac{wRT}{M} \times \frac{4}{\pi d^2}$$

$$\frac{dP_i}{dt} = \frac{1}{x}\left[\frac{wRT}{M} \times \frac{4}{\pi d^2} - P_i\frac{dx}{dt}\right]$$

$$\frac{dP_i}{dt} = \frac{1}{x}\left[\frac{wRT}{M} \times \frac{4}{\pi d^2} - \frac{\rho_i RT}{M}\frac{dx}{dt}\right]$$

$$\frac{dP_i}{dt} = \frac{1}{x}\frac{RT}{M}\left[w \times \frac{4}{\pi d^2} - \rho_i\frac{dx}{dt}\right]$$

$$\frac{dP_i}{dt} = \frac{P_a \times 22400 \times (273 + T_a)}{273 \times 28.8 \times x}\left[w \times \frac{4}{\pi d^2} - \rho_i\frac{dx}{dt}\right]$$

$\frac{dP_i}{dt} = \frac{P_a \times (273+T_a)}{0.351 \times x}\left[w \times \frac{4}{\pi d^2} - \rho_i\frac{dx}{dt}\right]$ (3) $\longrightarrow$

Initial condition is at t=0, P_i=P_{atm}-$\rho(l-x)g$

Solving Equation (1) and (3) simultaneously gives the values of x and P_i with time.

Experimental Setup & Procedure

The experimental setup consists of a rotatable mini-channel attached to a pump through valves which allows liquid to flow through the tube. A schematic of the draining setup is shown in figure 3. It comprises of a bank of liquid filled glass tubes of 1.2 m length and 2mm and 4mm inner diameter (only one tube is shown in fig for clarity). The inner diameters are measured by Vernier calipers and also noted by measuring the volume of water required to fill a known length of the tube.

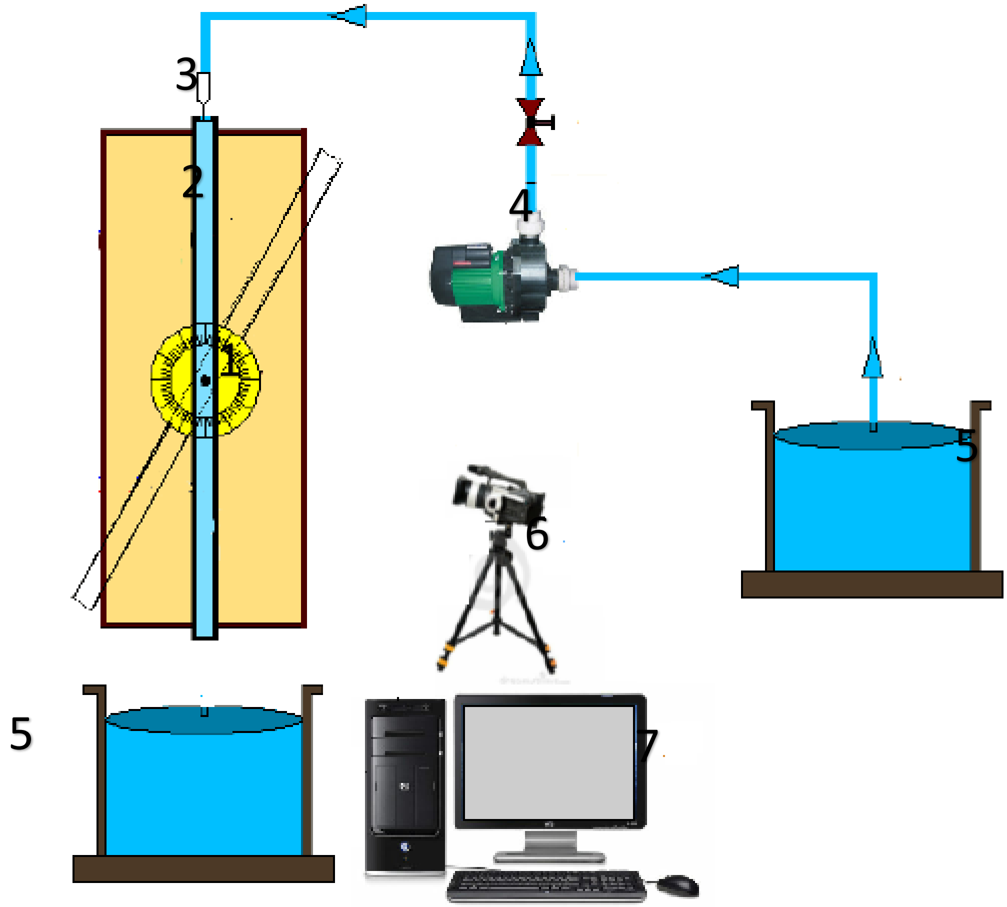


Figure 3

1. Protractor to Set Angle
2. Mini-Channel
3. Syringe Needle
4. Pump
5. Reservoir
6. High Speed Camera
7. Computer Connected to High Speed Camera

The exact dimensions thus obtained are reported in Table 1. The diameter range is selected such that it encompasses the critical dimension below which flow of liquid from the tube is prevented by tube effects, The diameter has been reported by Zukoski (1966) as $1.9a$ where a, the tube length of the liquid is $\sqrt{\frac{2\sigma}{\rho g}}$ and is 7.2 mm for water.

Fluid (ppm of SDS solution)	**Density (kg/m^3)**	**Viscosity (N-s/ m^2)**	**Surface tensi (dyne/cm)**	$\boldsymbol{Ka} = (\frac{\rho^3 g v^4}{\sigma^3})^{1/6}$
0	998	0.79	78	0.016
1000	997.8	0.79	58	0.017
2000	997.8	0.79	45.2	0.020
3000	997.8	0.79	38.5	0.021

Table 1: Physical properties of fluids

Further, the study is conducted in the non-viscous limit 4.5 lv < $1.9a$, where $l_v \equiv (v2/g)^{1/3}$ is the viscous length, that is with liquid characterized by a Kapitsa number, <0.06.

Experiments are performed with water and surfactant (SDS) solution of different concentration (1000 ppm, 2000 ppm, 3000 ppm). Measurements of the fluid physical properties (density, surface tension and viscosity) as reported in Table 1 reveal that SDS alters the surface tension of water while the other properties remain unaltered.

Before each individual run, the tubes are cleaned thoroughly with detergent solution, rinsed successively with water and methanol and allowed to dry. Valves are opened to fill the tube using a pump. As the liquid starts to flow out of the tube, the camera records the trajectory of the interface and the experiments are repeated

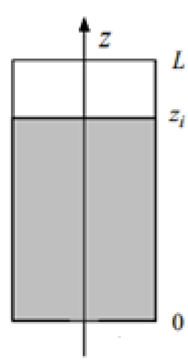


Figure 4

Experiments have been performed for partially open tops. Hypodermic needles of nominal diameter 0.394 mm and length 38 mm are inserted in the rubber to form a partially open top. The time and rate of draining is noted for 1, 2, and 3 needles. Care is taken to ensure that the needle just pierces the cork but does not extend into the liquid since in the latter case some liquid rises through the needle and influences the rate of draining.

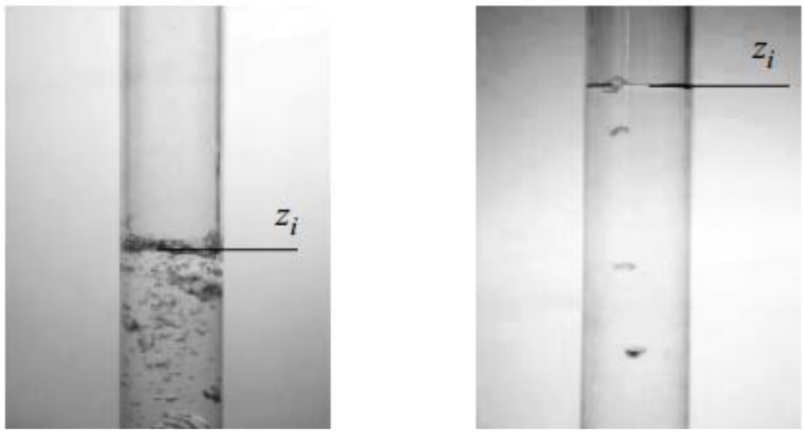


Figure 5

The rate of draining in 2mm and 4mm tubes are very fast and cannot be measured using stop watch method. Figures 4 and 5 describe the interface levels during draining in vertical tubes. This interface level is tracked using image analysis techniques to measure the drainage time by plotting the position of interface level over time during draining. Figure 6 shows the live experimental setup in the lab.

