Entrance Length of Polymer Flows

By

Kevin Nelson

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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(MECHANICAL ENGINEERING)

Approved by,

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(Dr. Azuraien Jaafar)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Kevin Nelson)

ABSTRACT

Most industrial applications involve flow through pipes in the world today, besides water piping many other fluids are being transported through pipes such as petroleum, sludge, drilling mud, chemicals which are of various viscosity and shear-stress profiles which affects flow performance. Therefore in this study, research is conducted on non-Newtonian polymer fluids with viscosity effects flowing through a flow loop piping; flow characteristics data is taken in order to the determine entrance length for the flow and is compared with water. Results are documented and delineated; the successful completion of this study is expected to contribute in assuring accurate data collection from such pipes in order to fill the gap of the limited studies conducted in this field as well as prevent pressure losses and velocity drops in industrial pipelines.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

The study of fluid flowing through a close conduit has been the subject of interest since the early work by [1] which concerned a Newtonian fluid. Flow of a non-Newtonian (polymer additives) fluid has multiple applications in the industry, especially in the oil and gas industry where the drilling fluid is concerned. Besides that, the other industries that practice this concept are the food, chemical and pharmaceutical industries. Many studies by researchers have been conducted in order to enhance the flow and improve the efficiency of the non-Newtonian fluid in the pipe flow through studying the entrance length required for these polymers to be fully developed in order to minimize the pressure drop and velocity loss in the transition from laminar to turbulent flow until turning fully developed. This is because the developing region of the flow is characterized as unstable and thus not valid as a data source for flow properties because flows encountered in practice are turbulent. As a result, to be able to conduct valid and valuable experiments in the flow loop, the data has to be taken from the fully developed region of the flow where it is stable. Therefore the main purpose of this study is to identify and acquire the entrance length data required for the flow to be fully developed for several polymer flows and to successfully characterize the entrance length hence delineating and documenting it. In order to identify and study the phenomenon, gathering of information regarding the involved fields and producing a literature review is done before conducting experiments in the flow loop where the pressure drop and flow rate are respectably measured. Theories and calculations are then applied to calculate the entrance length required. The outcome is then compared with Newtonian flow (water) and is documented for future uses.

Hence, as mentioned above, successful data understanding could make a difference in the industries using this polymer in their applications by enhancing the flow rates for efficient productivity besides than guiding engineers is piping design. Another outcome is to fill in the gap in literature as there is very little literature provided on the entrance length related to turbulent flows.

1.2 Problem Statement

The developing region of the Flow is characterized as unstable and thus not valid as a data source for flow properties. As a result, to be able to conduct valid and valuable experiments in the flow loop, the data has to be taken from the fully developed region of the flow.

1.3 Objective of Study

1. To get better understanding and depth knowledge of developing flow, Fully Developed Flow and flow regimes of polymers flow.

2. To identify and acquire the Entrance length data for Polymer Flows.

3. To successfully characterize the Entrance Length of Polymer flows and methodically delineate and document it.

1.4 Scope of Study

This project aims to perform experiments on the flow loop using water (Newtonian fluid), polyacrylamide polymer (Non-Newtonian fluid) and Xanthan Gum (Non-Newtonian fluid) in order together data at various points such as the flow rate and pressure drop using the flow meter. Therefore, using experimental method to gain the entrance length region and conduct comparison between the fluids. This project encompasses the following:

1- To perform data collection through flow loop experiments,

2- To use experimental means to calculate the entrance length so as the laminar, transition and turbulence region,

3- To do comparison between the two types of fluid, study the differences and methodically delineate and document it.

1.5 Project Feasibility

This is feasible of the project is guaranteed since all needed facilities such as laboratory equipment and the flow loop are available at the place of study "University Technology PETRONAS, UTP" and the theories and formulas has been taught in the Fluid Mechanics 1 and 2 courses as well as gained from the internet and textbook. Therefore, based on the proposed methodology and Gantt chart, we are able to complete all the activities within the timeframe.

CHAPTER 2
LITERATURE REVIEW

This chapter will deal with the literature research of the type of fluid flow regime and entrance length theory along the pipeline. In this project, the experiment will be using Xanthan Gum and Polyacrylamide polymer as the agent with 5 different concentrations to see the effects on the entrance length reduction effectiveness in water system (pipeline).

Turbulent flow is believed can caused increase in frictional drag and pressure loss along the pipeline. Increase in pressure loss will become a major difficulty for the flow assurance of the transported fluid since it can slow down the flow rate. However, by using polymers, it is proven that it can reduce the turbulence degree and further increase the pressure drop along the pipeline.

2.1 Newtonian and Non-Newtonian Fluid

2.1.1 Newtonian Fluid

A fluid is described as Newtonian when the viscous stresses are proportional to the strain rate [1], [2]. Newtonian fluids have the simplest mathematical models that account for their viscosity where basically no fluid in reality fits the definition therefore common liquids such as water, gasses or air are assumed to be Newtonian under normal conditions. Newtonian fluids are named after Isaac Newton, the person who brought about the relation between the shear strain rate and shear stress for such fluids. [3] For a Newtonian fluid under steady, simple shear flow [4]

Equation 1: $$\mathbf{U = \dot{\gamma} y \quad v = w = 0}$$

Where $\dot{\gamma}$ shear rate, and the only stress acting on the fluid is the shear stress in the direction of flow, τ as shown in **figure 2.1** which is a function of shear rate and viscosity, η [4]

Equation 2: $\boldsymbol{\tau = \eta\dot{\gamma}}$

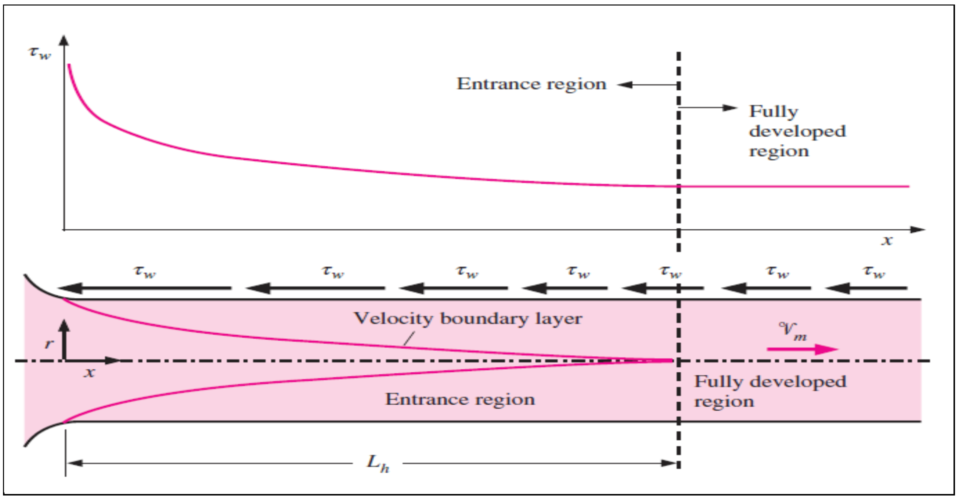

FIGURE 2.1: The variation of wall shear stress in the flow direction

2.1.2 Non Newtonian Fluid

A non-Newtonian fluid is a fluid where the viscosity is dependent on shear rate however some have shear independent viscosity. In a non-Newtonian fluid, the relation of the shear stress and shear rate are different hence can even be independent of time. This makes the constant coefficient of viscosity indefinable although the viscosity concept is very much used to characterize the shear properties of fluid. Non-Newtonian fluids are better studied using other rheological properties where the stress and strain rate is related under different conditions. The properties are studied using tensor-valued constitutive equations which are common in continuum mechanics. [5]

The shear viscosity is defined analogously to the viscosity of a Newtonian fluid. [4]

Equation 3: $$\boldsymbol{\eta(\dot{\gamma})=\frac{\tau(\dot{\gamma})}{\dot{\gamma}}}$$

Where, $\boldsymbol{\eta}$ is a function of shear stress rate with the exception of yield stress and boger fluids. The function used in this study to determine the shear stress would be;

Equation 4: $$\Delta \boldsymbol{P} = \frac{\boldsymbol{\tau_w 4L}}{\boldsymbol{d}}$$

Where if manipulated;

Equation 5: $$\boldsymbol{\tau_w} = \frac{\Delta \boldsymbol{Pd}}{\boldsymbol{4L}}$$

Another type of non-Newtonian fluid is the viscoelastic fluid which has elastic recovery as well as viscous properties. All viscoelastic fluids can be categorized as non-Newtonian but not likewise. [6] For a simple shear flow, a viscoelastic fluid would give two extra normal stresses apart from the shear stress alone. When a viscoelastic fluid is sheared, some of its energy would be stored in the elastic form and not all is dissipated as pure viscous fluids. Due to its elasticity, when shearing applied is stopped, the energy stored is released but it would consume some time to stop therefore, it is said to have stress relaxation. [4], [6].

One more type of non-Newtonian fluid is pseudoplastic fluid or shear thinning where its viscosity decreases with the increasing shear rate from intermolecular interaction or entanglement taken apart thus enabling other particles or molecules to move past each other easily. [7] This fluid is then said to possess yield stress. Only if the force applied is greater than its binding force, which has reached its critical yield stress, the molecular hold among each other would break hence allowing flow to occur. This critical yield stress is termed the yield stress of the material. [4] Thixotropy is a situation where the viscosity decreases under constant shear rate, then a gradual recovery over time as the shear rate is stopped. Many gels and colloids have thixotropic behavior where they are initially in solid form but become fluid when meddled with. [4]

2.1.3 Comparison between shear stress and shear rate of Newtonian and Non-Newtonian fluids.

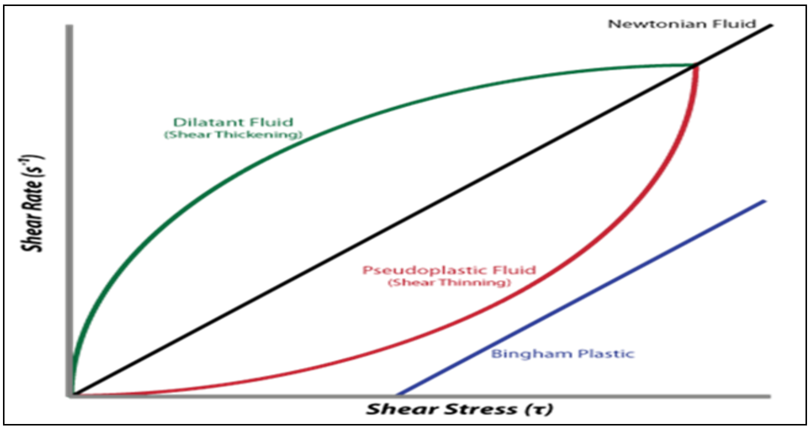

FIGURE 2.2: Shear Stress versus Shear Rate Diagram [8]

Newtonian fluids are fluids where the relation between shear stress and shear rate is proportional where it is also a coefficient of viscosity as indicated in **Figure 2.3**. The behavior of Newtonian liquid is as follows:

1) Shear stress is only generated in shear flow.

2) Shear viscosity does not vary with shear rate.

3) The viscosity is constant with respect to time.

4) Viscosities measured in different deformation are always proportionate to one another.

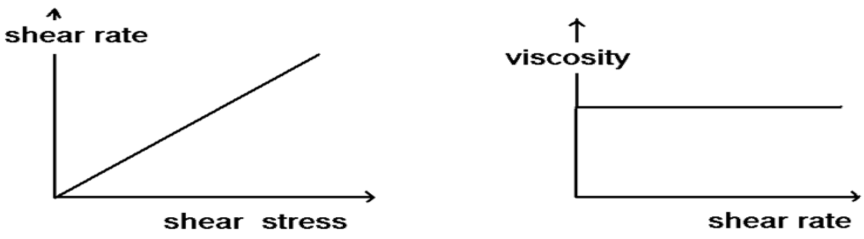

FIGURE 2.3: Newtonian Shear Stress vs Shear Rate [9]

Non -Newtonian fluids flow properties differ from the behavior of Newtonian. It is always related to the viscosity (which is a measure of the fluids ability to resist deformation by shear or tensile stresses) where the viscosity is dependent on shear rate. This is because the viscosity of non-Newtonian fluid changes as the shear rate is varied. There are several types of non-Newtonian fluid behavior which is defined by the viscosity changes in response to shear rate [14]. Among them are

1) Pseudoplastic/Thixotropic

-A decreasing viscosity with increasing shear rate. This behavior is also termed shear thinning (paint and emulsions) as indicated in **figure 2.4**.

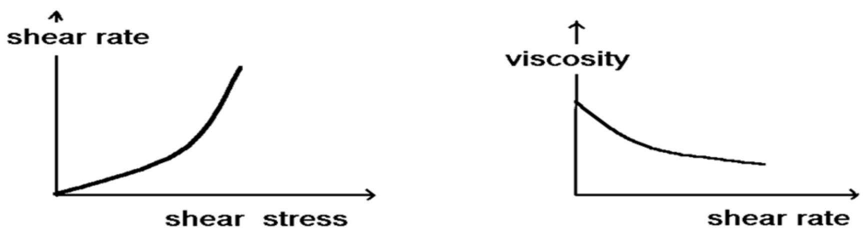

FIGURE 2.4: Psuedoplastic Fluid Shear Stress vs Shear Rate [9]

2) Dilatant

–An increasing viscosity with increasing shear rate as shown in **figure 2.5** below. Also termed shear thickening fluid (Clay slurries, cornstarch in water, and/ water mixture).

FIGURE 2.5: Dilatant Fluid Shear Stress vs Shear Rate [9]

3) Bingham Plastic

-Solid under static conditions. A certain amount of force or yield value has to be applied to the fluid before any flow is induced. Once exceeded the yield value, the flow will begin as displayed in **figure 2.6**. This type of liquid may display Newtonian pseudoplastic or dilatant flow characteristics. (Tomato ketchup)

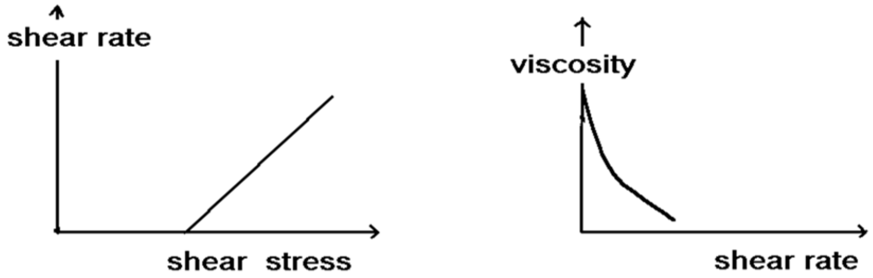

FIGURE 2.6: Bingham Plastic Fluid Shear Stress vs Shear Rate [9]

2.2 Entrance Length: Newtonian vs. Non-Newtonian

The benefits and importance of understanding the development length of a pipe flow to fully develop or in other words for the velocity profile and pressure drop per unit length to become non-varying in the axial direction has been long established and since then recognized. The development length is not only practiced in design of pipe flow systems for instance, but it is also beneficial for engineers to study such flows and their transition from laminar to turbulence. [10]. Many studies have been conducted in order to define the relation between the non-dimensional entrance length (X_D/D) and the Reynolds number ($X_D/D = C_1Re$) in terms of analytical [11], [12], [13] numerical [14], [15], [16] and experimental [17], [18] methods. However from the paper of Durst et al. [19], he disagreed as these studies incorrectly provided the variation of X_D in the form of $X_D/D = C_1Re$ as these relationship does not imply with the creeping flow limit of Re->0. As a matter of fact, at low Reynolds number, diffusion plays a major role therefore the correct function of the development length should be

Equation 6: $$X_D/D = C_0 + C_1Re$$

And to further support his theory, Durst et al. [19] conducted a detailed numerical study and proposed the non-linear equation

Equation 7: $$X_D/D = [(0.619)^{1.6} + (0.0567Re)^{1.6}]^{1/1.6}$$

Which is valid for $0<Re<\infty$. Therefore we also can know that the transition from laminar to turbulence could be delayed if the Reynolds number [10] is higher therefore we could understand well the situation for Newtonian fluid where the correlation is available.

For non-Newtonian fluid flows, in comparison to the situation for Newtonian fluid flows, the literature is a little scarcer although less contradictory. In Table 1 below, most of the previous investigations using the “power-law” model in this area is summarized. Much as Durst et al. [19] observed for Newtonian fluid flows, nearly all of these previous studies produce a relationship of

Equation 8: $$X_D/D = C(Re)$$

Where $C = f(n)$ and n is the power-law index. These correlations neglect the effects of diffusion, which eventually becomes important with the decreasing Reynolds number. Based on the numerical results gained, a correlation of the form of $X_D/D = C(Re)$ will be only valid if the Reynolds number is more than 20. Moreover, there are clear differences for the “high Reynolds number” estimation in the Newtonian limit, (n=1). Only three studies carried out are within ±10% of the robust value of 0.0567Re determined recently in the numerical study of Mehrota and Patience [20], 0.056Re; and Ookawara et al. [21], 0.0575Re. Ookawara et al.[21] is the only study in the literature that proposes both correlations of the correct form (maximum 5.8% error) in agreement with Durst et al. [19] in the Newtonian limit. However, Ookawara et al. [21] predicts that in the creeping-flow limit, the development length is independent of the power-law index, n and equal in magnitude terms to the Newtonian development length. Such a result may seems surprising given the nonlinearity that is retained in the governing equations through the power-law equation which is in contrast to the corresponding equations for creeping Newtonian flow, which are, of course, linear.

Table 2.1: Summary of previous investigations of development-length requirements for non-Newtonian power-law pipe flow [22]

Author	Method	Parameter Range	Re Definition	Re Range	*XD*= *f*(Re)	Newtonian prediction
Collins and Schowalter *[3]*	A	$0<n<1$	Re_{CS}	No range provided	$X_D/D=C(Re)$ where $C=f(n)$	$X_D/D=0.061(Re)$
Mashelkar *[11]*	A	$0<n<1$	Re_{CS}	"High Re"	$X_D/D=C(Re)$ where $C=f(n)$	$X_D/D=0.049(Re)$
Soto and Shah *[12]*	N	$n=0.5$, 0.75 and 1.5	Re_{CS}	No range provided	$X_D/D=(0.15-0.085n)Re_a$	$X_D/D=0.065(Re)$
Matros and Nowak *[13]*	A	No limit provided	Re_{MR}	No range provided	$X_D/D=Re\left\{0.0865\left[\frac{2(n+1)}{3n+1}\right]^{-2}\right\}$	$X_D/D=0.0865(Re)$
Mehrota and Patience *[14]*	N	$0.6<n<1.5$	Re_{MR}	>200	$X_D/D=0.056(Re)$	
Ookawara et al. *[15]*	N	No limit provided	Consult ref	<50	$X_D/D=\sqrt{(0.655)^2+(0.0575)^2+(Re)^2}$	
Gupta *[16]*	A	$0.3<n<2.0$	Re_{MR}	No range provided	$X_D/D=C(Re)$ where $C=f(n)$	$X_D/D=0.04(Re)$
Chebbi *[17]*	A	$0<n<1.5$	Re_{CS}	No range provided	$X_D/D=C(Re)$ where $C=f(n)$	$X_D/D=0.09(Re)$

However, there has not been much literature findings on turbulent flow as this section is more complicated and varies with different experiments conducted depending on the pipe, flow and fluid characteristics. Therefore this experiment could help fill a gap in the knowledge of turbulent entrance length. Based on current textbooks [23] the entrance length is the length from the entrance region of the pipe till the section where the fluid has fully developed.

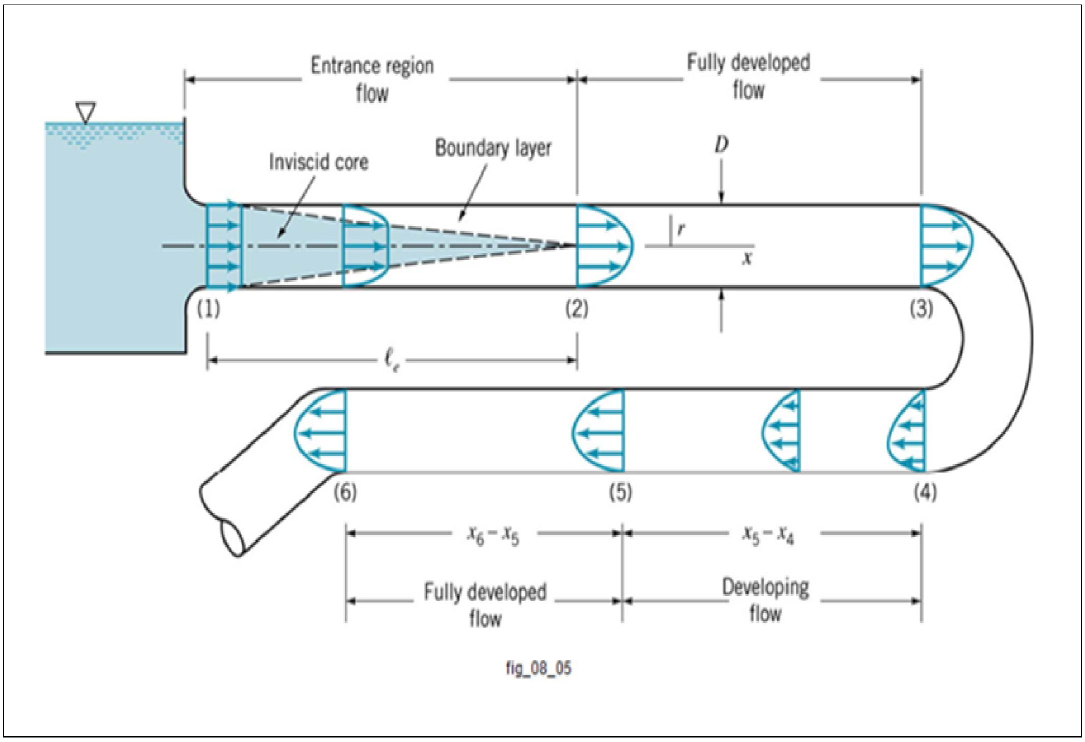

FIGURE 2.7: Entrance Length Area In Pipe Flow [23]

From **Figure 2.7** above, fluid enters the pipe with approximately a uniform velocity profile at section (1). As the fluid moves through, viscous effects may cause it to stick to the wall of the pipe. Thus a boundary layer where the viscous effects are important is produced along the wall causing the initial velocity profile to change with distance along the pipe, x until it reaches the entrance length at section (2), beyond where the velocity profile does not vary with x anymore. The shape of the velocity profile depends on whether the flow is laminar or either turbulent, so as the length of the entrance region, X_D. As including the other properties of the pipe flow the dimensionless entrance length, X_D/D, correlates well with the Reynolds number, Re. Hence the typical and standardized entrance length specified is: [23]

Equation 9: $X_D/D = 0.06Re$ **(for laminar flow)**

And

Equation 10: $X_D/D = 4.4Re^{1/6}$ **(for turbulent flow)**

As observed from the equations, for a low Reynolds number the entrance length can be quite short (X_D=0.6D if Re=10) whereas for a larger Reynolds number the length could be longer or perhaps equal to many diameters of the pipe (X_D=120D for Re=2000).In reality for engineering problems, 10^4<Re<10^5 leads to the margin of 20D<X_D<30D. This results is much smaller compared to the laminar flow formula, therefore this is where Re is only limited to Re<2300 for laminar until it is considered turbulent if Re>4000. This overall makes the entrance length for laminar longer for larger Reynolds number compared to turbulent flow of large Reynolds number theoretically. [23]

However, once the flow has reached the end of the entrance region, which is section (2) of the figure, the flow becomes simpler as it is stabled where the velocity is a function of distance from the center line, r, and independent of x. This is true until the characteristic of the pipe changes either in diameter, bend, valve, or in some way at section (3). Flow between (2) and (3) is termed fully developed flow. After the change in characteristic, at section (4) the flow will begin to develop again for a length until it is stable at (5) and will go on with its profile until another change in (6). In many cases the fully developed length is longer than the developing length whereas is other cases the distance between two characters of the pipe is so short that the fully developed flow is never achieved and this could decrease efficiency of design as well as flow.[23].

2.3 Laminar, Transition and Turbulence Region for Newtonian and Non-Newtonian Fluid

2.3.1 General Background of Laminar, Transition and Turbulence Phenomena

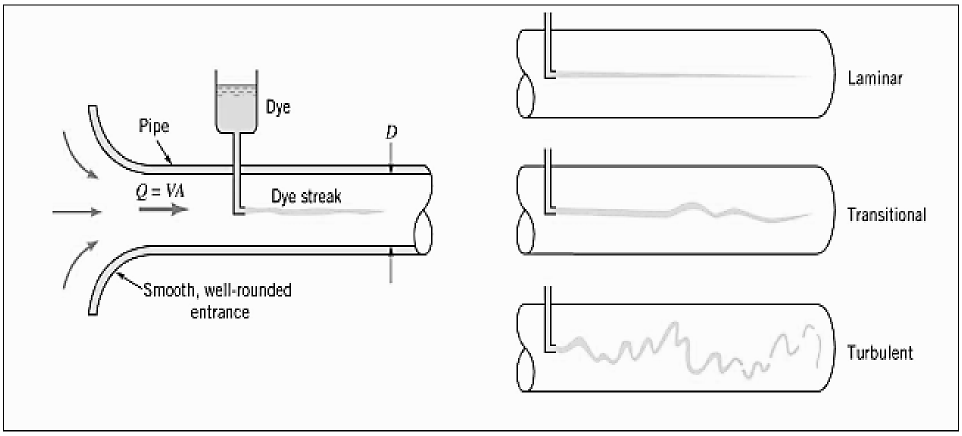

FIGURE 2.8: Indications of Laminar, Transitional and Turbulent Using Dye Streak [24]

From **figure 2.8** above, the characteristic of the streak line formed by the dye is dependent on the fluid's velocity where:

- When the velocity of the fluid is slowest, the dye well defines a streak line and the flow in this situation is termed laminar flow
- As the momentum is gradually picked up and the fluid moves with an intermediate velocity, irregularities happen to the streak line however the streak line is still well defined. This situation is termed transitional flow
- But as the flow picks up momentum and moves even faster, the streak line becomes uneven where it blurs and spreads the dye out. In this situation the streak line fluctuates randomly with time and is termed turbulent flow.

From **figure 2.9** blow, if we examine closely the velocity of component, *x* at a point *A* we can determine the velocity roughly at the respected points:

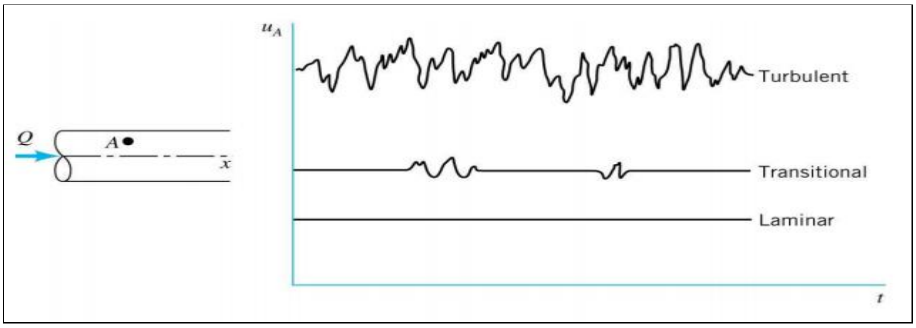

FIGURE 2.9: Velocity Components in a Pipe Flow [24]

- The flow at the laminar area has a constant velocity, U_A which is also the smallest value
- Whereas in the transitional zone the flow has mostly a constant U_A but with random fluctuations
- However at the turbulent region, the flow adopts a fluctuating U_A about some mean value. At this region the flow rate is also the largest

2.3.2 Newtonian and Non-Newtonian laminar and turbulent pipe flow

Fluid flow can be described into 2 behaviours which is laminar flow and turbulent flow. [24]. In laminar flow, the fluid flow in a uniform manner. Dye streak that is injected into the flow produced a smooth and straight line in laminar region. In contrast, dye streak will form random zig-zag motion in turbulent flow. In turbulent flow, the fluid is flowing in highly disorder or chaotic manner. The transformation between laminar flow into turbulent flow is called transition state.

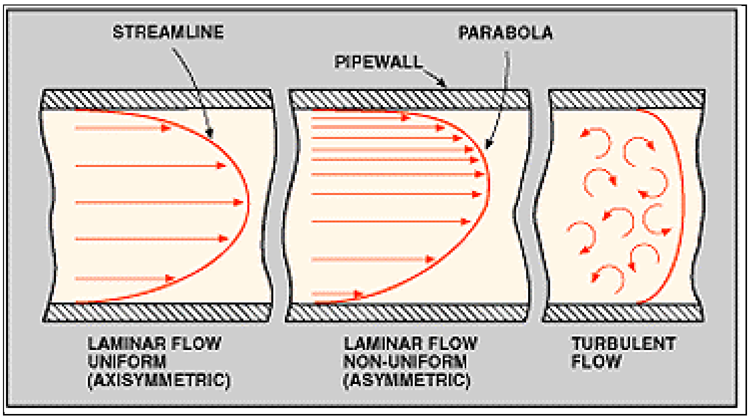

Figure 2.10: Laminar flow and turbulence flow in a pipeline side view

During the fluid flow, not all fluid particles travel at the same velocity within a pipe. The fluid velocity in a pipe changes from zero at the inner wall surface to maximum at the center of the pipe. The fluid velocity is zero at the wall due to no-slip condition and the velocity must be highest at the center to keep mass flow rate.

The shape of the velocity curve, which is represent in the velocity profile across any given section of the pipe, depends upon whether the flow is laminar or turbulent. If the flow in a pipe is laminar, the velocity distribution at a cross section will be parabolic in shape with the maximum velocity at the center being about twice the average velocity in the pipe. In turbulent flow, a fairly flat velocity distribution exists across the section of pipe, with the result that the entire fluid flows at a given single value. **Figure 2.11** below illustrates the above theory of velocity profile in the pipe.

The collision of the fluid particles of the fluid did cause the kinematic energy to be converted into thermal energy but the temperature rise is too small to be considered in calculation. For instance, in the absence of heat transfer, no significant changes in term of the temperature of the fluid that is noticeable.

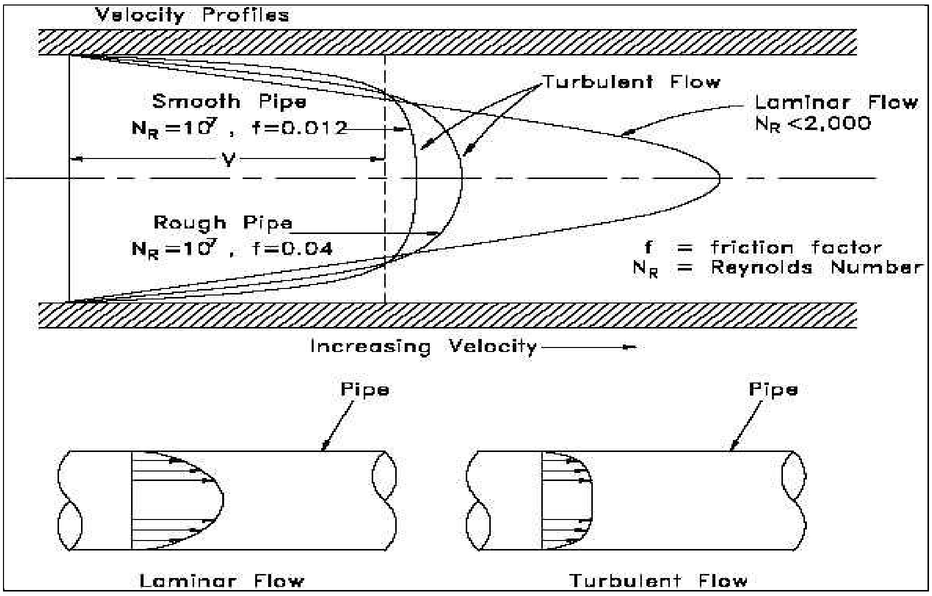

Figure 2.11: Laminar and Turbulent Flow Velocity Profile

Characterized by the distance to the wall, A. Cengel & John classified velocity profile in turbulent region into a few regions. The very thin layer next to the wall where viscous effect is dominant is the viscous sub layer. Next to the viscous sub layer is buffer layer, in which turbulent effect is significant, but the flow is still dominated by the viscous effect. Above the buffer layer is the overlap layer in which turbulent effect is significant. Above this layer is turbulent layer and the turbulent effect is much more significant compare to the overlap layer. Some literature classified these layers with other names.

The flow behavior can be distinguished based on the Reynolds number. Reynolds number is given as the ratio between inertial forces and viscous forces and flow behavior is dependent on which forces are more dominant.

$$\textbf{Equation 11:} \quad \boldsymbol{Re = \frac{\rho v D}{\mu}}$$

Dominant inertial force resulting in laminar flow and turbulent if the viscous tend to be dominant. Under most practical condition, fluid behaviors are classified according to following value of Reynolds number.

- Re < 2300 laminar flow
- 2300 < Re < 4000 transitional flow
- Re > 4000 turbulent flow

Two regions will be form inside the pipe which is entrance region and fully developed region. In hydrodynamic entrance region, the velocity profile of the fluid is being developed. After a certain distance from the entrance of pipe, the velocity profile will become constant and this region is known as hydrodynamic ally fully developed region. Velocity profile in the fully developed laminar flow has a parabolic shape and somewhat flatter in fully developed turbulent flow. Research area in this paper is focusing in fully developed turbulent region.

Turbulent flow is characterized by random and a rapid fluctuation of swirling region of fluid called eddies, throughout the flow. In turbulent flow, the swirling eddies transport mass, momentum and energy to other region of flow much more rapidly compare to laminar flow. [25]. In the study, it is observed that the viscous sub layer plays a passive role in drag reduction effect. However the buffer zone and logarithmic layer are considerately affected. The buffer zone increases in thickness with an increasing level of drag reduction. This will definitely result in high flow velocity in logarithmic layer, which is responsible for the increase in the flow rate with the introduction of drag reducing polymer.

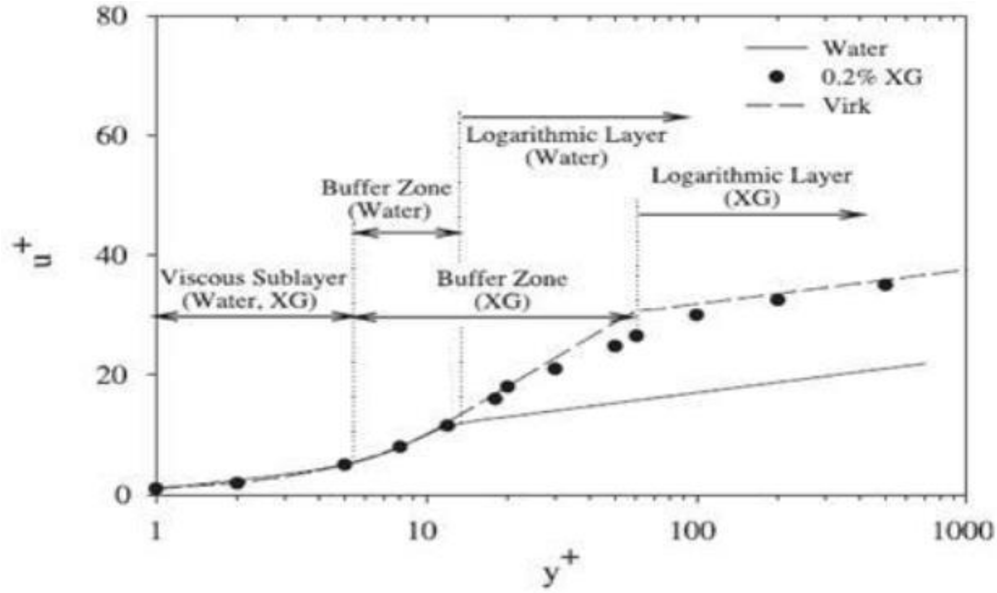

Figure 2.12: Thickness of buffer layer in water and Xanthan solution (polymer), [25]

As the mechanism involved, the drag reduction phenomenon is the attribute to the shear waves caused by the elasticity of polymer chain. This shear waves are argued to suppress the turbulent velocity fluctuations at small scales thereby reducing the viscous drag. In recent experimental work, it has been shown that turbulent shear stresses are substantially suppressed by polymer chain. This study revealed that unravelling of polymer chains is indeed an essential ingredient in the ability of a polymer to reduce viscous drag.