Figure 6

Object Tracking

Video tracking is the process of locating a moving object (or multiple objects) over time using a camera. The objective of video tracking is to associate target objects in consecutive video frames. The association can be especially difficult when the objects are moving fast relative to the frame rate. Another situation that increases the complexity of the problem is when the tracked object changes orientation over time. For these situations video tracking systems usually employ a motion model which describes how the image of the target might change for different possible motions of the object.

However, tracking of objects in moving frames need to be detected but in interface level tracking the detector cannot be reliable as the interface does not have any distinctive features. Hence, we have to apply a method where the detection can be done manually and then tracking and detection is done on run-time. The algorithm described is known as TLD – Track Learn Detect.

Algorithm

- The Object of interest is set by the user at the beginning.

- From that point, a model of the object is being maintained and updated along the run of the video.
- While the short-term tracker, implemented by optical flow (LK), is giving a good enough result, we have the object bounded.
- If we lose the object, we use the model to re-detect the object.

Implementation

- The Image Compering method

In an image & a bounding box, a value is set to each pixel (LBP value first, and then a converting table is used from 255 options to 10). Then, a vector of 10 is saved, by counting how much of each value we got and basically - this vector represent the property of the image and bounding box. The Actual implementation, is splitting the box to 4 equal parts, make 4 vectors as above - one for each - and the concatenated vector of length 40 is the property that is used. And, in addition, in the 41 cell of the vector we also save the amount of pixels the box had (for the comparing part) Comparing of two property's is just an Euclid distance between the two vectors, when each cell is taken as the cell divided in the total amount (cell 41), to support comparing two images of different sizes.

- The Model

The model is a set of property vectors. At the beginning, the property of the bounding box set by the user is added and for each new property is added if it is close enough to the model.

- The THRESHOLD

Comparing two property's result as a distance, to decide if that distance is "close enough", a THRESHOLD is used. At the beginning, all the first frames after the user set the object are assumed to still contain the object. And so all properties of the model are added (high threshold). Then a new threshold is calculated by taking a mean over the previous distances we got. And from this point, the new THRESHOLD is used to decide if the object is still there (and continue with short-term tracking), or if we lost the object, and in that case we use the detector part to re-find it.

- The Detector

In order to find the object, the object is searched around the frame for something that is close enough to the model, and if there are a few matching - the best one is found. The basic idea is to do a grid search all over the frame, but since this will take too much time, searching is started close to where the object was last seen, and if not found, then in the next frame the search radius is widened after a few frames, and if all of the frame is searched then there is a chance we do not find it because it is not visible (out of the frame or hidden behind something) and so in this point we use 3 methods to improve the speed:

- Every frame is not searched but instead some frames are skipped.
- All the frame is not searched, a random search is used.
- Instead of comparing the all box right away - one quarter is compared to the same quarter in the model and only if it is good enough further comparisons are performed

- Pruning events

Since the process is not perfect, the model might be added with property that do not really represent the object, and so a process is required which removes this property from the model: this are called "pruning events". The idea is to take the property from the model that gave "false positive" and remove them. "False positive" - is when a distance to the model is calculated that is lower than the threshold, but from its coordinate which we find out that it is not the object. In that case, that part of the model is contributing to the messing of the model - and so we remove it from the model.

Interface Tracking Results

The TLD algorithm was implemented on C++ and then was tested on prototype videos for interface level tracking. Figure 7 shows two frames from tracking video where the blue rectangular box shows the position of interface level between water and air. This blue box center was obtained to get the pixel value of interface level which can be plotted as a function of time to get the velocity profile of interface level during draining.

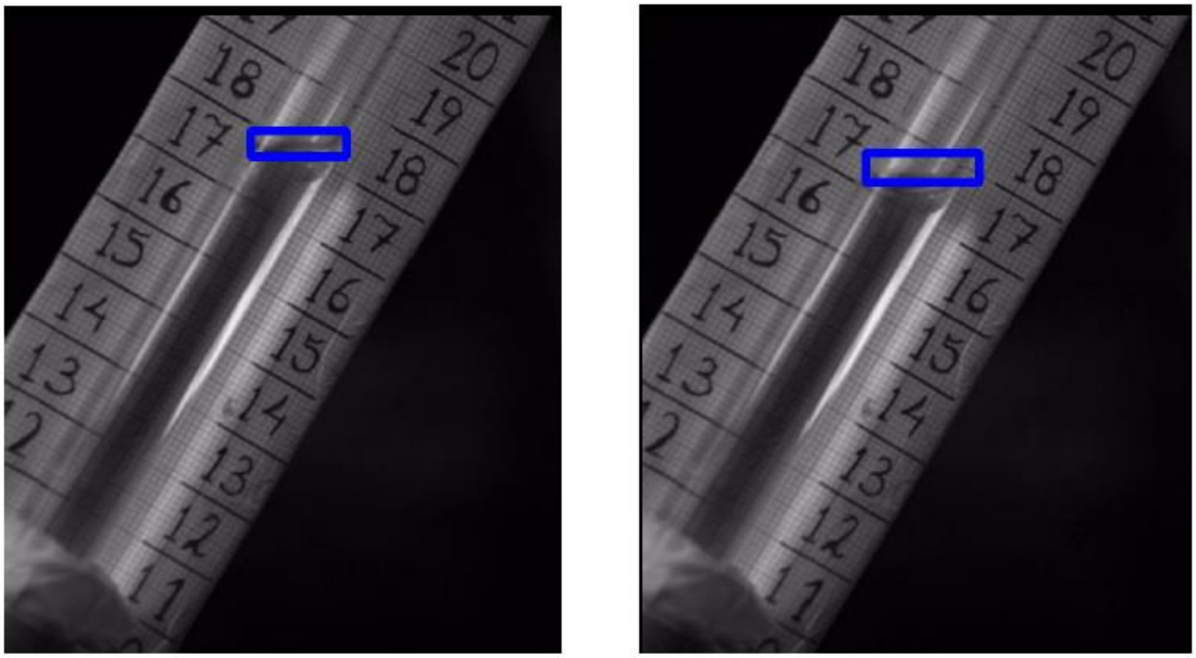


Figure 7

Experimental Observations and Results

The experiment was performed using 34 mm lens for 1000 ppm, 2000 ppm and 3000 ppm for single, double and triple needles with 3 readings per case. TLD was tested on these videos but tracking performance was not good due to lack of detailing of the interface level. The camera needed to cover considerable amount of vertical tube for proper analysis. So the videos were taken in two halves, the upper and lower. However, even then the detailing of the image on a frame was not good enough and the detected features in the interface bounding box drawn for detection were no reliable and enough. Hence, the TLD did not work on the videos taken using the available lens.

Figure 8

A different method was then used to get draining characteristics in vertical tubes. The automatic detection of interface did not work but human eyes can see it after zooming into a frame of the video. Each video was divided into 100 frames and the position of interface level was noted manually for every video. These 100 points for every video was plotted as x/L vs time with x being the position and L, the length of tube. Figures 9, 10 and 11 show selected three frames with arrows pointed to interface levels.