2.4 Polymer Fluid Used for Test

2.4.1 Polyacrylamide

Polyacrylamide (PAM) is a water soluble polymer made from acrylamide subunits. The molecular formula for PAM is C3H5NO as shown in **figure 2.13**. [26] PAM is commonly used to enhance the viscosity in water. It is a synthetic base chemical that suits a wide range of industrial applications. Among its largest use in industry are for wastewater treatment where it collects the fine particles together until they are large enough to be trapped by filters to form sludge. Another common use is to enhance oil recovery in oil and gas industries. This happens when PAM is added to the water as a function to push the locked oil in the reservoir towards the pump to increase productivity. [26]

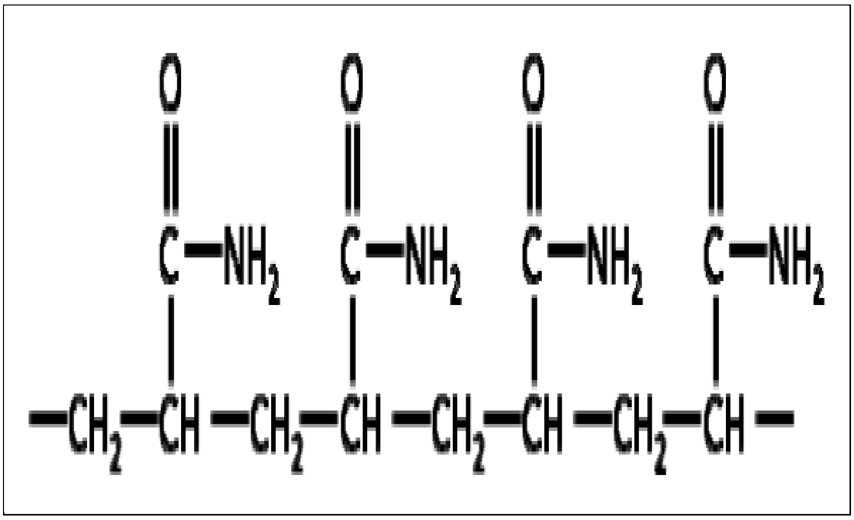

FIGURE 2.13: Chemical structure of Polyacrylamide [26]

2.4.2 Xanthan Gum (XG)

Xanthan gum is a polysaccharide formed by fermentation using xanthomonas campestris bacterium in a medium of carbohydrate, nitrogen and nutrient salts found in cabbage plants. Its molecular formula is $C_{35}H_{49}O_{29}$ as in **figure 2.14**. [27] It is able to produce large increase in viscosity of a fluid by just adding a minor amount close to one percent. It is a pseudoplastic fluid where its viscosity decreases with higher shear rates. One of its uses is in the oil industry where it thickens drilling mud in order to carry it back to the surface and when stopped, it remains suspended in the drilling fluid. Among its other general uses are for concrete underwater, food industries and cosmetics. [27]

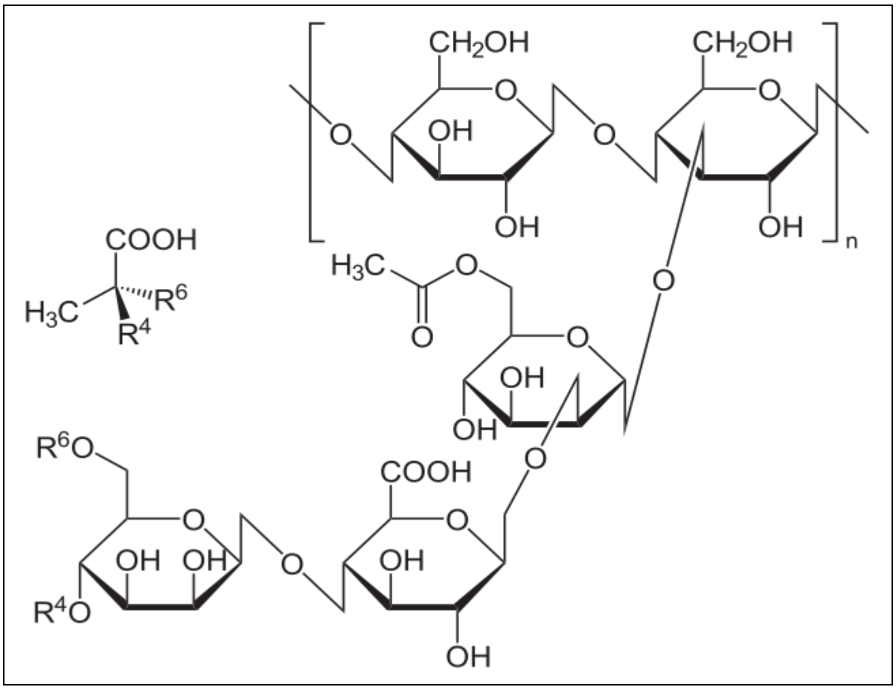

FIGURE 2.14: Chemical structure of Xanthan Gum [28]

2.4.3 Calculation of percentage and ppm (parts per million)

One of the requirements for this study is the mixing of polymers and water in order to conduct the experiment with the different concentrations of polymer. Therefore knowledge on the method of calculation for mixing is an important factor where it could play a huge role in the results obtained for this study. Some of the values throughout this experiment may b explained in either ppm or in percentage (%). Therefore a standard equation is used for conversions throughout this study. Among these equations are;

1. Percentage concentration to ppm (parts per million)

Equation 12: $$\frac{\%\ \boldsymbol{concentration}}{\mathbf{100}}\ \boldsymbol{x}\ \ \mathbf{10^6}$$

2. Ppm (parts per million) to grams (g)

Equation 13: $$\frac{\boldsymbol{Ppm\ x\ Liters\ of\ water}}{\mathbf{1000}}$$

CHAPTER 3

METHODOLOGY

This chapter is going to cover the process and flow through the project. Along with the project activities and Gantt chart, the milestone of the project and equipment used will also discuss in detailed throughout this chapter.

3.1 Procedure Identification

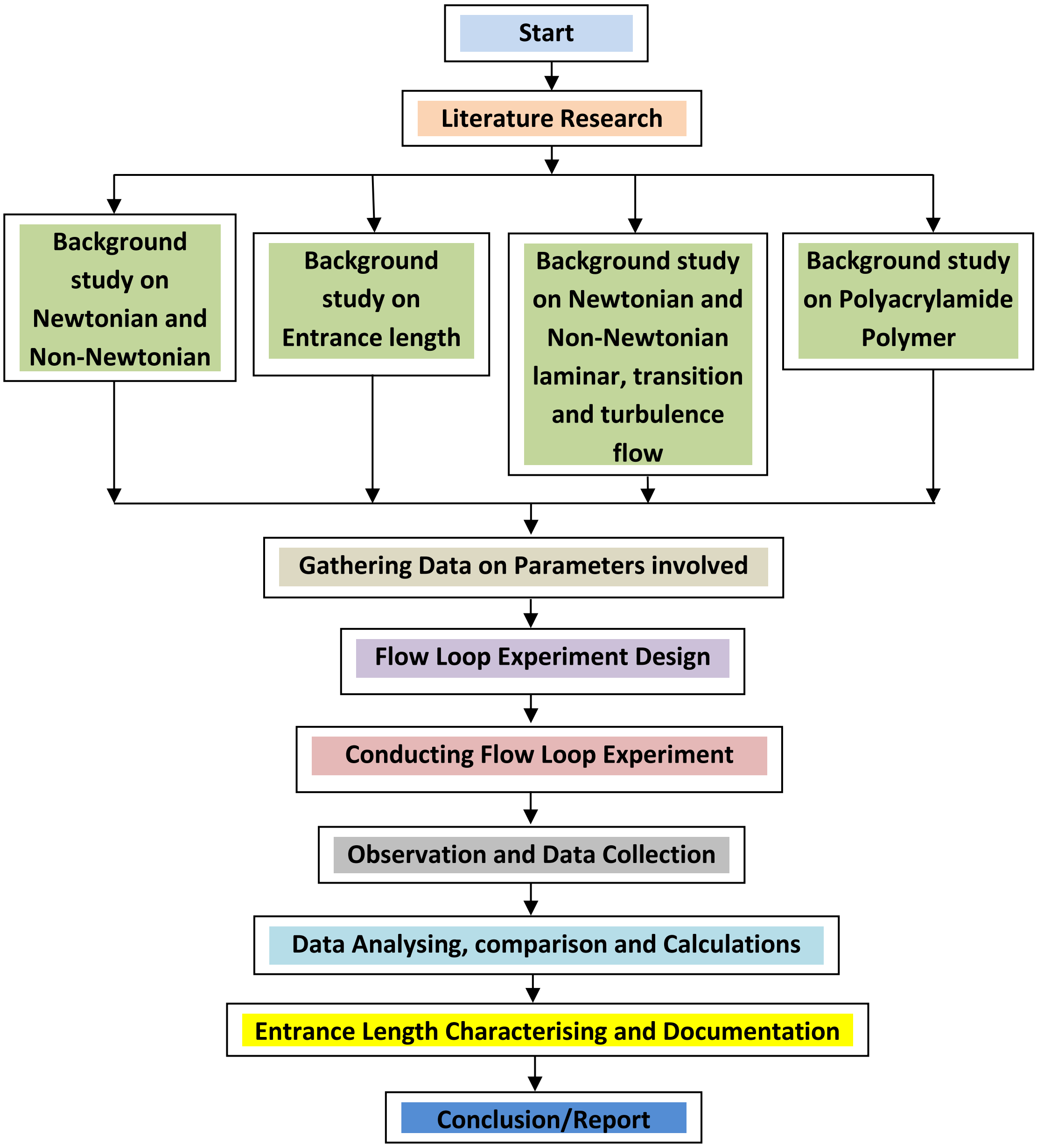

FIGURE 3.1: Methodology Chart

The project was initiated by firstly identifying and defining the problem statement of the project. Then, the project objectives were identified. Once the objectives has been known, an extensive study were done by the author on the project by gathering information and data through available journals, articles, books and references. This enables the author to understand more about the project to be carried out and enables the author to correlate the project with other previous researches done by researchers. Then gathering of data on the parameters involved were done in order to set a limitation of the knowledge to be applied where for instance the calculations involved, the types of polymers to be used as well as the type of flow loop used. Later a familiarization process of the flow loop is done in order to get to know the procedures and working principles and the equipment involved for gathering data in order to conduct an experiment, methods of mixing polymers into the flow loop, the problems surfacing while using the flow loop as well as mastering the control system of the flow loop. Once the familiarization process is done, the experiments are then conducted using different concentrations of polymer at various flow rates. Pressure drop is measured and obtained in order to identify the entrance length by comparing the pressure drop from each point before until it varies very minimal. An observation is done based on the results acquired in order to analyse the difference of entrance length among the polymer concentrations as well as the polymers and water which is in other words the difference among Newtonian and Non-Newtonian fluids. If the results are unsatisfactory the experiments are to be conducted again to obtain better results whereas if the results are acceptable the process is preceded on to documenting the results by graphical means and comparing it to the theory from previous researches and findings. Once the results are documented, the entrance length of the polymers are characterized and delineated. Now the final step is to complete a detailed report with the graphical figures and explanation of the theory and experiments conducted according to the procedures and requirements.

3.2 Tool Requirements

3.2.1 Polymer Flow Loop Test Rig

- Conduct experiments using water as well as polymers in order to obtain data on pressure drop, flow rate and entrance length.

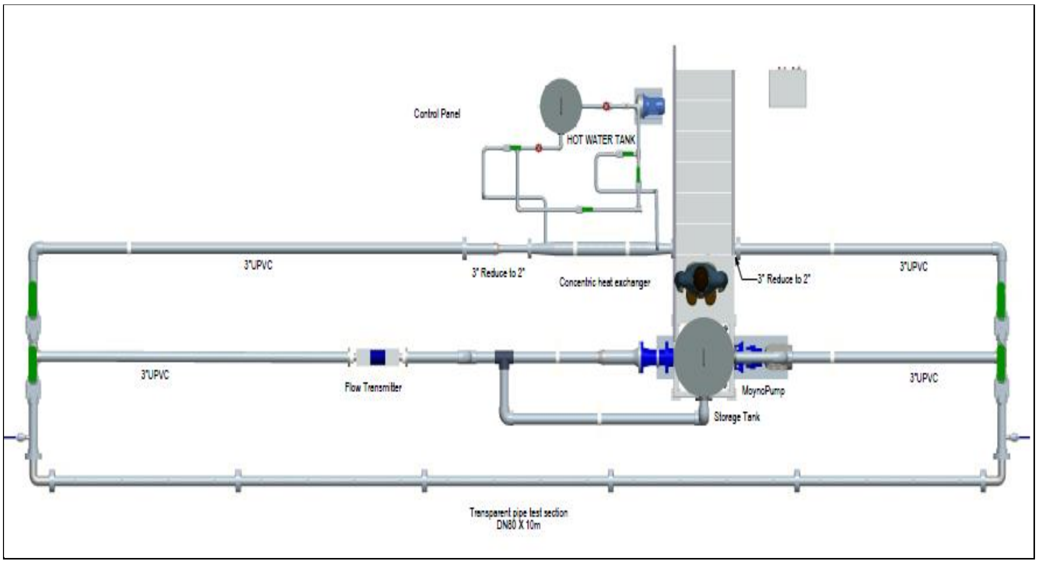

FIGURE 3.2: Polymer Flow Loop Test Rig

3.2.2 Micro Motion Coriolis Mass Flowmeter

- Flow rate measurement in flow loop

FIGURE 3.3: Flow meter

3.2.3 Differential Pressure Transducer (Portable)

- Measure the pressure at various points

FIGURE 3.4: Pressure Transducer

3.2.4 Flow Loop Software

- To read results in computer (BP591 Model Software)

3.3 Design and Setup

This project will be using the flow loop piping system where a pump is used to pump and circulate the fluid from the tank along the piping and then back again. Along the pipeline before the straight 10 meter length pipe is the flow meter where the flow rate value is displayed in order for an accurate flow rate to be used. Along the 10 meter measurement section are valves arranged with the fixed length of 0.45 meters. At this points are where the pressure difference is taken using the pressure transducer. The difference of pressure data is displayed at the pressure transducer itself and also can be read from the laptop. The readings are recorded by the software in the laptop and the data is then analyzed. The entrance length is to be taken at the point where the pressure difference stays constant or at a very minimal difference.

The other supporting data that is taken in account is the Shear Stress which is determined by the equation;

Equation 5: $$\boldsymbol{\tau_w = \frac{\Delta Pd}{4L}}$$

Another important data to be determined is the Reynolds Number as to confirm the flow is in turbulence. The following equation is applied;

Equation 11: $$\boldsymbol{Re = \frac{\rho v D}{\mu}}$$

where the viscosity is determined using the rheometer. The data is then studied and analyzed and the results will be discussed in the following chapter of this report.

3.4 Experimental Procedures

The experiment procedures to be conducted are as listed below. Some images of the setup can be viewed in the **Appendix**

1. The tank is filled with the fluid (water, Xanthan Gum mixture and Polyacrylamide mixture) to a certain point where the measurement reaches 408 liters.
2. If the mixture and Xanthan Gum and Polyacrylamide is added, the flow loop is left running at the lowest flow rate of 20 kg/min for 6 hours. The following concentration for the polymers in **Table 3.1** is mixed for every run.

Table 3.1: Concentration of Polymer used

Polymer Used	% concentration	Weight (grams)
Xanthan Gum and Polyacrylamide	0.01	40.8
	0.025	102
	0.05	204
	0.075	306
	0.1	408

3. Once the fluids are ready, the equipment are linked or connected to the computer using the usb cable so as the data could be recorded by the software.

4. The flow loop is then let to run at the flow rates required for the study

5. Once the parameter has been set (flow rate), the pressure transducer is used to measure the pressure difference at ten points with a distance of 0.9 meters from one another except for the last point which is 0.45 meters apart.

6. The data is automatically recorded by the software for two minutes run time per point.

7. Data is then averaged and analyzed into graphical form to be discussed.

3.5 Key Milestone

The important key milestones of this semester project are as follows:

TABLE 3.2: Key Milestone

Key Milestone	Period	Result
Project Title Assignment	Week 1 and 2	Achieved
Literature Research	Throughout project period	Accomplished to date
Extended Proposal	Week 5	Achieved
Proposal Defence	Week 7 and 8	Achieved
Flow Loop Familiarization	Week 8 and 9	Achieved
Draft Report	Week 8 and 9	Achieved
Interim Report	Week 14	Achieved

3.6 Ghant Chart

TABLE 3.3: Ghant Chart of Final Year Project

Milestone		Task \ Week	FYP 1															FYP 2														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Planning & research Phase		Project Title Assignment	■	■																												
		Literature Review			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		Entrance length			■	■	■	■	■	■																						
		Newtonian flow					■	■																								
		Non-Newtonian flow							■	■																						
		Newtonian vs Non-Newtonian								■	■																					
		Polyacrylamide (PAA)								■	■																					
		Xanthan Gum (XG)								■	■																					
Design, testing and analysis Phase	PAA	Training on flow loop / familiarization								■	■																					
		Acquiring samples of PAA									■																					
		Conduct Flow Loop Measurement									■	■																				
		Analysis on results											■	■																		
	Xanthan Gum	Acquiring samples of Xanthan Gum																		■												
		Conduct Flow Loop Measurement																		■	■											
		Analysis on Results																				■	■									
Presentation and report writing Phase		Report Writing			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
		Extended Proposal						■																								
		Draft report/ Progress on Interim/Interim Report								■	■	■	■	■	■	■																
		Progress Report																							■							
		Pre Sedex Poster and Presentation																										■				
		Dissertation (soft bound) and technical paper																												■		
		Oral Presentation																													■	
		Dissertation																														■

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The flow loop as shown in figure 3.2 above is used in this experiment is as shown in the figure 4.1 below. The test loop has a cross sectional area of 0.005397578 m^2 and a total length of 10 m, the sections used for testing purposes have a length of 0.9 meters form section 1 to 9 and 0.45 meters for section ten respectively. The pressure gradient was measured using pressure taps positioned at the top side of the test loop for a period of 2 minutes for each measurement. The temperature at the reservoir in the flow loop is continuously monitored to remain constant as temperature may change the fluid properties. A pressure transducer (Model PMD75) was used to measure the pressure difference of two points as mentioned.

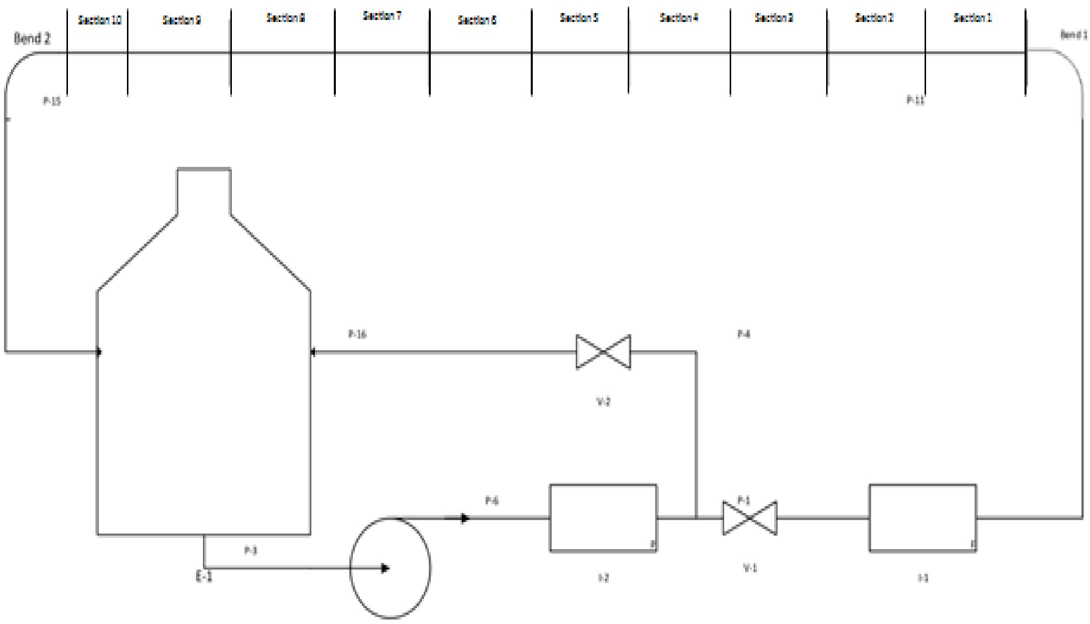

FIGURE 4.1: Flow Loop

The shear stress would be calculated using Equation 5 and was used in conjunction with a Rheometer (TI instruments AR-G2) to measure the viscosity of the non-Newtonian fluid inside the flow loop.

$$\textbf{Equation 4:} \quad \Delta P = \frac{\tau_w 4L}{d}$$

The dimensionless entrance length is determined from the graphs of dimensionless entrance length against the pressure drop per length. The criteria used in verifying the entrance length is by calculating the percentage difference of pressure drop per length from the first point to the last point. The dimensionless entrance length is determined to be the point when the pressure drop per length percentage variance does not exit the limit determined from the data whereby, it does not exit the certain limit for three consecutive points. Hence, we can assume that the entrance length begins at the first of the three consecutive points where by using **Equation 4** to get the approximate entrance length. **Figure 4.2** below is an example of how the entrance length is determined from the variance of the three consecutive points not exiting the limit set upon. The results for the dimensionless entrance length against the pressure drop per length for the experiment using water and polymer concentrations will be discussed in the following subtopic.

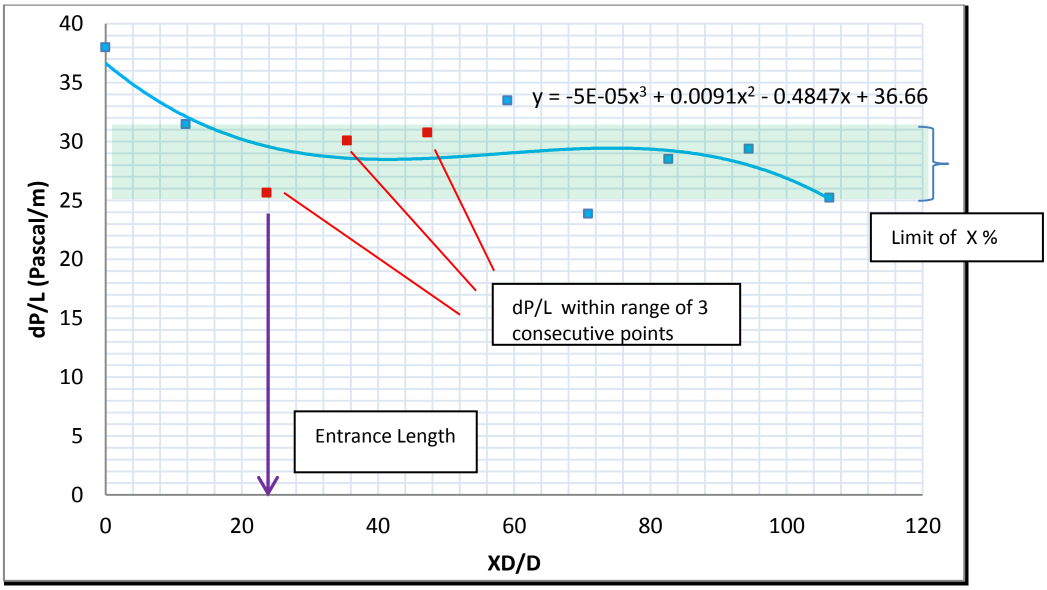

FIGURE 4.2: Example criteria used to determine the entrance length

4.2 Results for Water

The experiment was carried out with plain tap water flowing through the flow loop. Water is measured in order to find the difference in the entrance as a reference when xanthan gum and polyacrylamide polymers are used. The pressure difference was taken and the data was analyzed in a graphical form. These results will later be compared with the results obtained from polymer data. Among the different flow rates used to gather data are corresponding to a Reynolds Number, Re of 21342.28. The results obtained are as follows.

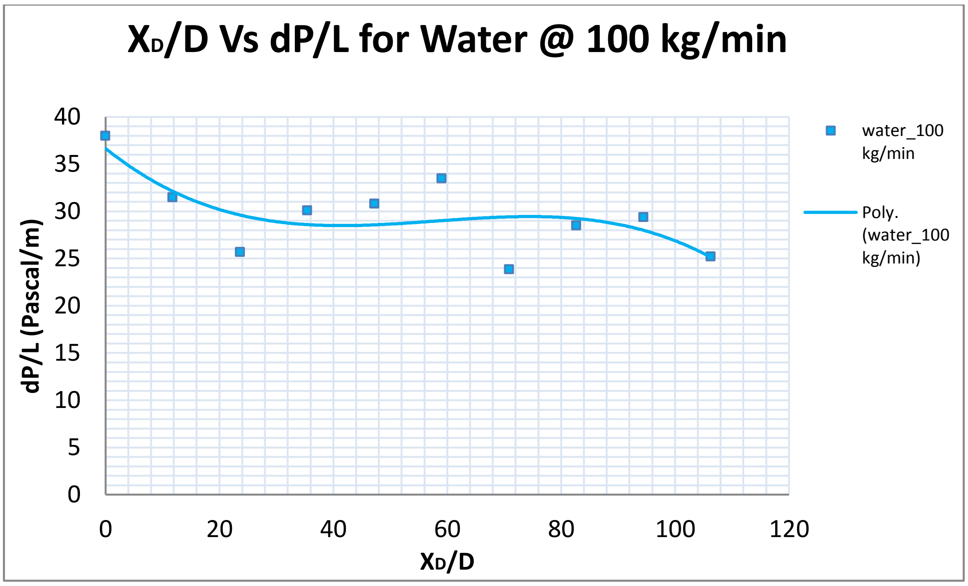

Figure 4.3: Graph for water at 100 kg/min (Re = 21342.28)

As we can see from the graph above, water flowing at 100 kg/min mass flow rate through the test tube at a Reynolds number of 21342.27541 which is at turbulent flow has an entrance length of 1.83 meters. The entrance length is defined as a part at which the pressure difference, dP/L is reaching a constant limit where the percentage, % difference is maintained at 15 % consecutively from point three to point five. This, for instance shows the entrance length of water at the velocity of 0.3095 m/s requires 1.83 meters to develop from laminar to transition then turbulent where it is then stable. Entrance length is determined when the pressure difference becomes even or there is only a very slight difference.

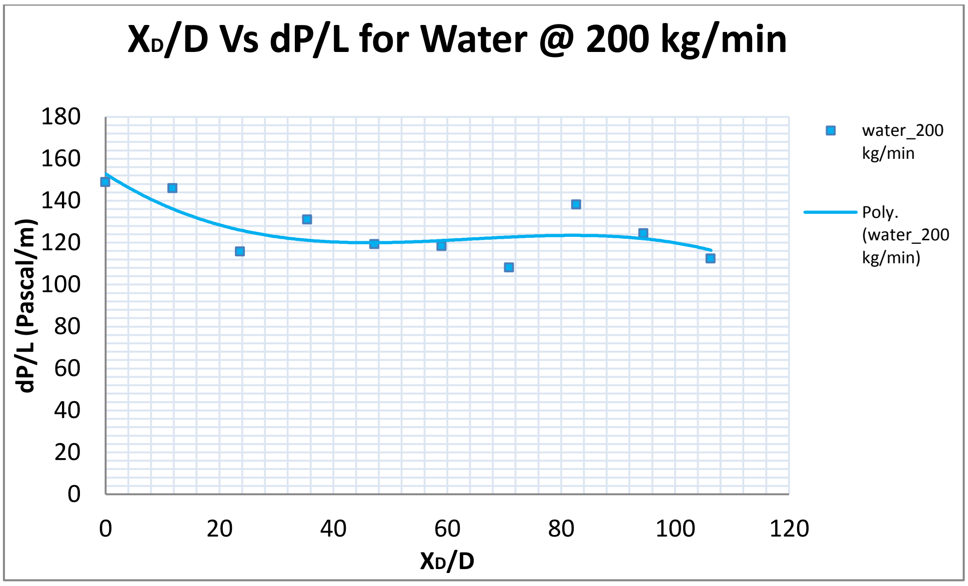

Figure 4.4: Graph for water at 200 kg/min (Re = 42714.63)

As we can see from the graph above, water flowing at 200 kg/min through the test tube at a Reynolds Number of 42714.63 has an entrance length of 2.08 meters. This shows the entrance length of water at this a velocity of 0.6194 m/s requires 2.08 meters to develop from laminar to transition then turbulent where it is then stable where the pressure does not exit a limit of 10% from point four to six. Entrance length is determined when the pressure difference becomes even or there is only a very slight difference. We also notice that the pressure is higher as the velocity is higher compared to 100 kg/min.

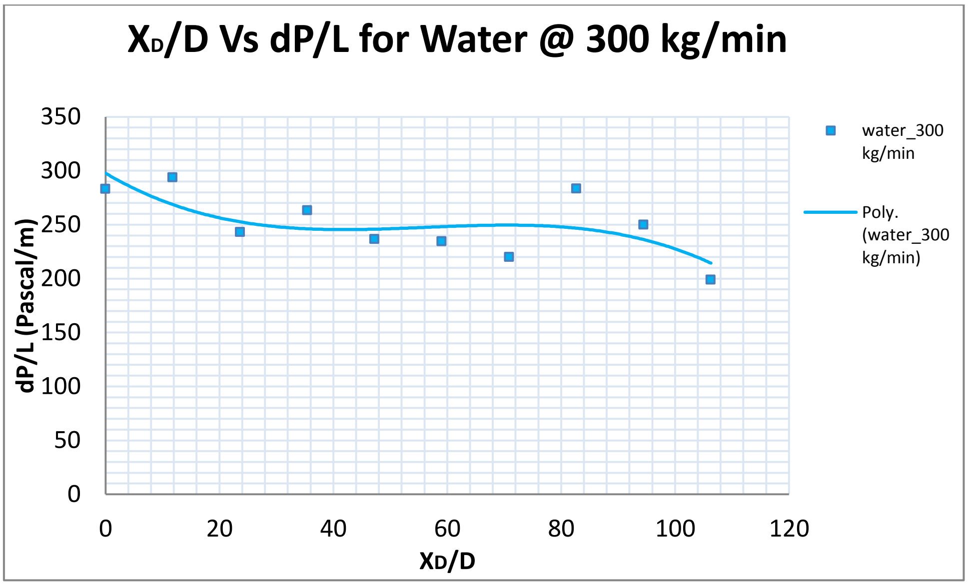

Figure 4.5: Graph for water at 300 kg/min (Re = 64071.95)

Table 4.1: Properties of water at 100, 200 and 300 kg/min flow rate

Fluid Type	Entrance Length(m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D	Theoretical X_D/D
Water	1.83	27.0805	0.0012	0.3095	21342	24	23.17
Water	2.7	97.293	0.0012	0.6194	42715	35.43	25.66
Water	3.6	224.947	0.0012	0.92512	64071	47.24	29.28

As we can see from the graph above, water flowing at 300 kg/min through the test tube at a Reynolds Number of 64071.94 has an entrance length of 2.7 meters. This shows the entrance length of water at this a velocity of 0.9291 m/s requires 2.7 meters of the dimensionless length, X_D/D to develop from laminar to transition then turbulent where it is then stable. Entrance length is determined when the pressure difference becomes even or there is only a very slight difference of 15 %. We also notice that the pressure drop is higher as the flow rate is increasing and hence confirming the theory. However as for the entrance length there has been differences in values compared to the results of the theory, this could be because the location flow which is perhaps close to the outlet. Measurements conducted at even lower flow rates showed significant data scatter possibly due to vibrations of the pump at the lower threshold.

4.3 Results for Xanthan Gum

The experiment was carried out with tap water mixed with five concentrations of Xanthan Gum which are 0.01 %, 0.025%, 0.05 %, 0.075% and 0.1% flowing through the flow loop. The polymer fluid is measured in order to find the difference in the entrance which is later to be compared. The pressure difference was taken and the data was analyzed in a graphical form. Among the different flow rates used to gather data are 100 kg/min, 200 kg/min and 300 kg/min corresponding to the Re values as stated in **Tables 4.4 – 4.6**. The results obtained are as follows.