Figure 9

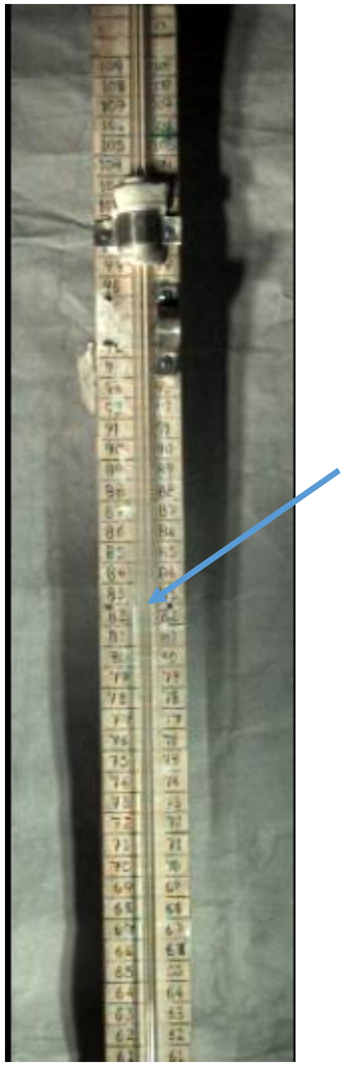


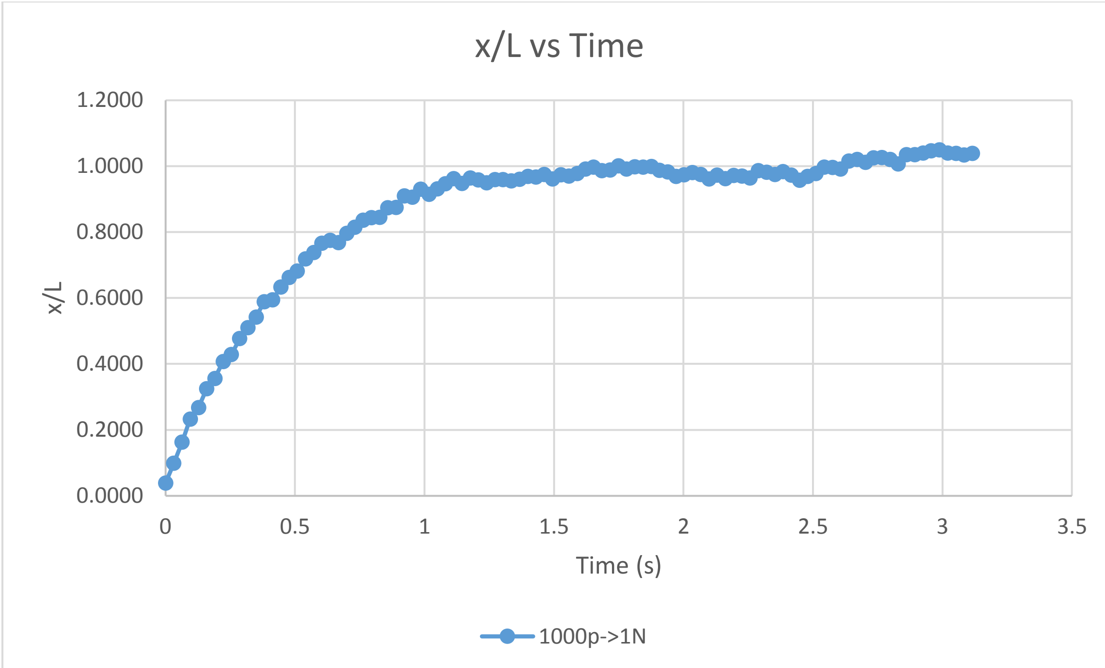
Figure 10

Figure 11

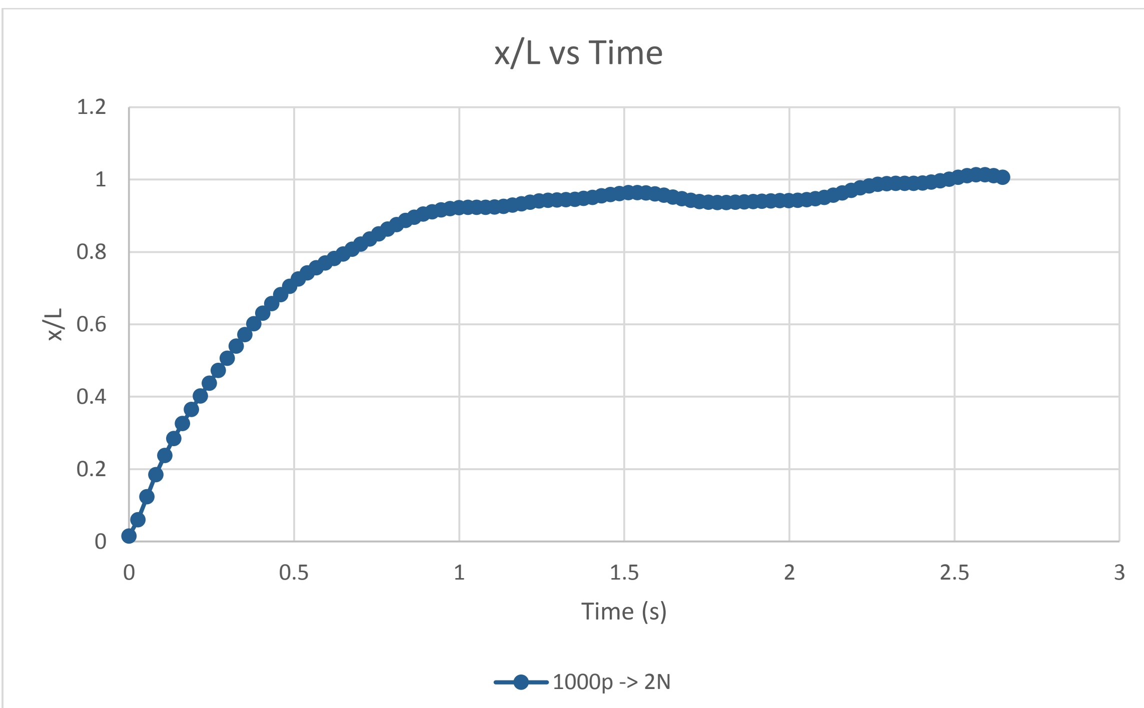
Results for 2 MM Diameter

1000 PPM Solution

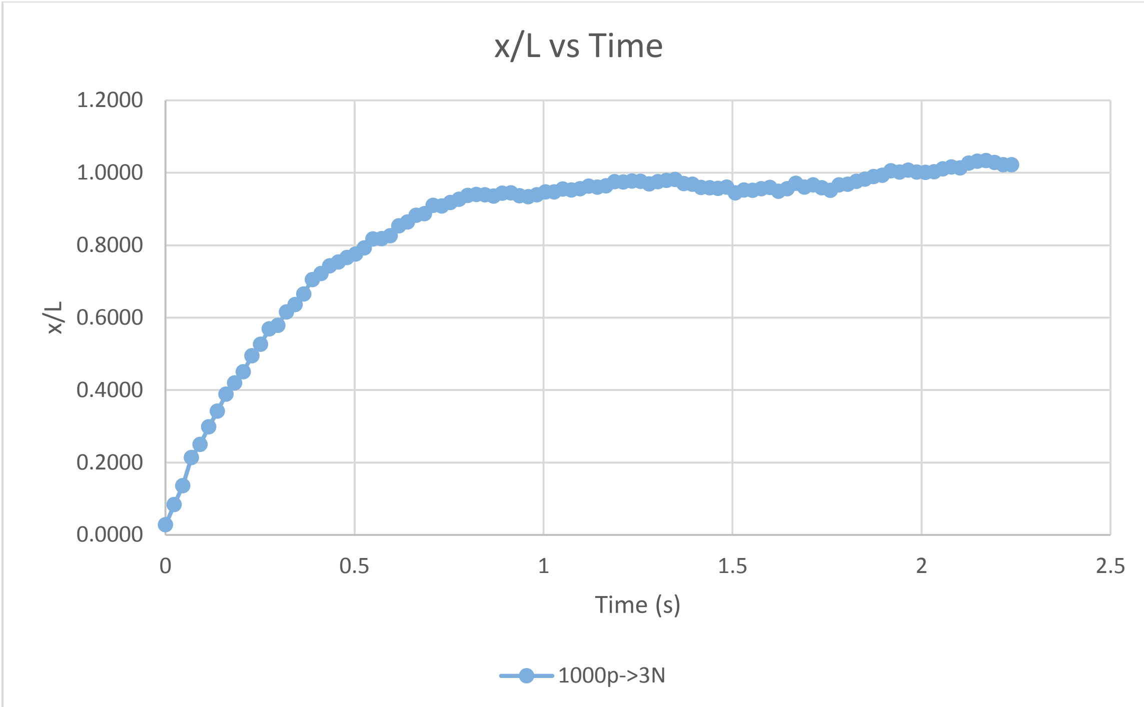
- 1 Needle



- 2 Needle