4.3.1 Xanthan Gum at 100 kg/min

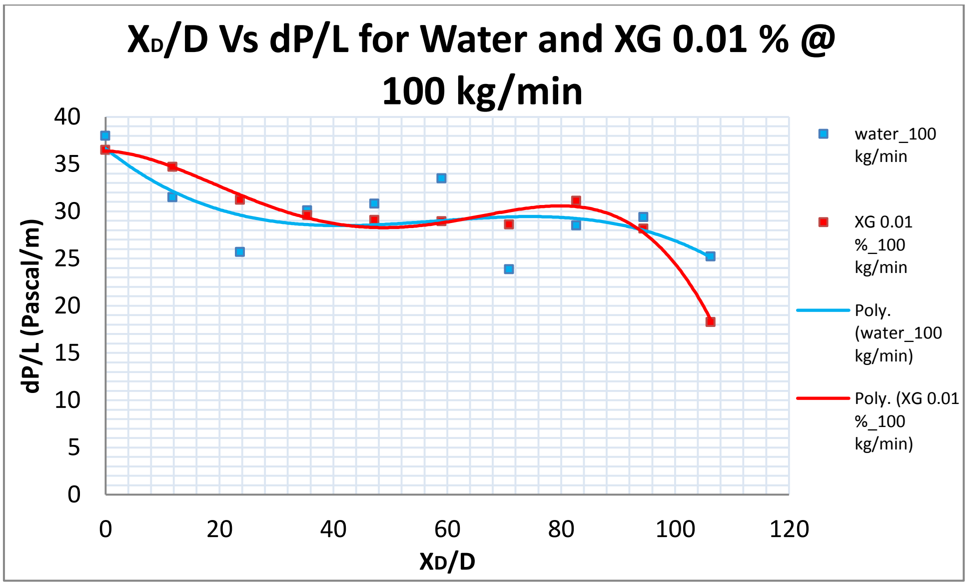

Figure 4.6: Graph for Water and Xanthan Gum 0.01 % at 100 kg/min

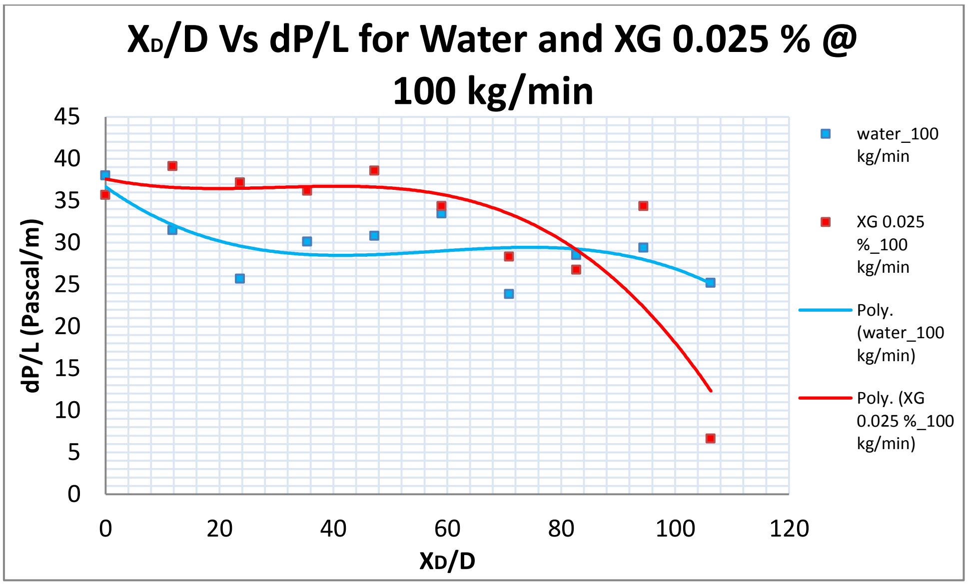

Figure 4.7: Graph for Water and Xanthan Gum 0.025 % at 100 kg/min

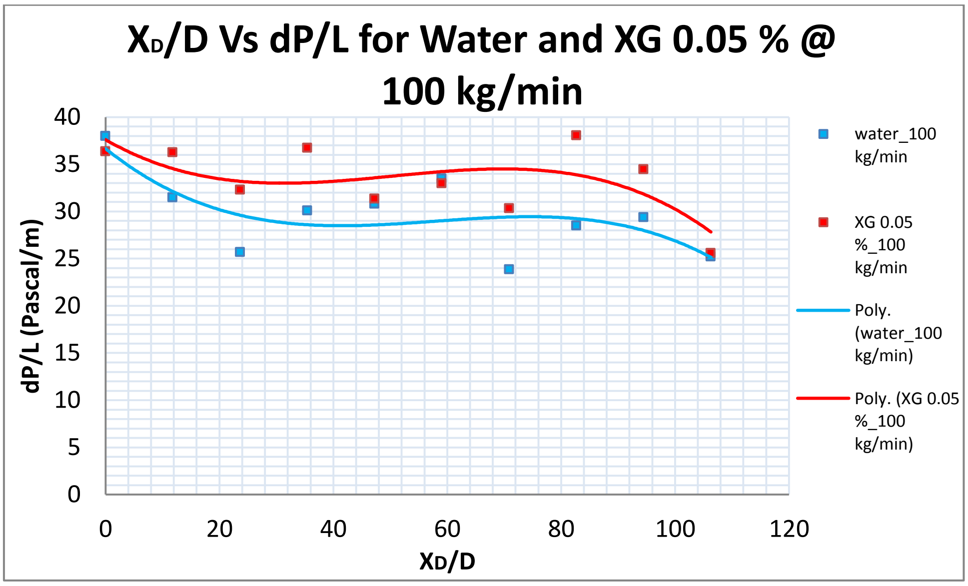

Figure 4.8: Graph for Water and Xanthan Gum 0.05 % at 100 kg/min

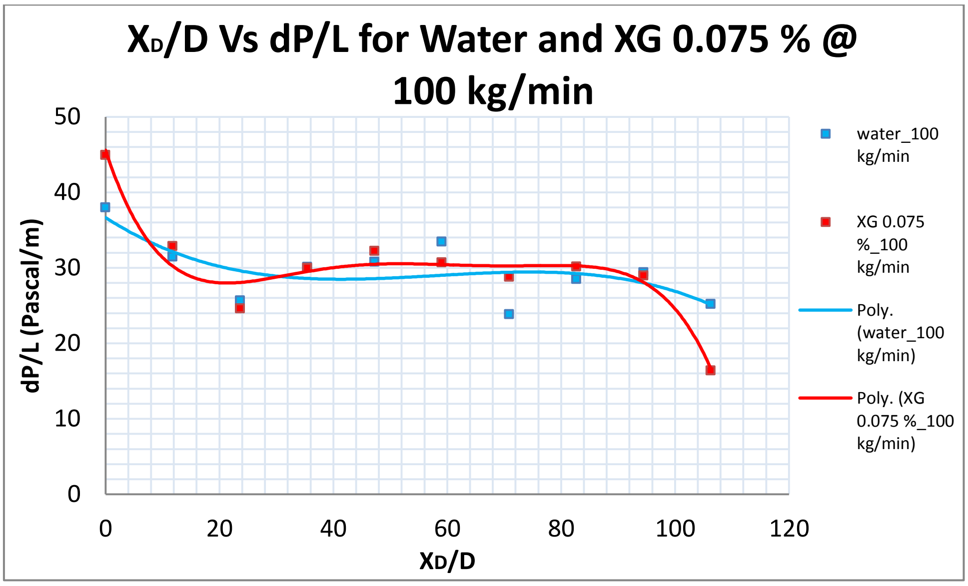

Figure 4.9: Graph for Water and Xanthan Gum 0.075 % at 100 kg/min

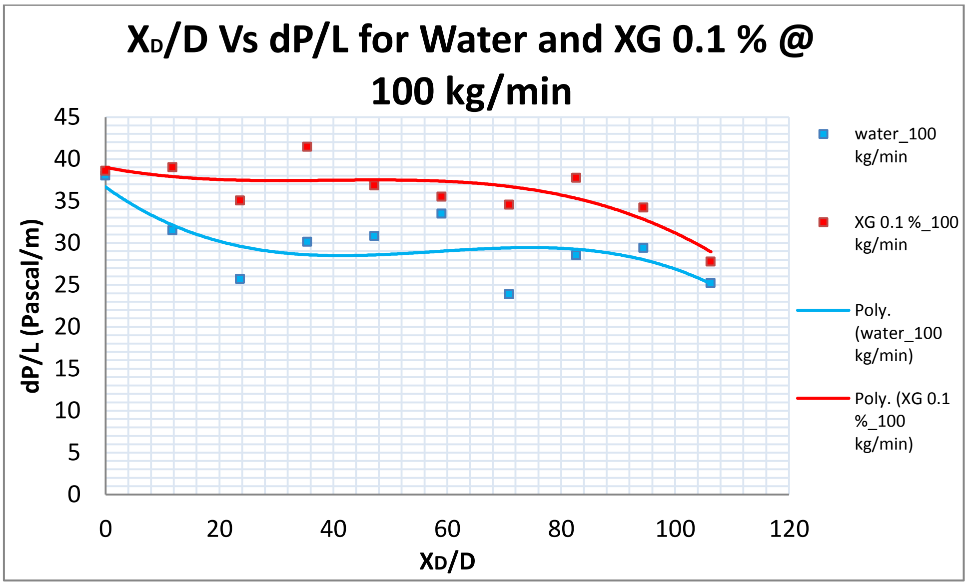

Figure 4.10: Graph for Water and Xanthan Gum 0.1 % at 100 kg/min

Table 4.2: Properties involved for 100 kg/min flow rate of Xanthan Gum concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D
Xanthan Gum 0.01%	1.799	26.61	0.001785	0.310	14358	23.62
Xanthan Gum 0.025 %	1.799	32.54	0.002418	0.311	10659	23.62
Xanthan Gum 0.05 %	1.799	29.05	0.003964	0.312	6465	23.62
Xanthan Gum 0.075 %	3.6	29.01	0.005193	0.312	4934	47.24
Xanthan Gum 0.1 %	1.00	31.53	0.006963	0.312	3679	11.81

As we can see from the graphs above, for Xanthan Gum at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 100 kg/min through the test tube, there is a significant difference in the development of the entrance length. However, based on the criteria used the entrance length for the following concentrations indicate the section where the entrance length has developed. The accurate value of the entrance length may be visually seen from the results of the graph and according to the slope where the polynomial lines become straight is the entrance length. Therefore visually, the results do support the theory as there is a slight reduction in the formation of the entrance length as the concentration of polymer increases. The entrance length is reduced as the Xanthan Gum polymer percentage increases. However as for Xanthan Gum Thickness of 0.075 there might have been some errors during the data collection or the equipment as the results varies from the common pattern.

4.3.2 Xanthan Gum at 200 kg/min

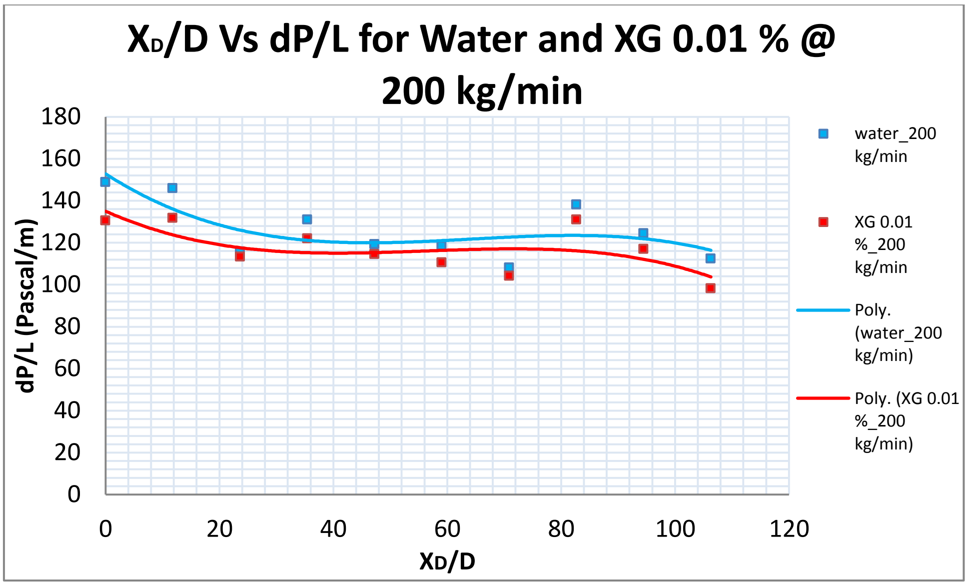

Figure 4.11: Graph for Water and Xanthan Gum 0.01 % at 200 kg/min

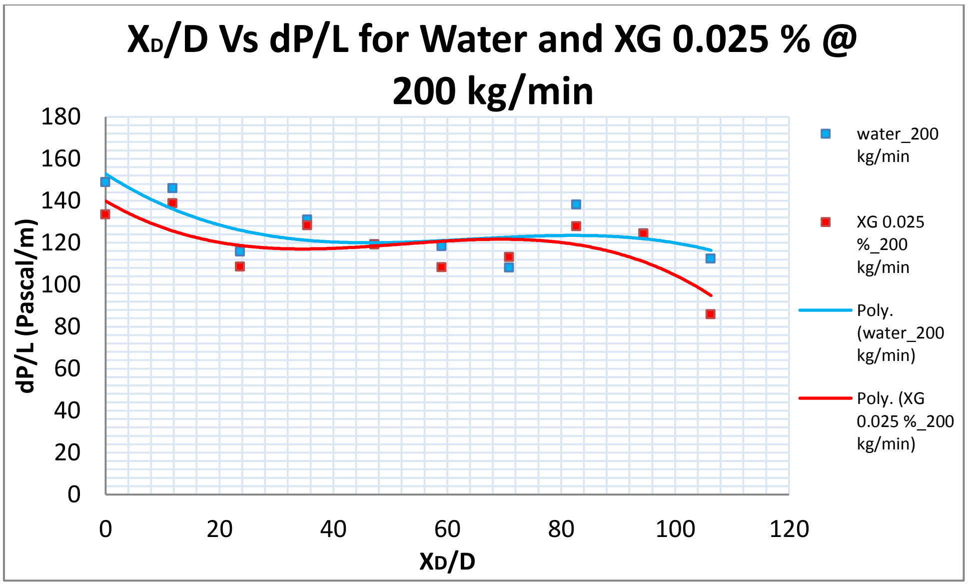

Figure 4.12: Graph for Water and Xanthan Gum 0.025 % at 200 kg/min

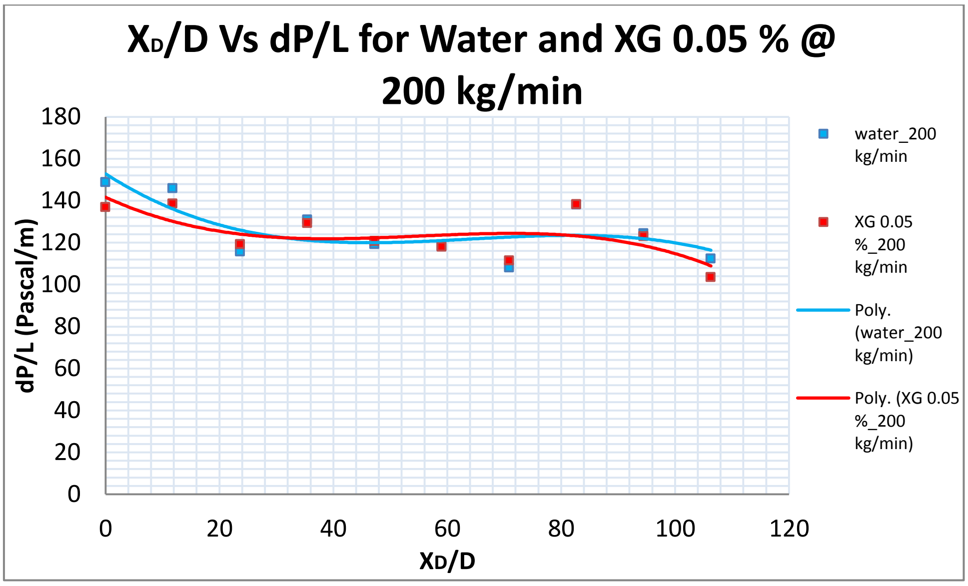

Figure 4.13: Graph for Water and Xanthan Gum 0.05 % at 200 kg/min

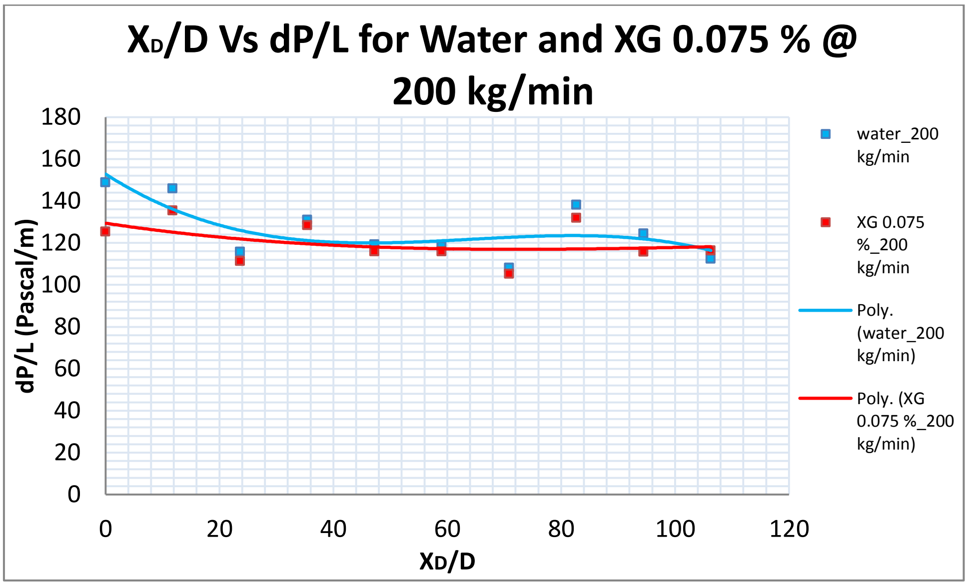

Figure 4.14: Graph for Water and Xanthan Gum 0.075 % at 200 kg/min

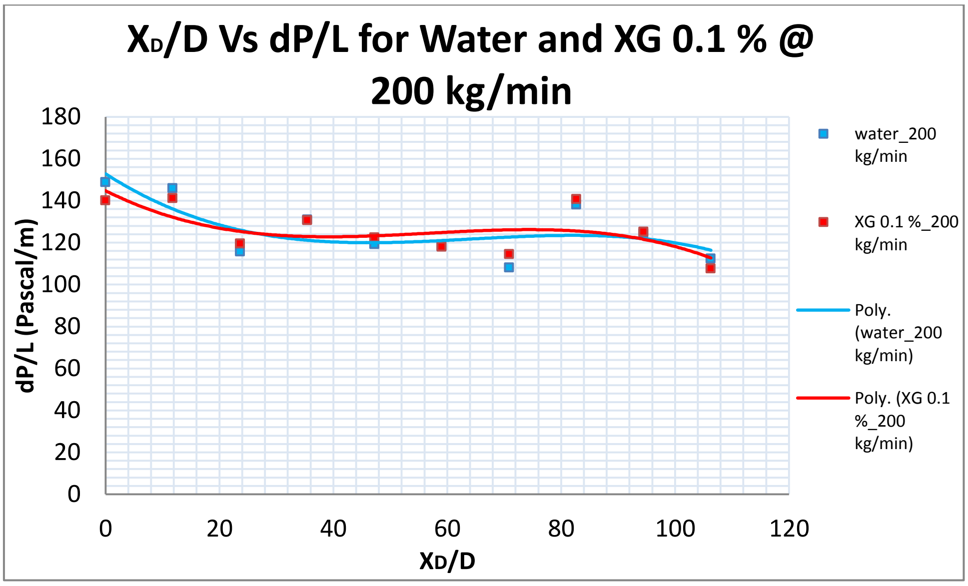

Figure 4.15: Graph for Water and Xanthan Gum 0.1 % at 200 kg/min

Table 4.3: Properties involved for 200 kg/min flow rate of Xanthan Gum concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	XD/D
Xanthan Gum 0.01%	2.7	93.68	0.001785	0.615	28572	35.43
Xanthan Gum 0.025 %	2.7	101.81	0.002418	0.617	21198	35.43
Xanthan Gum 0.05 %	2.7	100.30	0.003964	0.618	12931	35.43
Xanthan Gum 0.075 %	2.7	104.22	0.005193	0.619	9871	35.43
Xanthan Gum 0.1 %	1.8	106.11	0.006963	0.619	7361	23.62

As we can see from the graphs above, for Xanthan Gum at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 200 kg/min through the test tube, there is a significant difference in the development of the entrance length. The entrance length is reduced as the Xanthan Gum polymer percentage increases. The pressure for each Xanthan Gum percentage does not vary significantly. However, based on the criteria only the highest concentration does show a reduction in the length. The reduction for the other concentrations are very slight hence may only be determined visually on the graph where the polynomial graph forms a linear line.

4.3.3 Xanthan Gum at 300 kg/min

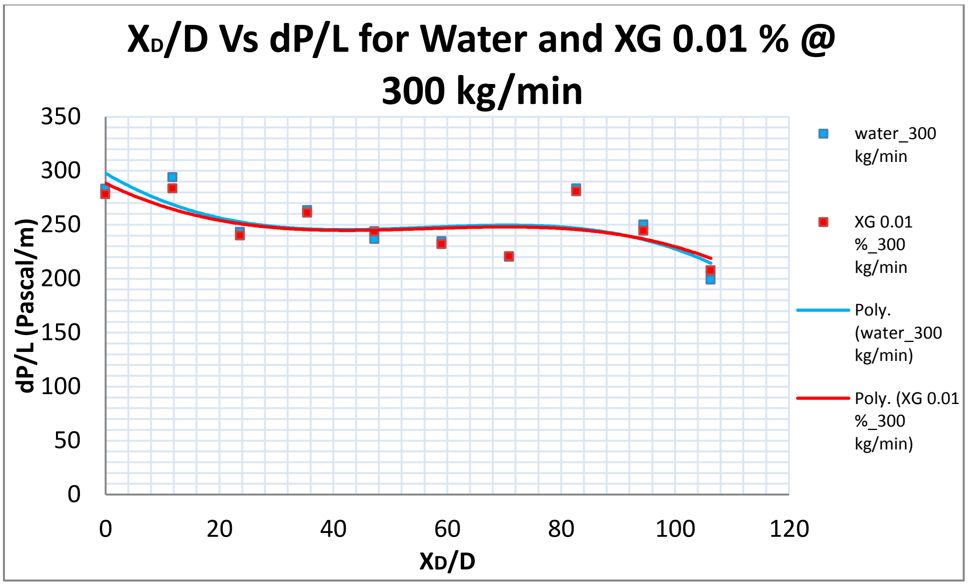

Figure 4.16: Graph for Water and Xanthan Gum 0.01 % at 300 kg/min

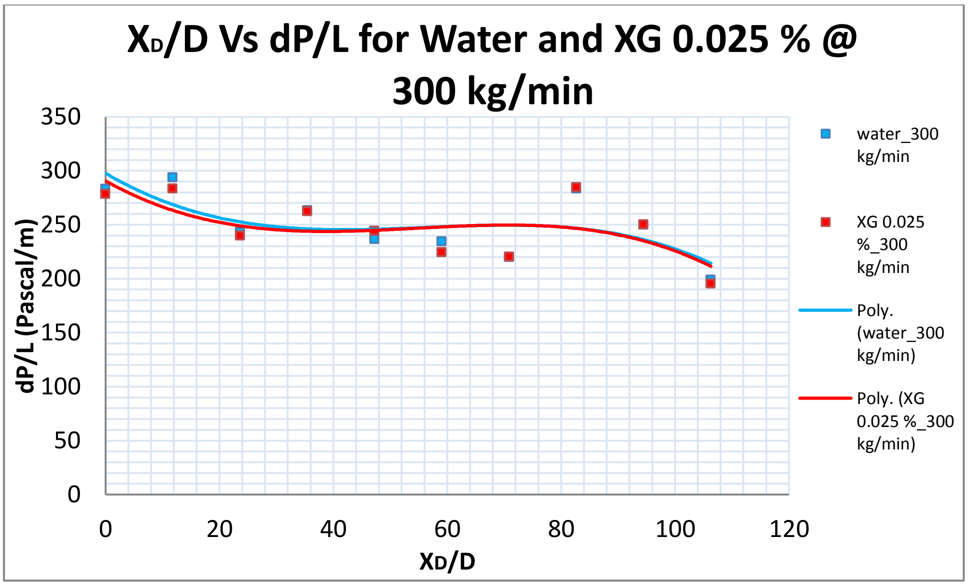

Figure 4.17: Graph for Water and Xanthan Gum 0.025 % at 300 kg/min

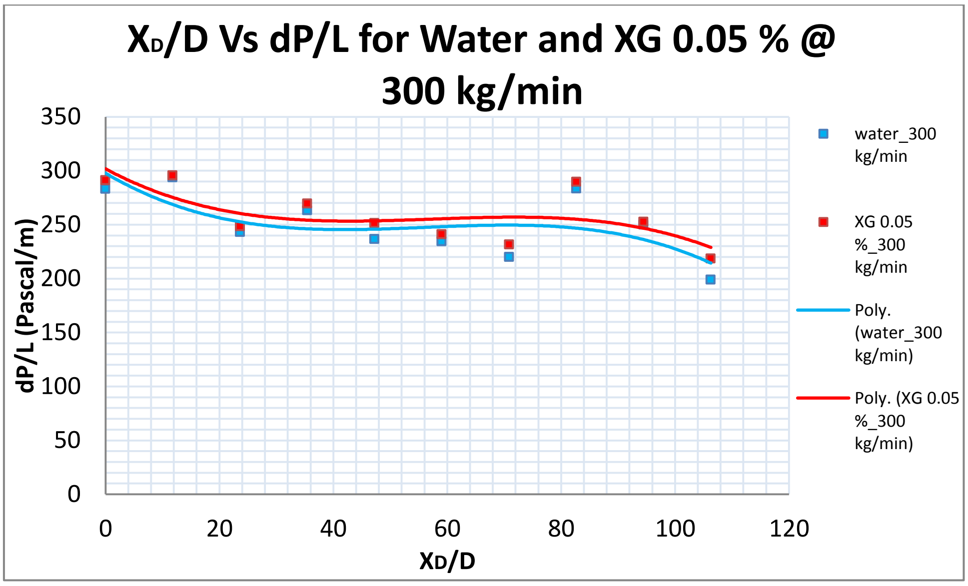

Figure 4.18: Graph for Water and Xanthan Gum 0.05 % at 300 kg/min

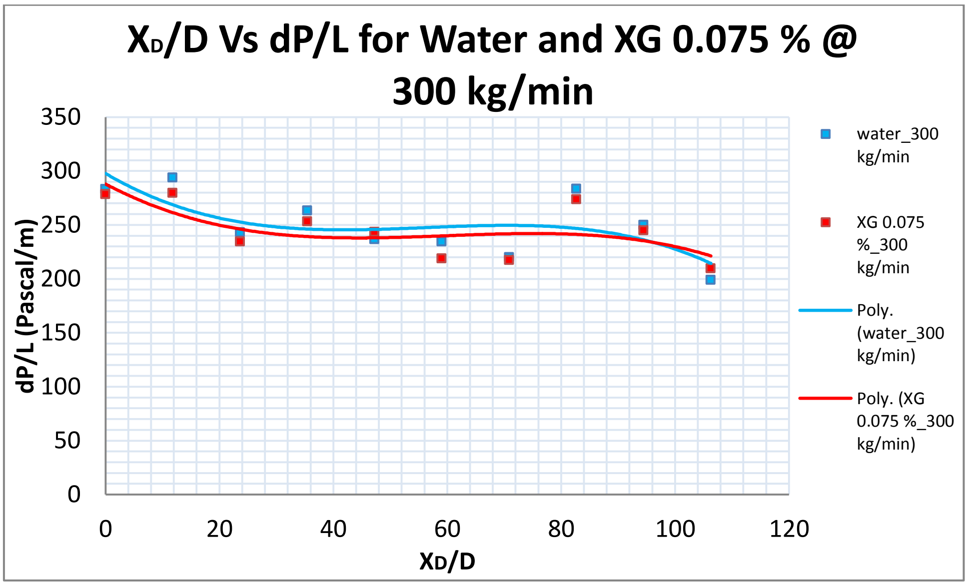

Figure 4.19: Graph for Water and Xanthan Gum 0.075 % at 300 kg/min

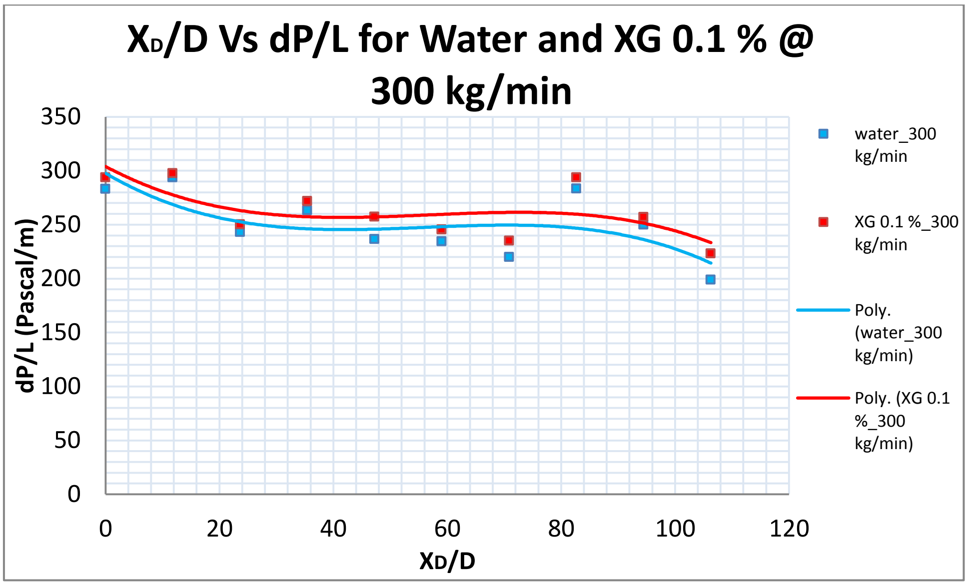

Figure 4.20: Graph for Water and Xanthan Gum 0.1 % at 300 kg/min

Table 4.4: Properties involved for 300 kg/min flow rate of Xanthan Gum concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D
Xanthan Gum 0.01%	3.6	219.65	0.001785	0.925	42939	47.24
Xanthan Gum 0.025 %	3.6	225.23	0.002418	0.926	31691	47.24
Xanthan Gum 0.05 %	2.7	227.25	0.003964	0.927	19396	35.43
Xanthan Gum 0.075 %	2.7	246.12	0.005193	0.928	14756	35.43
Xanthan Gum 0.1 %	2.7	264.44	0.006963	0.929	11029	35.43

As we can see from the graphs above, for Xanthan Gum at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 300 kg/min through the test tube, there is a significant difference in the development of the entrance length. The entrance length is reduced as the Xanthan Gum polymer percentage increases. The pressure for each Xanthan Gum percentage does not vary far.

4.4 Results for Polyacrylamide

The experiment was carried out with tap water mixed with five concentrations of Polyacrylamide which are 0.01 %, 0.025%, 0.05 %, 0.075% and 0.1% flowing through the flow loop. The polymer fluid is measured in order to find the difference in the entrance which is later to be compared. The pressure difference was taken and the data was analyzed in a graphical form.

4.4.1 Polyacrylamide at 100 kg/min

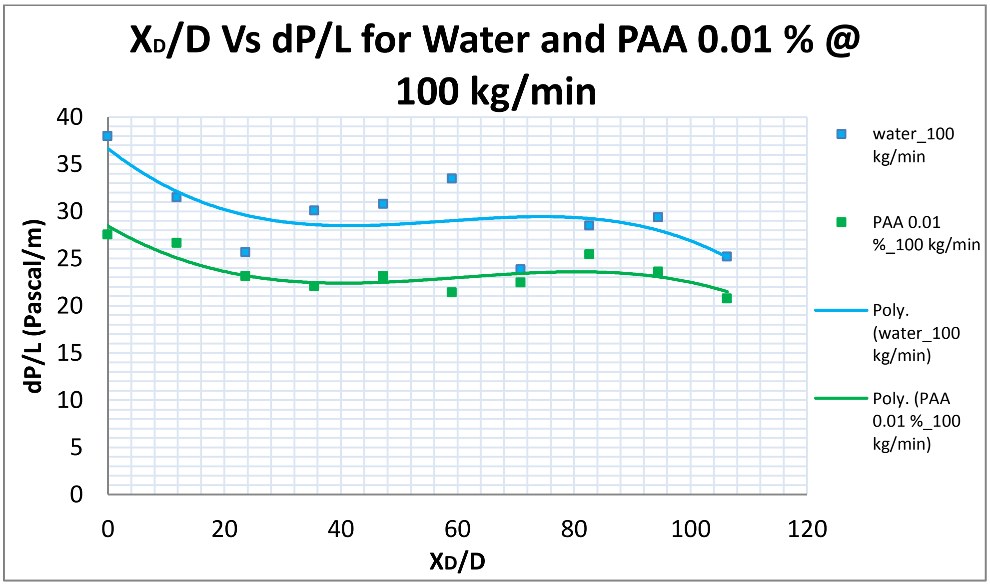

Figure 4.21: Graph for Water and Polyacrylamide 0.01 % at 100 kg/min

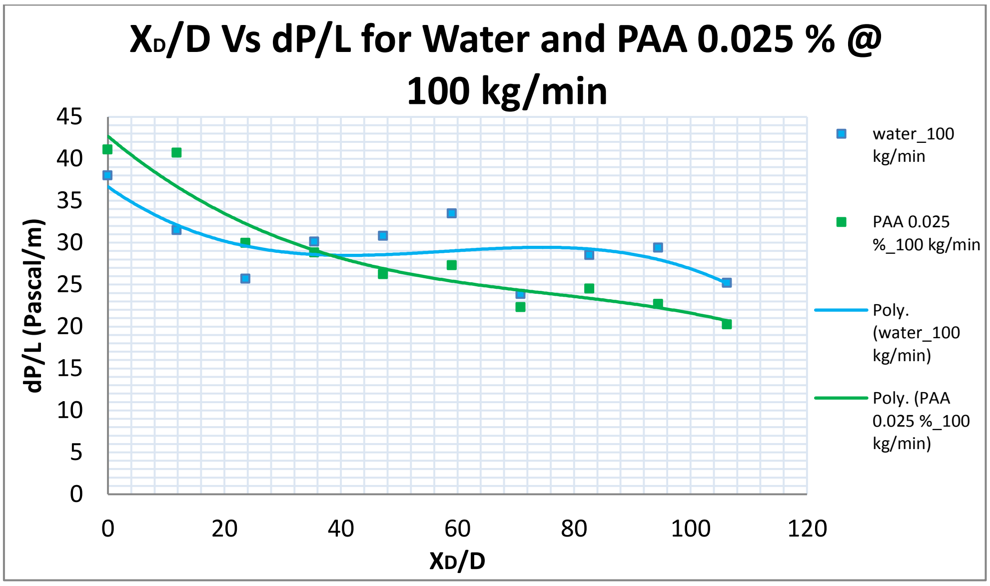

Figure 4.22: Graph for Water and Polyacrylamide 0.025 % at 100 kg/min

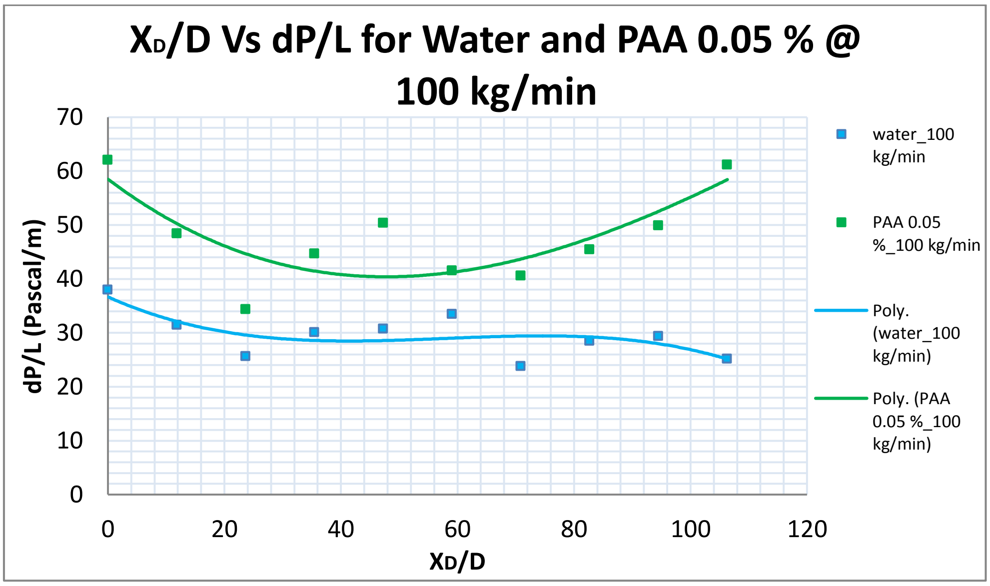

Figure 4.23: Graph for Water and Polyacrylamide 0.05 % at 100 kg/min

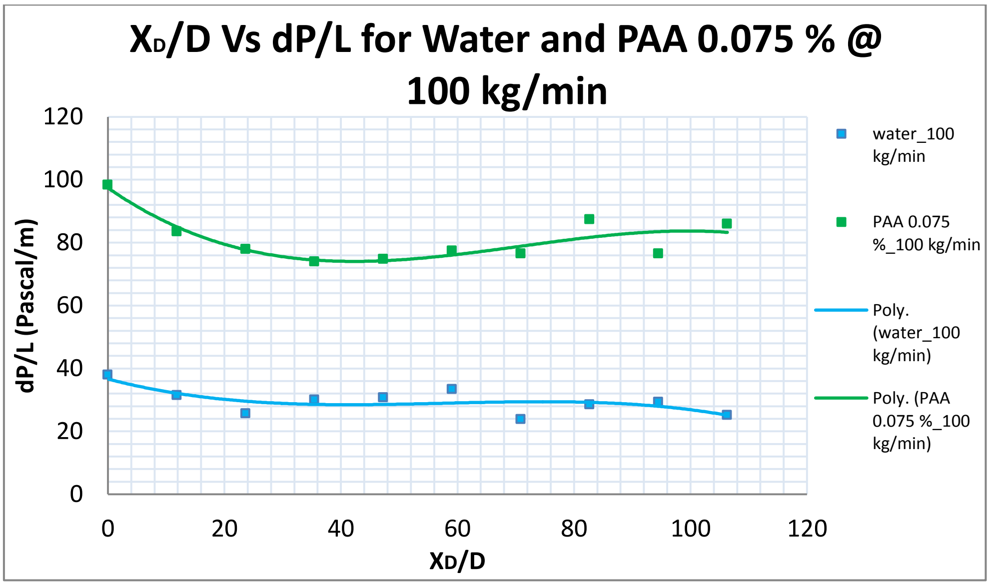

Figure 4.24: Graph for Water and Polyacrylamide 0.075 % at 100 kg/min

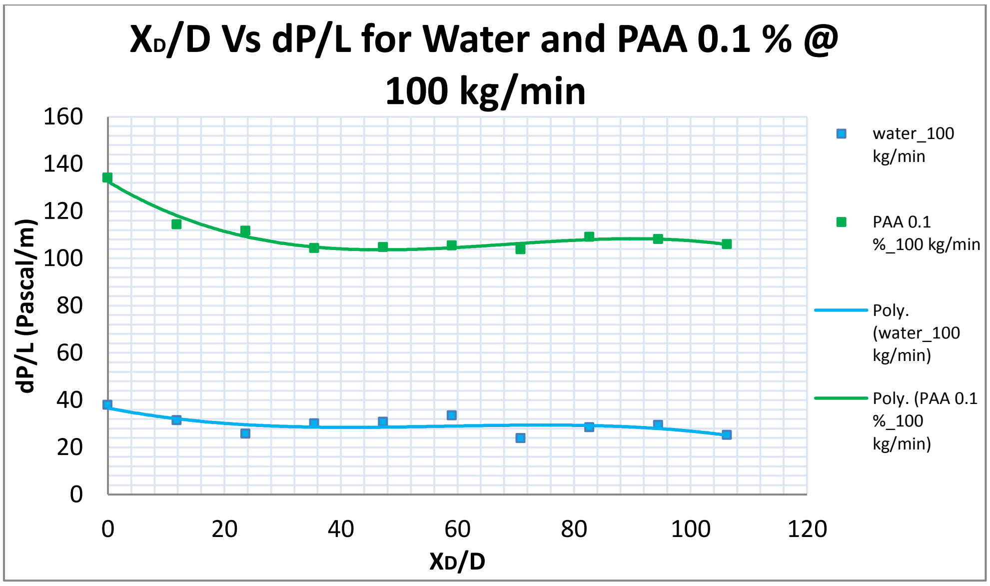

Figure 4.25: Graph for Water and Polyacrylamide 0.1 % at 100 kg/min

Table 4.5: Parameters involved for 100 kg/min flow rate of Polyacrylamide concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D
Polyacrylamide 0.01%	1.8	19.87	0.002244	0.309	11421	23.62
Polyacrylamide 0.025 %	1.8	25.92	0.003016	0.309	8500	23.62
Polyacrylamide 0.05 %	1.8	40.22	0.004462	0.309	5732	23.62
Polyacrylamide 0.075 %	1.8	70.13	0.00609	0.309	4208	23.62
Polyacrylamide 0.1 %	1.00	100.50	0.007563	0.309	3389	11.81

As we can see from the graphs above, for polyacrylamide at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 100 kg/min through the test tube, there is a significant difference in the development of the entrance length. The entrance length is reduced as the polyacrylamide polymer percentage increases. Besides that the pressure is also noticed to increase along with the polyacrylamide polymer thickness. He same criteria has been applied for the results therefore the variance of the entrance length may only be seen visually and has a very slight difference.