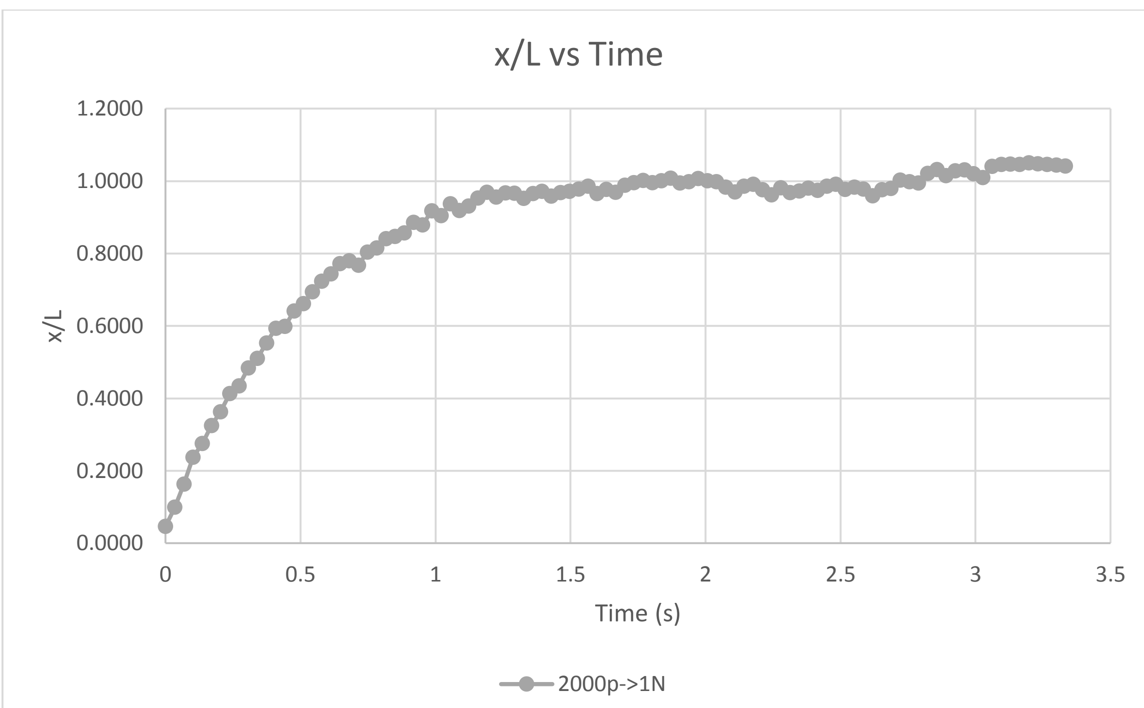


- 3 Needle



2000 PPM Solution

- 1 Needle



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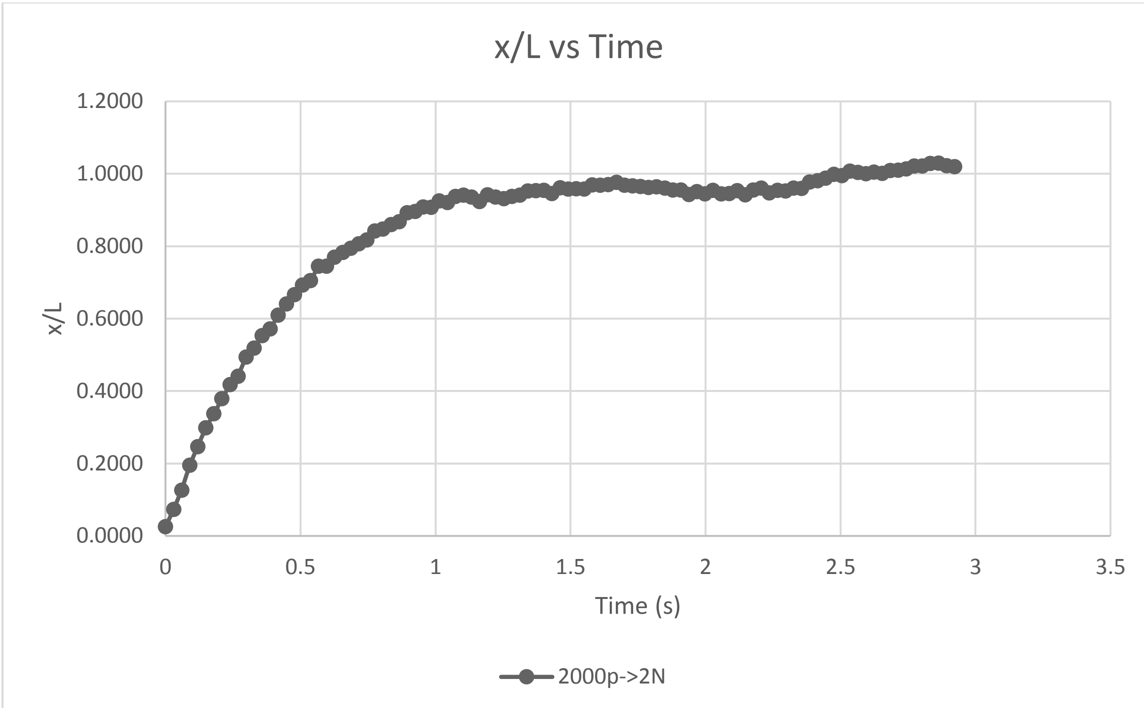
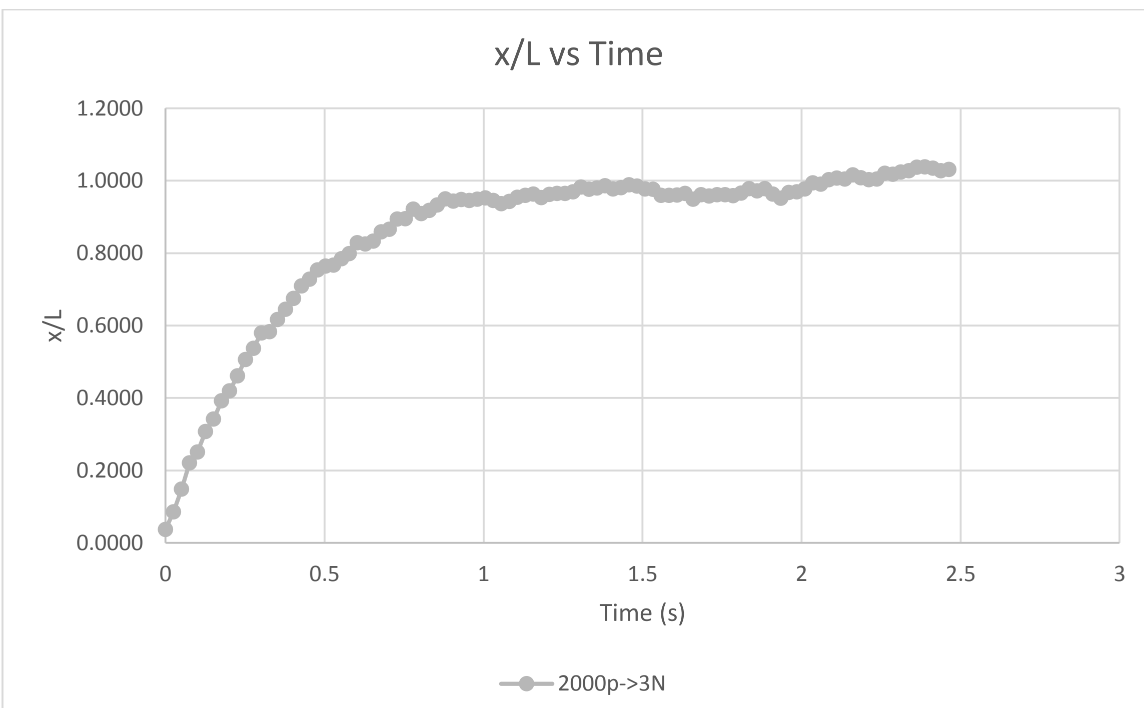
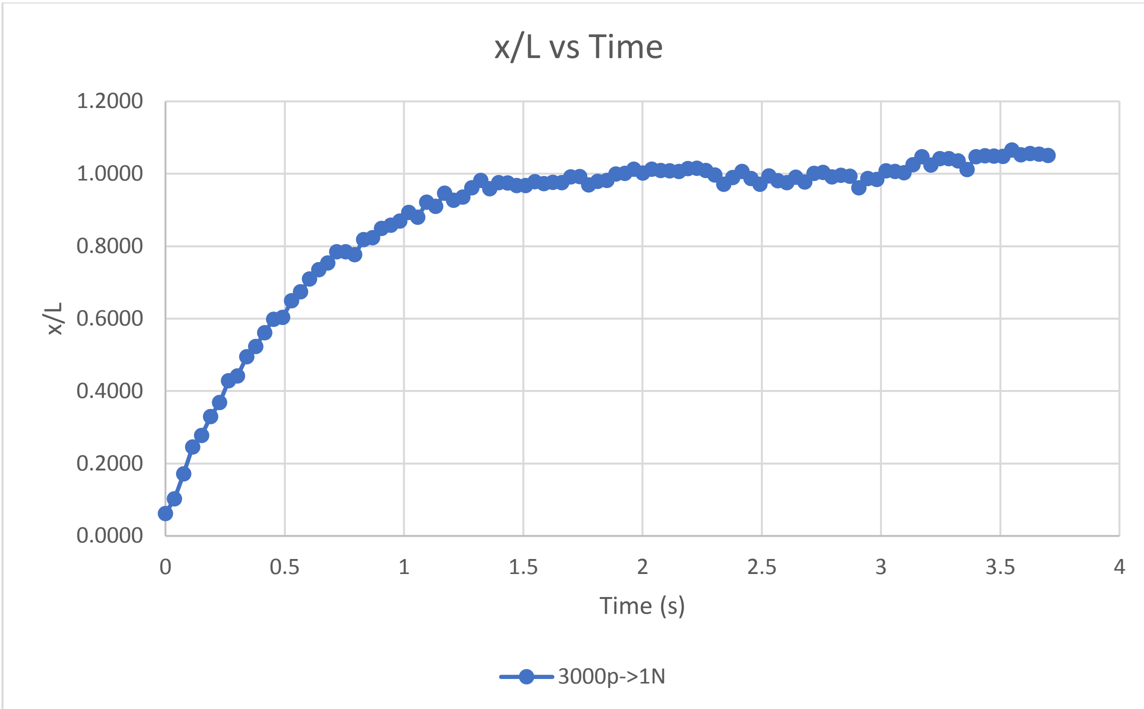