4.4.2 Polyacrylamide at 200 kg/min

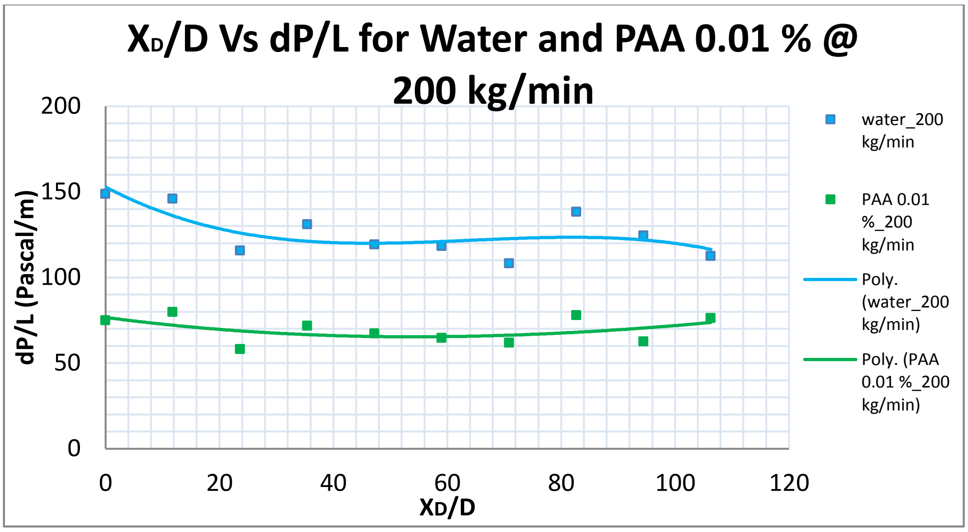

Figure 4.26: Graph for Water and Polyacrylamide 0.01 % at 200 kg/min

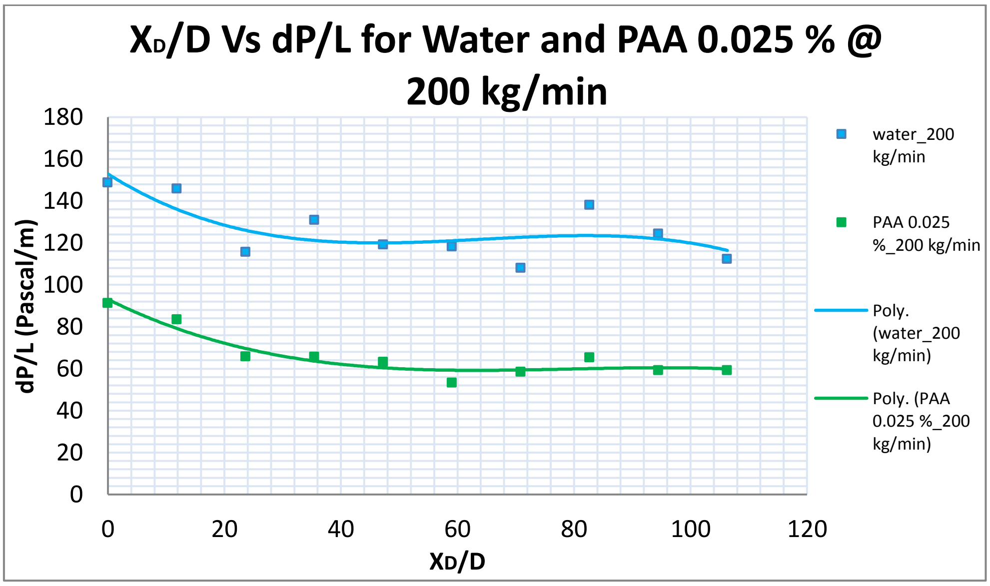

Figure 4.27: Graph for Water and Polyacrylamide 0.025 % at 200 kg/min

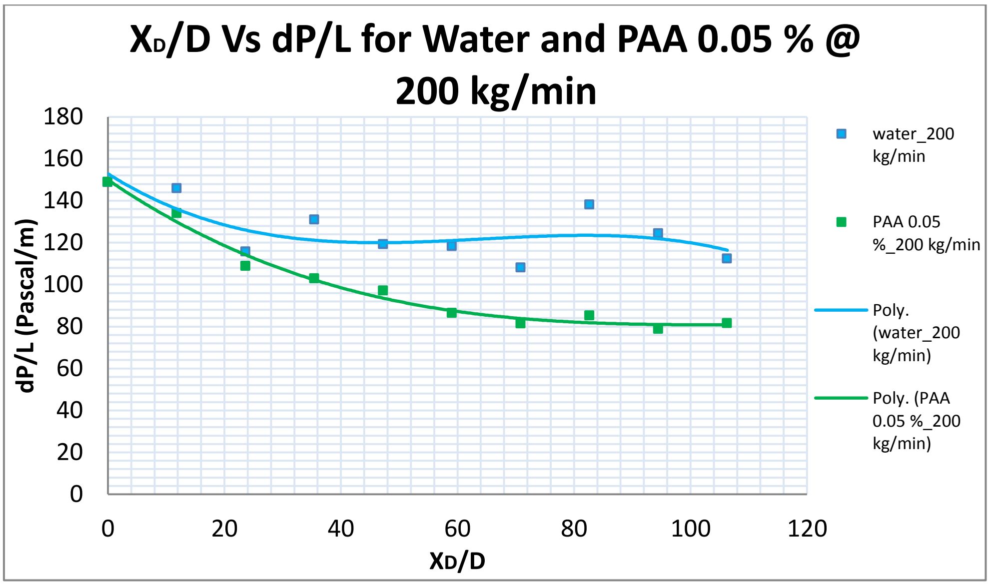

Figure 4.28: Graph for Water and Polyacrylamide 0.05 % at 200 kg/min

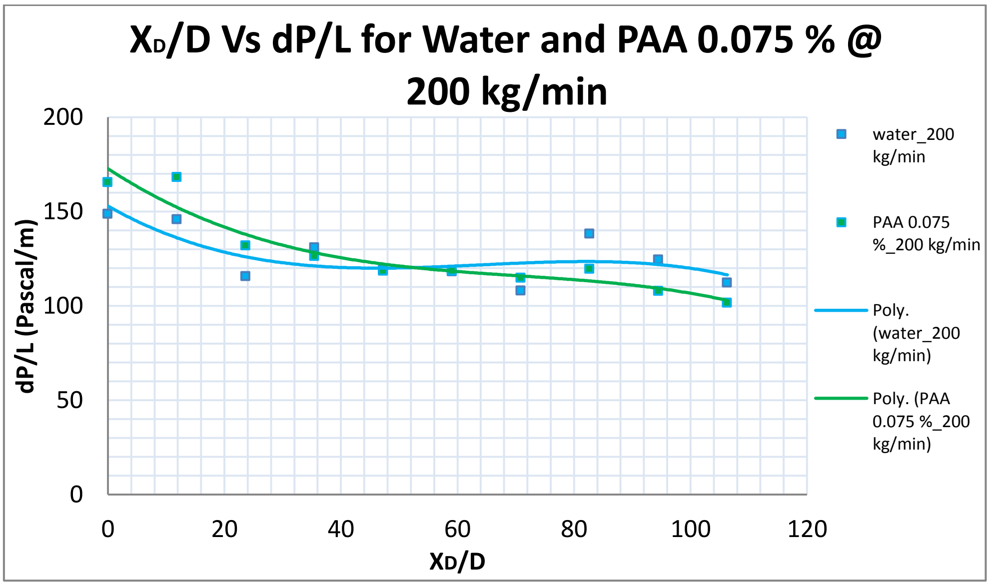

Figure 4.29: Graph for Water and Polyacrylamide 0.075 % at 200 kg/min

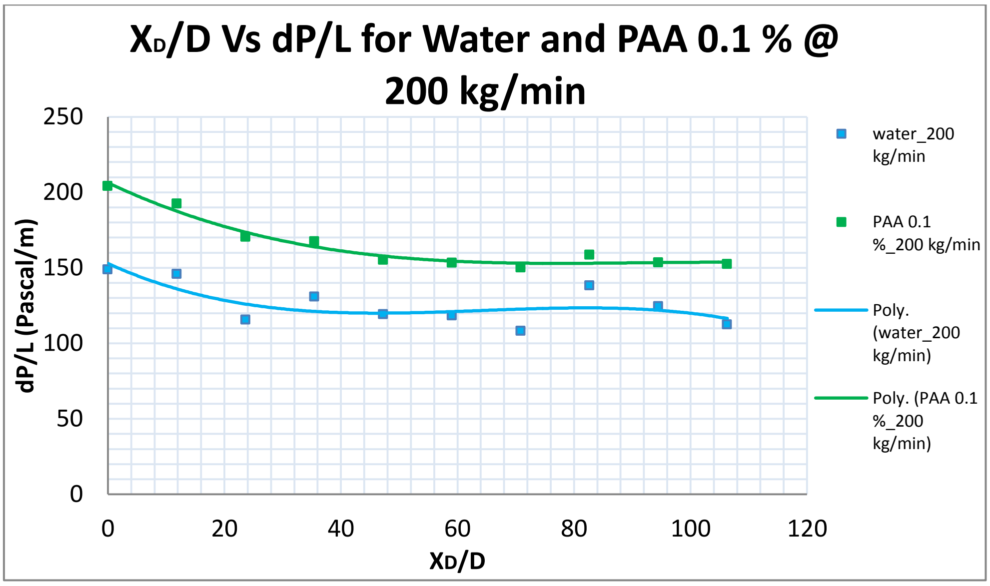

Figure 4.30: Graph for Water and Polyacrylamide 0.1 % at 200 kg/min

Table 4.6: Properties involved for 200 kg/min flow rate of Polyacrylamide concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D
Polyacrylamide 0.01%	2.7	55.52	0.002244	0.618	22842	35.43
Polyacrylamide 0.025 %	2.7	52.65	0.003016	0.618	16995	35.43
Polyacrylamide 0.05 %	2.7	73.20	0.004462	0.618	11488	35.43
Polyacrylamide 0.075 %	2.7	106.65	0.00609	0.619	8417	35.43
Polyacrylamide 0.1 %	1.8	138.01	0.007563	0.619	6777	23.62

As we can see from the graphs above, for polyacrylamide at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 200 kg/min through the test tube, there is a significant difference in the development of the entrance length. The entrance length is reduced as the polyacrylamide polymer percentage increases. Besides that the pressure is also noticed to increase along with the polyacrylamide polymer thickness. However the overall pressure is at a higher value as the velocity of the fluid is higher compared to 100 kg/min.