- 3 Needle



3000 PPM Solution

- 1 Needle



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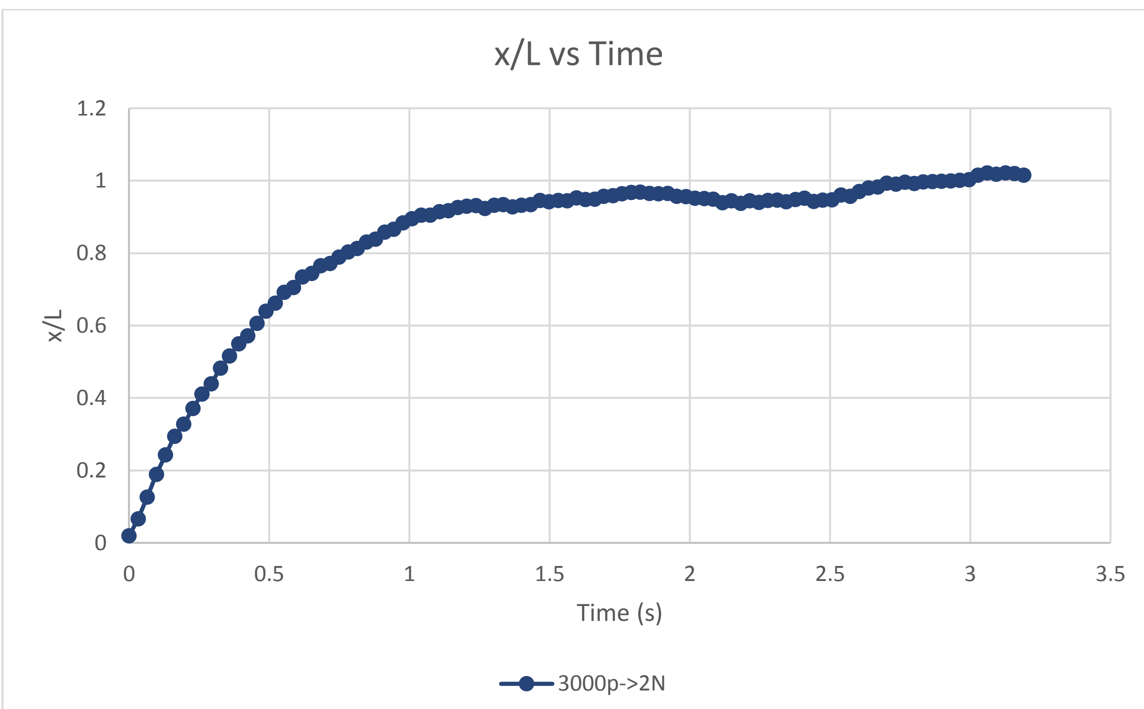
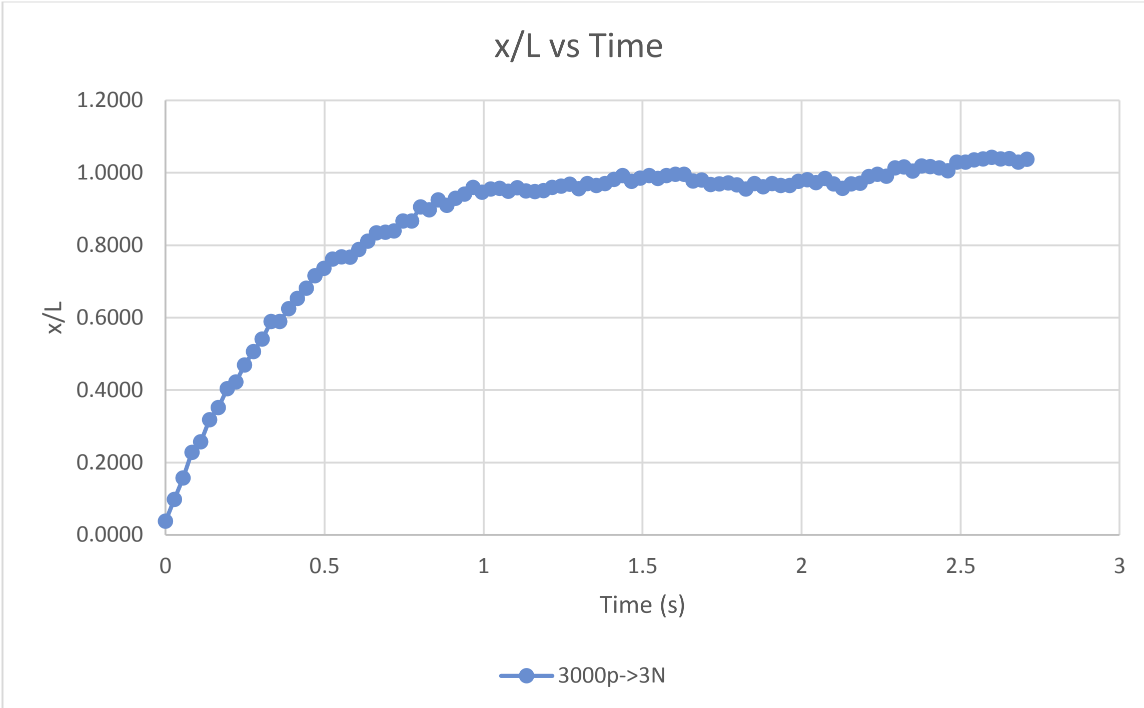


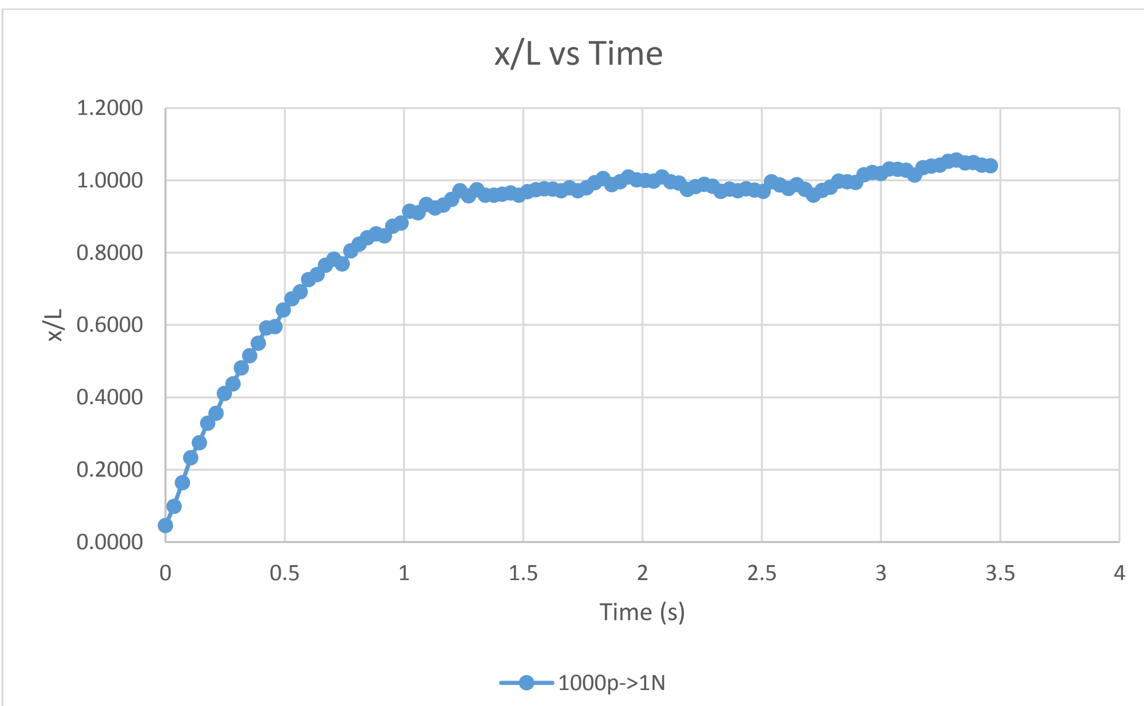
– 3 Needle



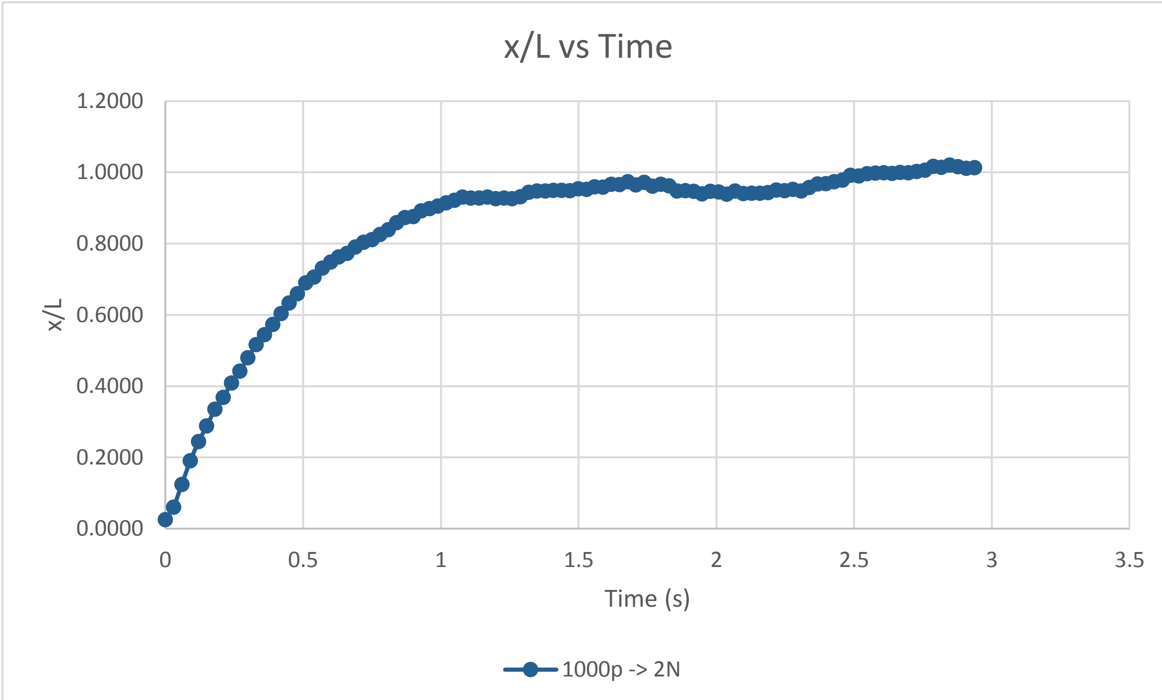
Results for 4 MM Diameter

1000 PPM Solution

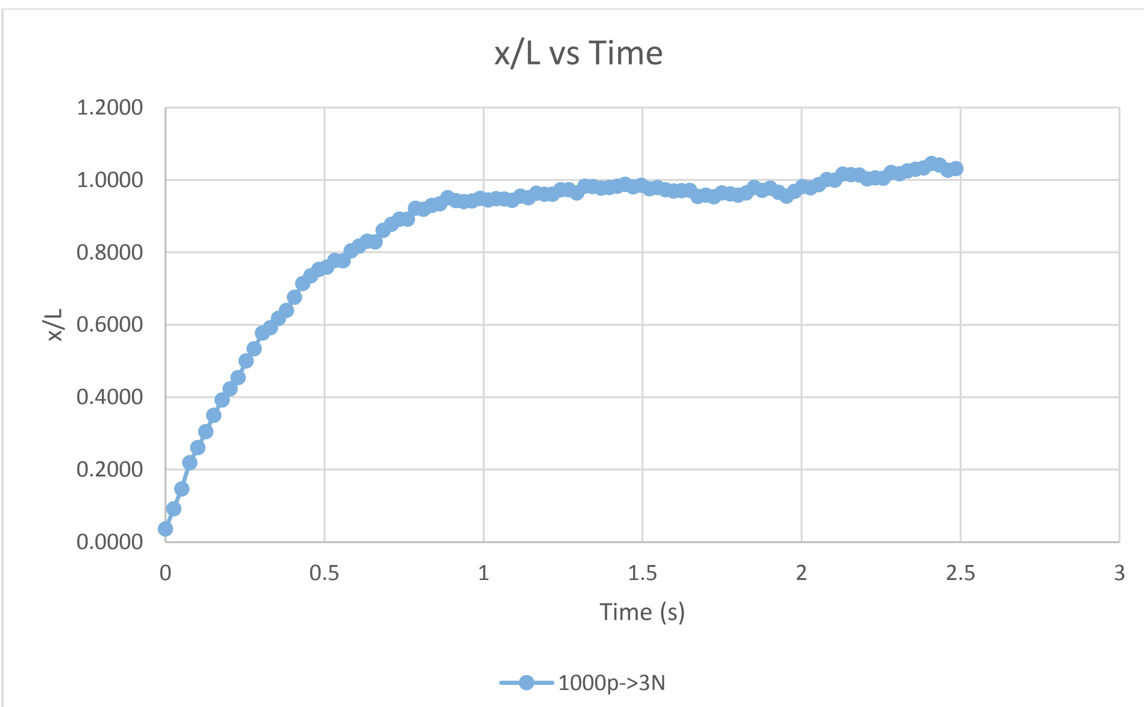
- 1 Needle



- 2 Needle

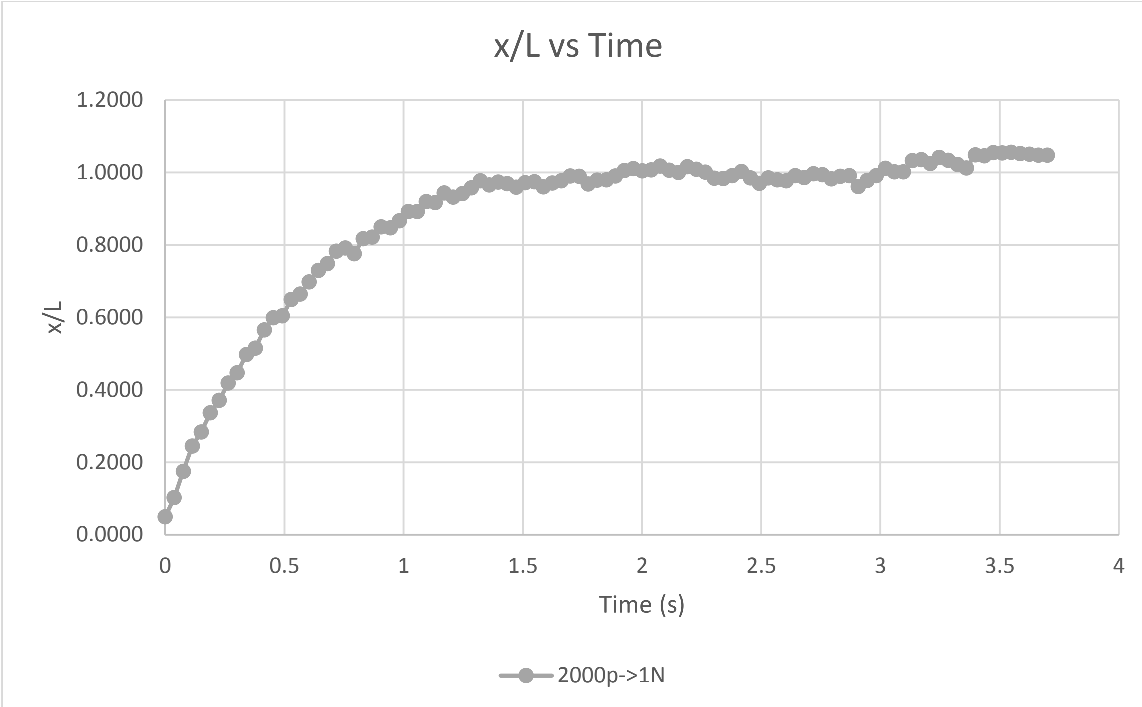


- 3 Needle

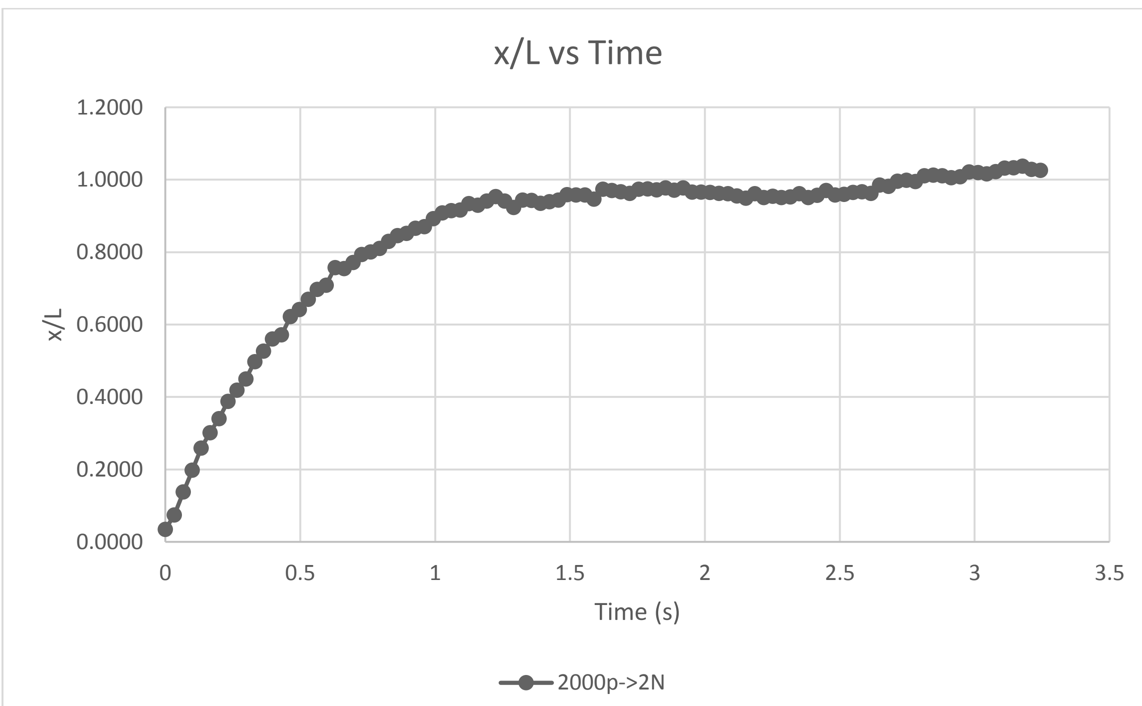


2000 PPM Solution

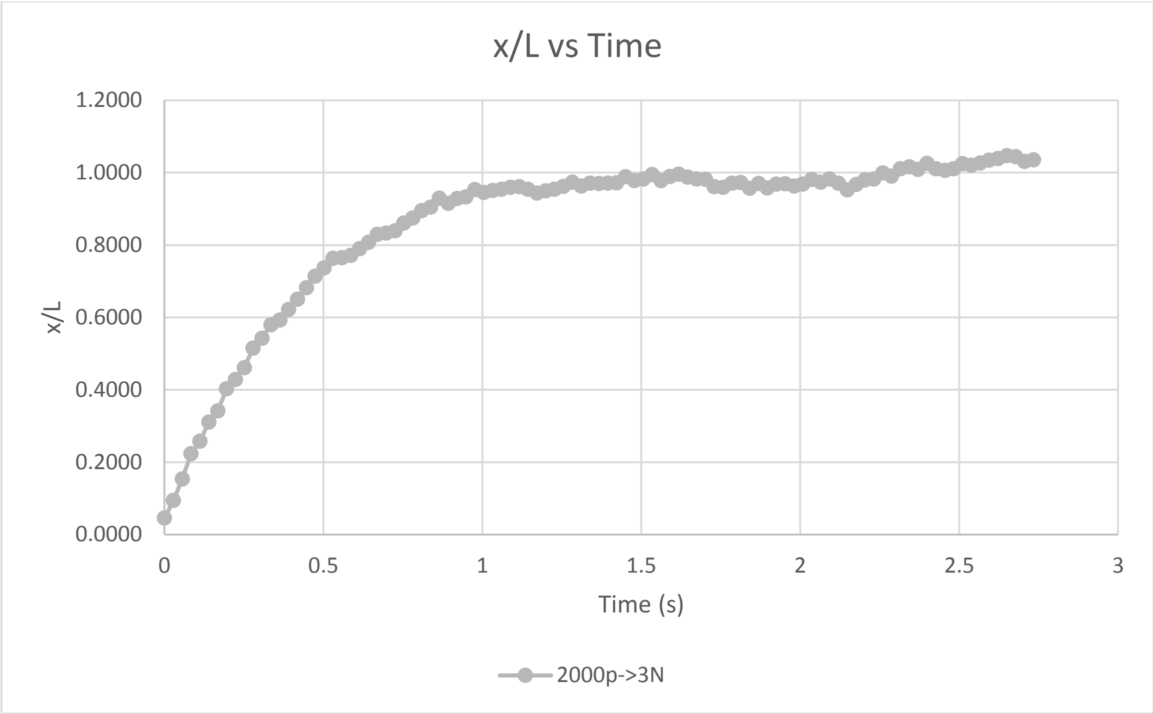
- 1 Needle



- 2 Needle

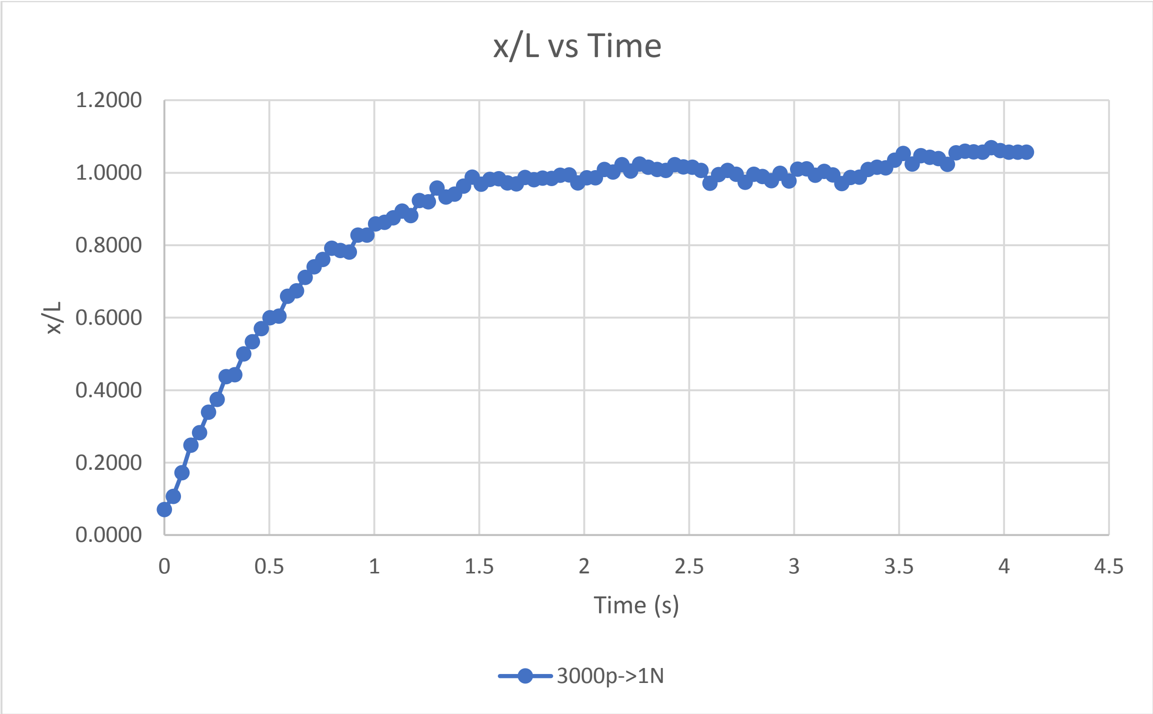


- 3 Needle

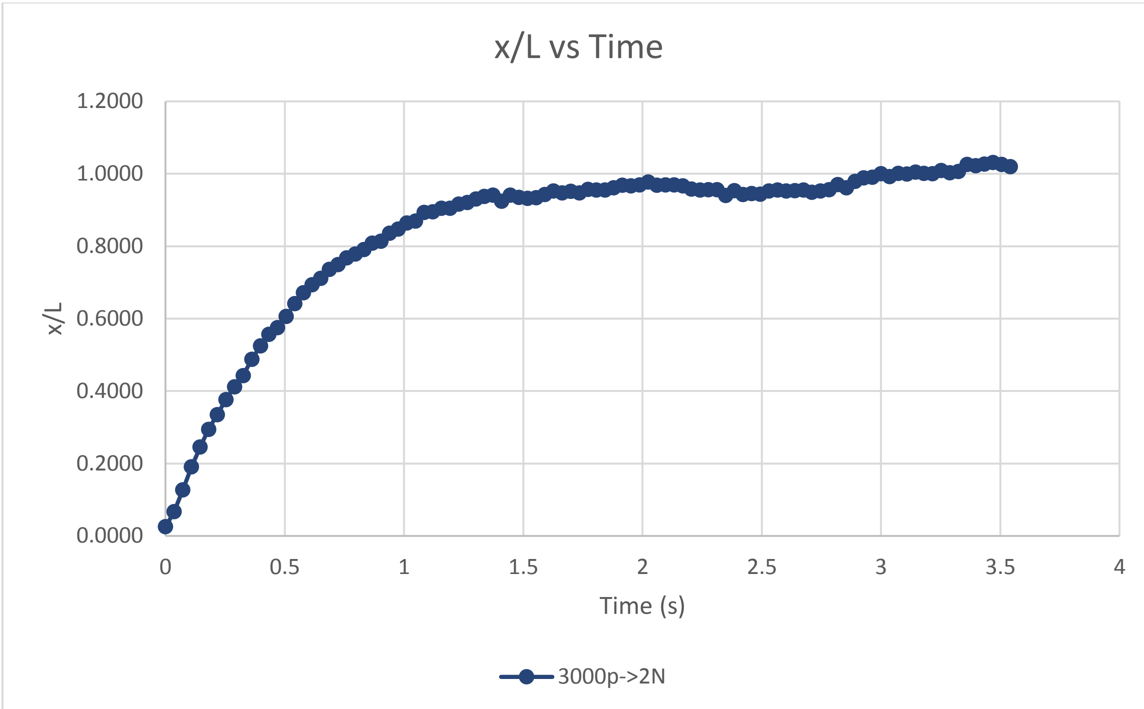


3000 PPM Solution

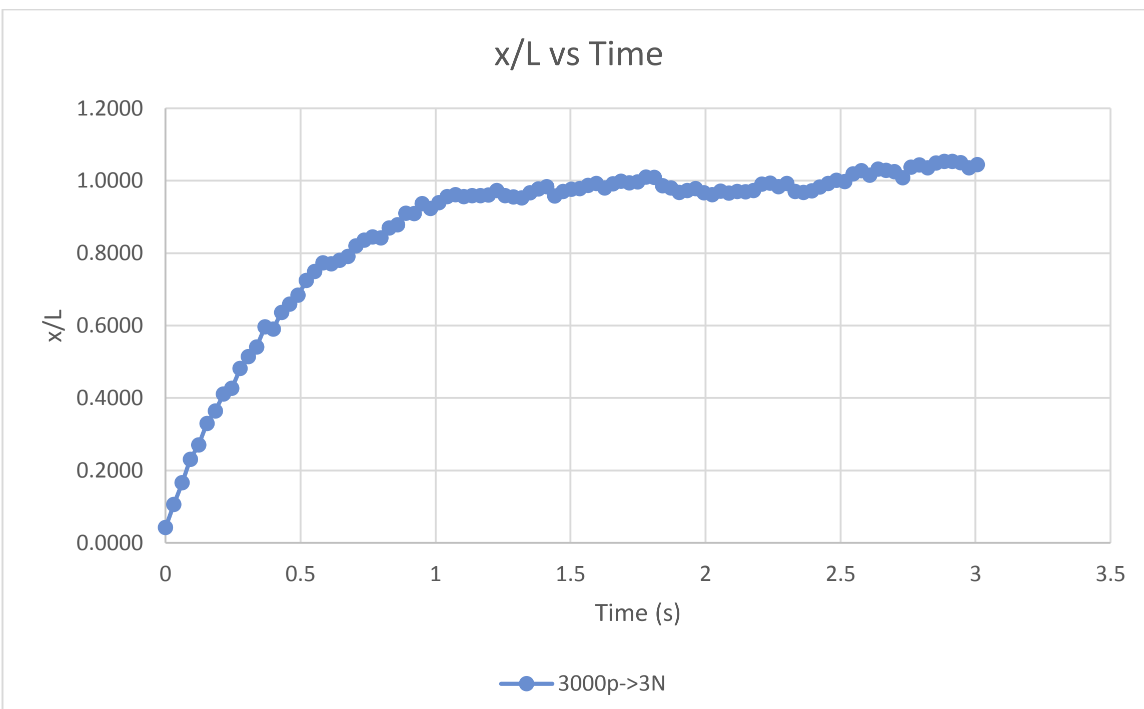
- 1 Needle



- 2 Needle


x/L vs Time
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)
3000p->2N

- 3 Needle


x/L vs Time
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
x/L
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)
3000p->3N

Conclusion

Interface Level Tracking algorithm was implemented and tested for it performance on prototype videos. Experiments were performed recording videos of draining in mini-channels which were then tested using automatic interface tracking which did not give good results due to poor quality of video due to large distance of camera from vertical tube during recording. So, interface level was tracked manually skipping frames compromising the accuracy and continuity of the data points. But, graphs were plotted which gave was according to results that must be obtained according to literature.

Future Work

1. Simulation of developed model to validate results with experimental data.
2. Developing and Simulation of the model for inclined tubes.
3. Perform experiment with wider lens to get more accurate data by automatic tracking.

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