4.4.3 Polyacrylamide at 300 kg/min

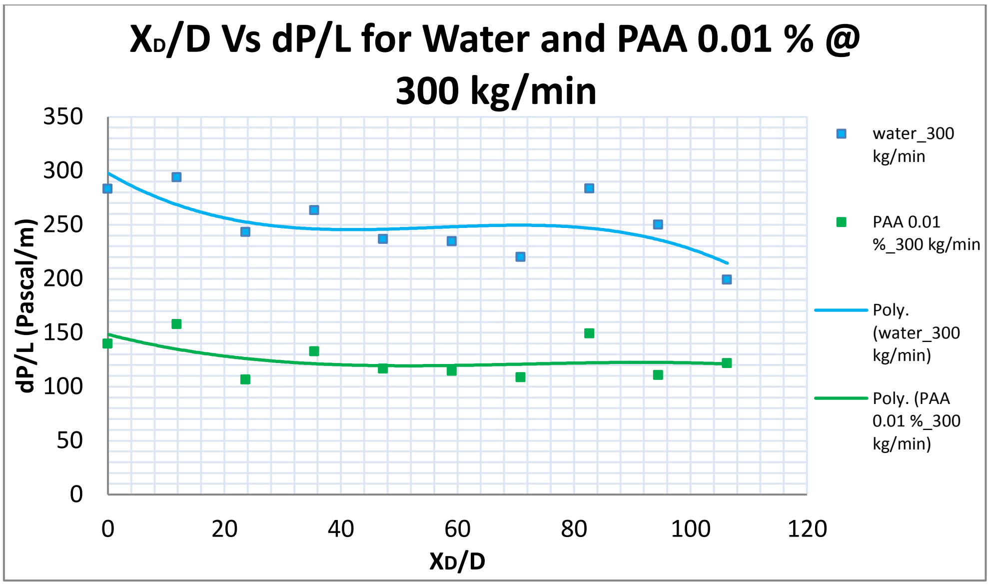

Figure 4.31: Graph for Water and Polyacrylamide 0.01 % at 300 kg/min

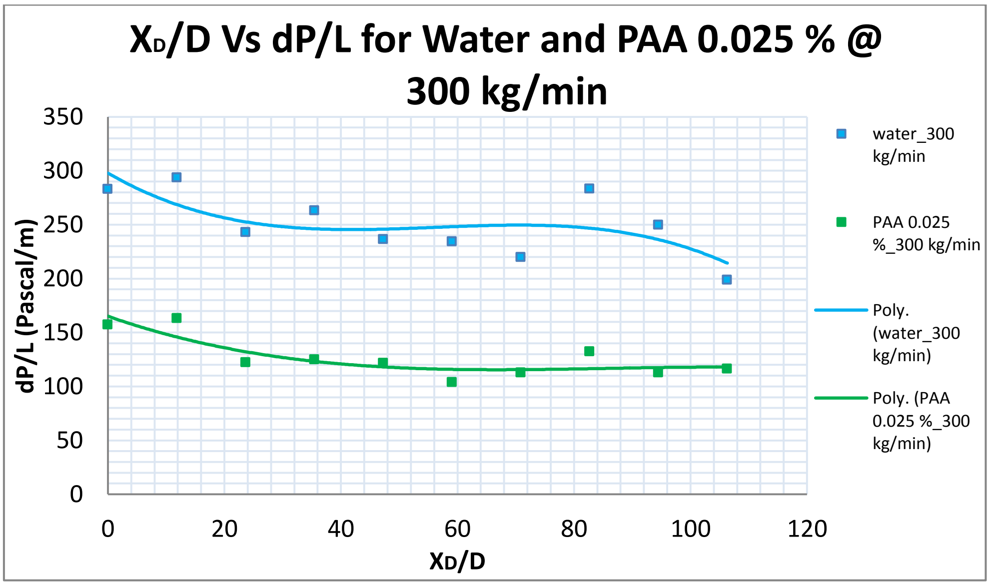

Figure 4.32: Graph for Water and Polyacrylamide 0.025 % at 300 kg/min

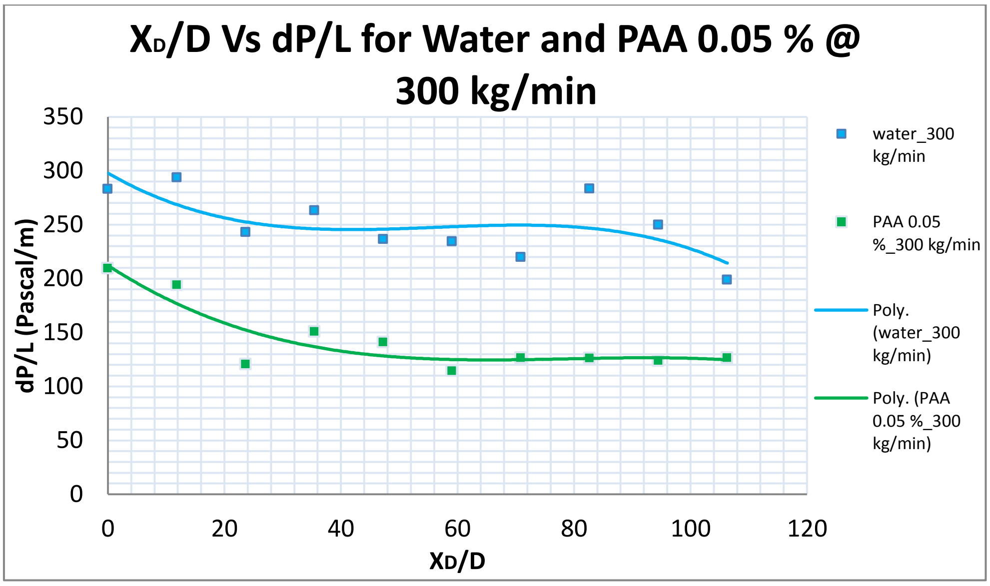

Figure 4.33: Graph for Water and Polyacrylamide 0.05 % at 300 kg/min

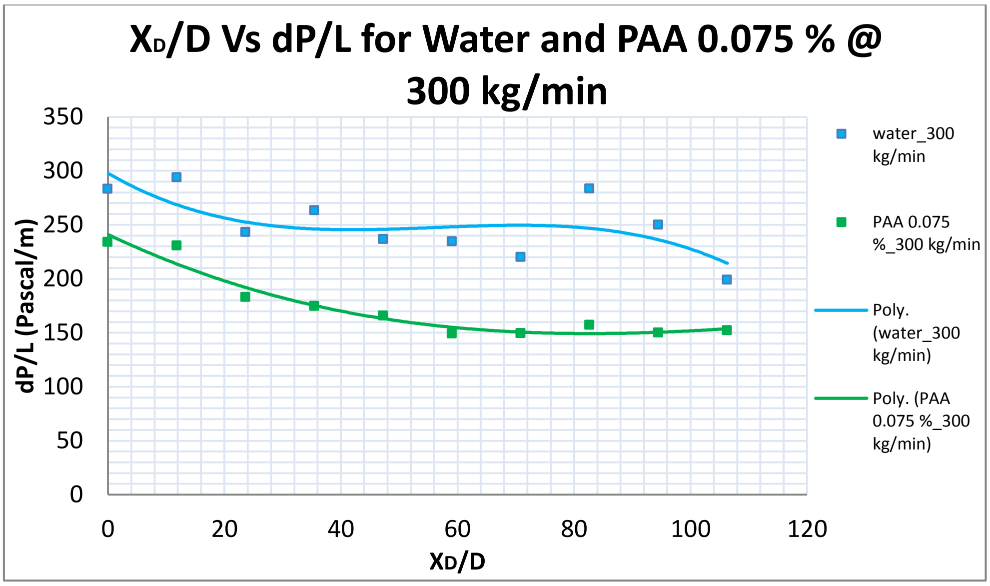

Figure 4.34: Graph for Water and Polyacrylamide 0.075 % at 300 kg/min

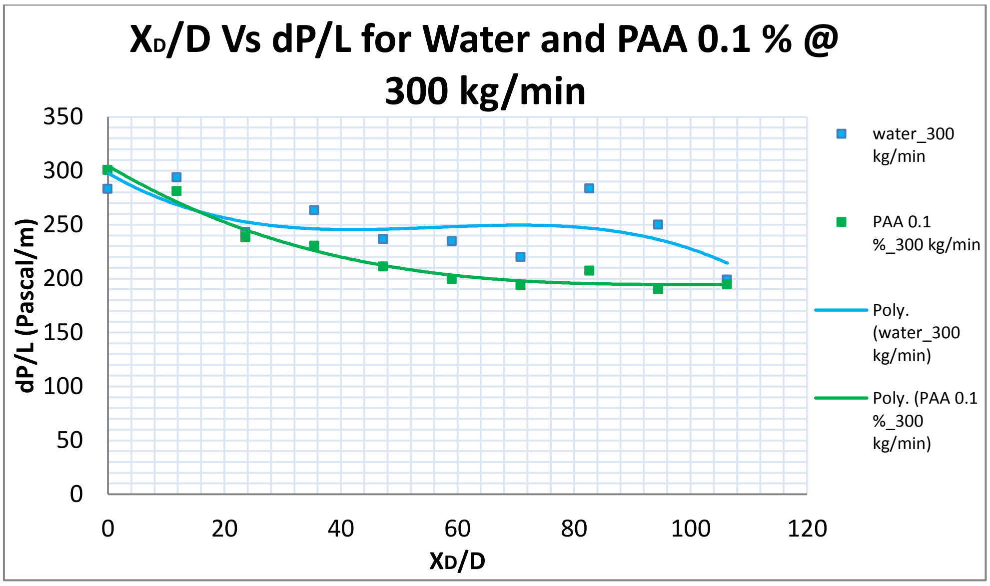

Figure 4.35: Graph for Water and Polyacrylamide 0.1 % at 300 kg/min

Table 4.7: Properties involved for 300 kg/min flow rate of Polyacrylamide concentrations

Fluid Type	Entrance Length (m)	Pressure Drop (Pa/m)	Viscosity (Pa.s)	Velocity (m/s)	Reynolds Number	X_D/D
Polyacrylamide 0.01%	3.6	99.35	0.002244	0.927	34262	47.24
Polyacrylamide 0.025 %	2.7	101.55	0.003016	0.928	25408	35.43
Polyacrylamide 0.05 %	3.6	113.63	0.004462	0.929	17185	47.24
Polyacrylamide 0.075 %	2.7	141.36	0.00609	0.931	12625	35.43
Polyacrylamide 0.1 %	2.7	174.28	0.007563	0.937	10162	35.43

As we can see from the graphs above, for polyacrylamide at 0.01, 0.025, 0.05, 0.075 and 0.01 % against water flowing at 300 kg/min through the test tube, there is a significant difference in the development of the entrance length. The entrance length is reduced following a pressure change of 15% of 3 consecutive points as the polyacrylamide polymer percentage increases. Besides that the pressure is also noticed to increase along with the polyacrylamide polymer thickness. However the overall pressure is at a higher value as the velocity of the fluid is higher compared to 100 kg/min and 200 kg/min.

Furthermore, in order to justify our finding with that of theory which states that the higher the viscosity or percentage concentration polymer added, the shorter the entrance length would become. The data taken was prepared in graphs **(Figure 4.35, figure 4.36 and figure 4.37)** in the following subsection indicating the influence of the percentage concentration against the entrance length of the flow for water and the two polymers used which are polyacrylamide and xanthan gum.

4.5 Performance Comparison of XG and PAA

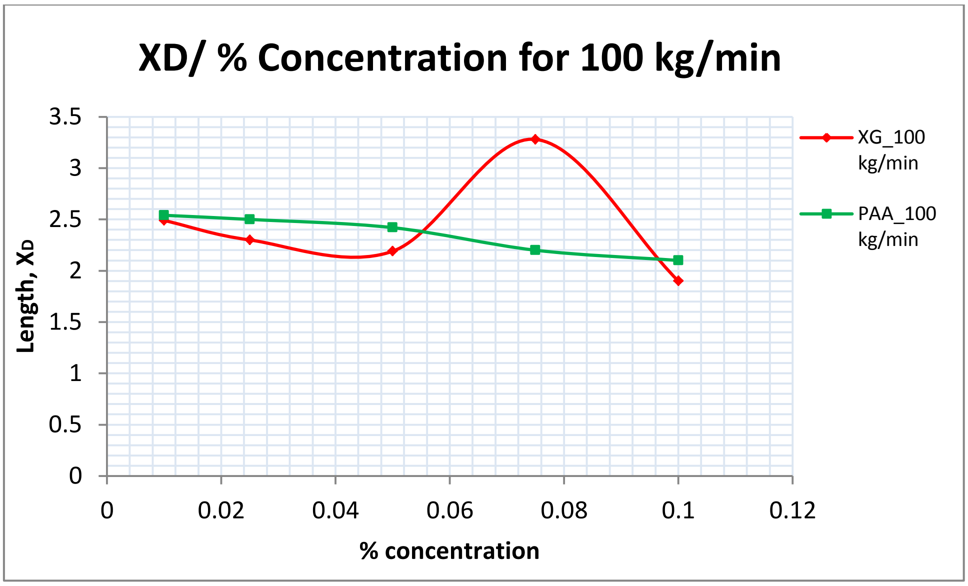

Figure 4.36: Graph of Length and % concentration polymer at 100 kg/min

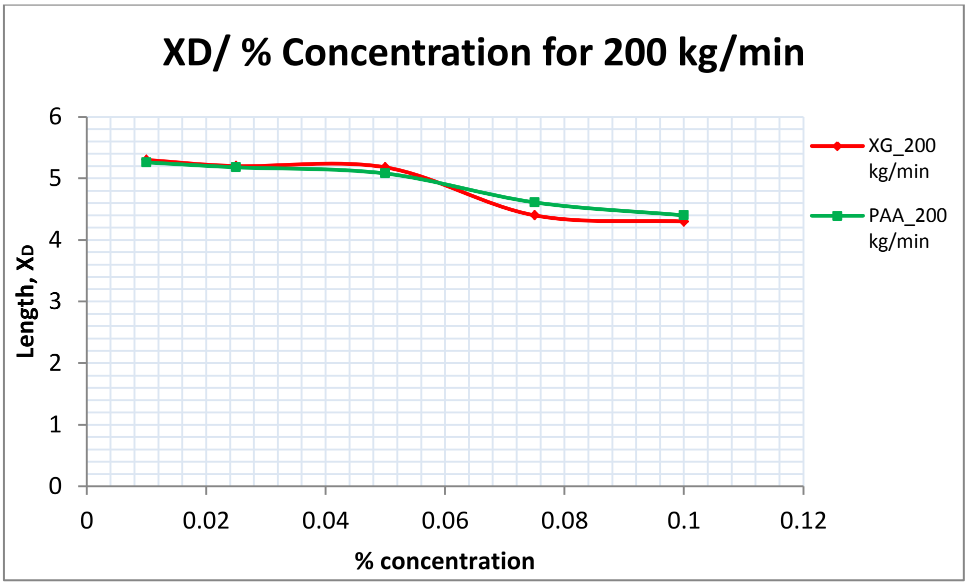

Figure 4.37: Graph of Length and % concentration polymer at 200 kg/min

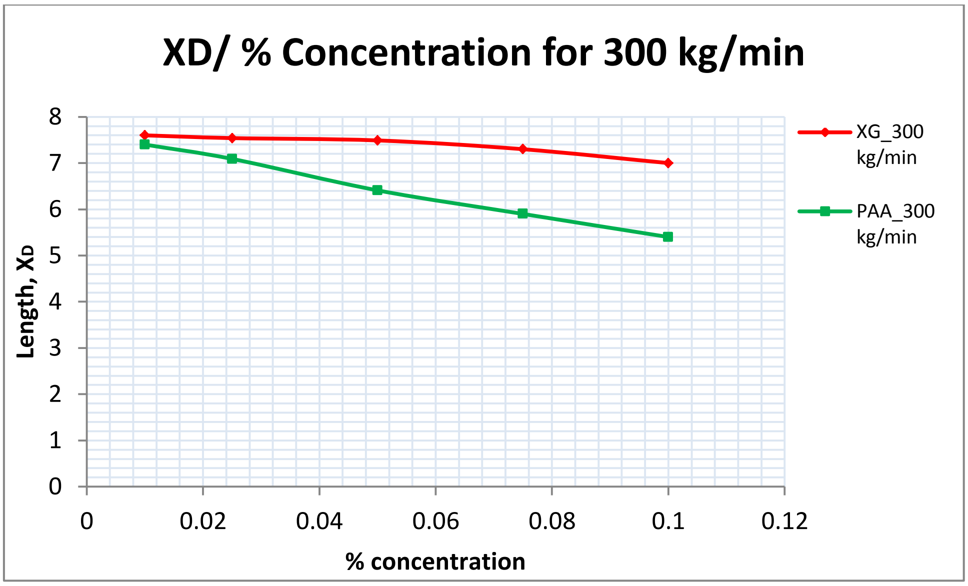

Figure 4.38: Graph of Length and % concentration polymer at 300 kg/min

As we can see from the graphs above, there is a significant chance in the entrance length as the concentration of the polymers are added respectively, from the common pattern, we can conclude that the higher the concentration the shorter the entrance length would be. Therefore, using data from this experiment we have also proven that viscosity has influence on the entrance length of pipe flow.

Another consideration done in order to verify the theory stated is to prove that the flow rate which is an important factor in this study also has a great influence on the entrance length. Below are the results of the findings in **Figure 4.38 – 4.42**.

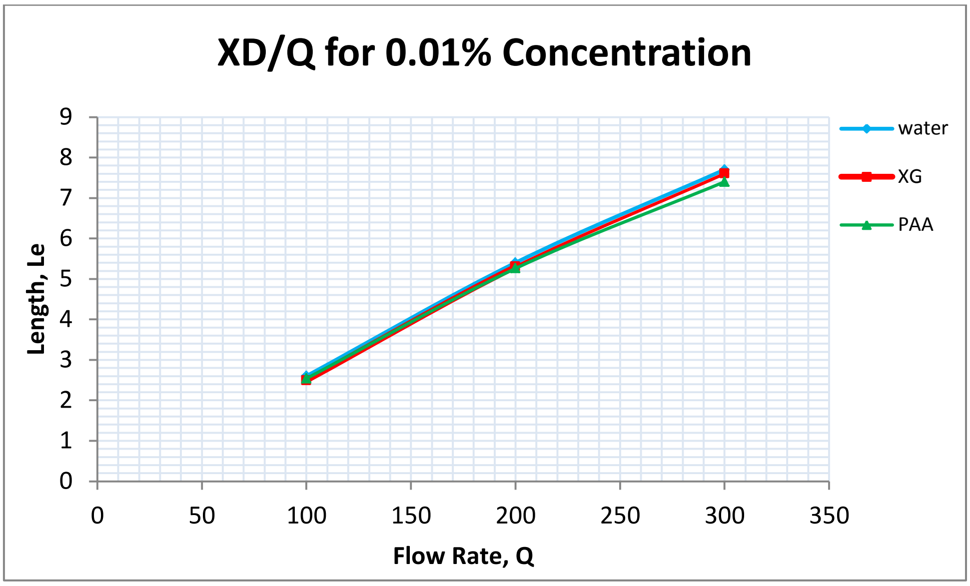

Figure 4.39: Graph of Length and Flow Rate of 0.01 % polymer concentration

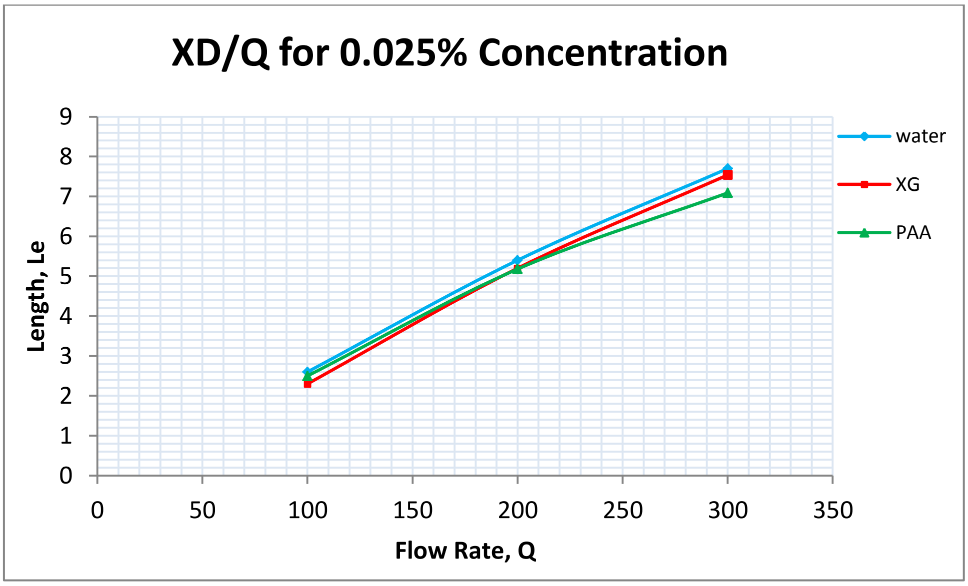

Figure 4.40: Graph of Length and Flow Rate of 0.025 % polymer concentration

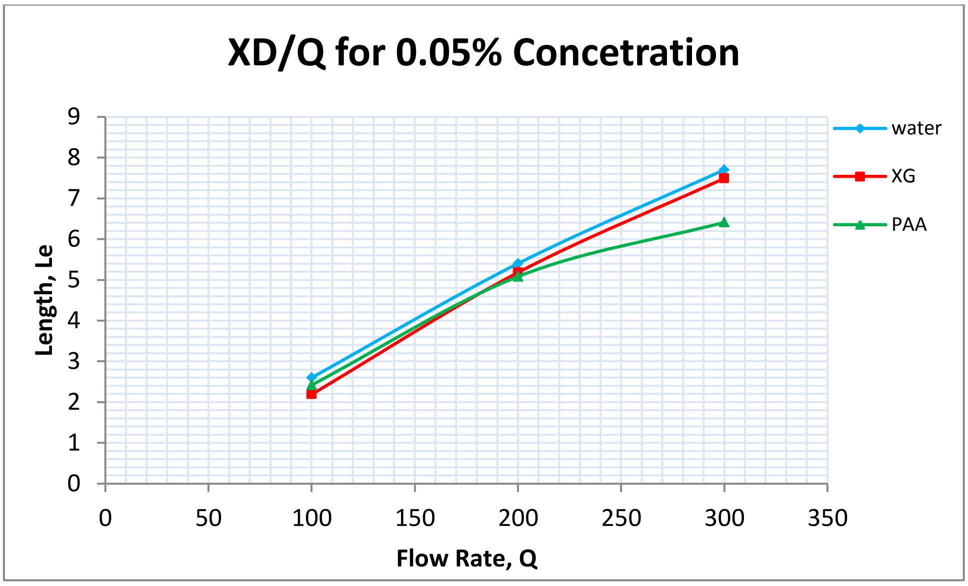

Figure 4.41: Graph of Length and Flow Rate of 0.05 % polymer concentration

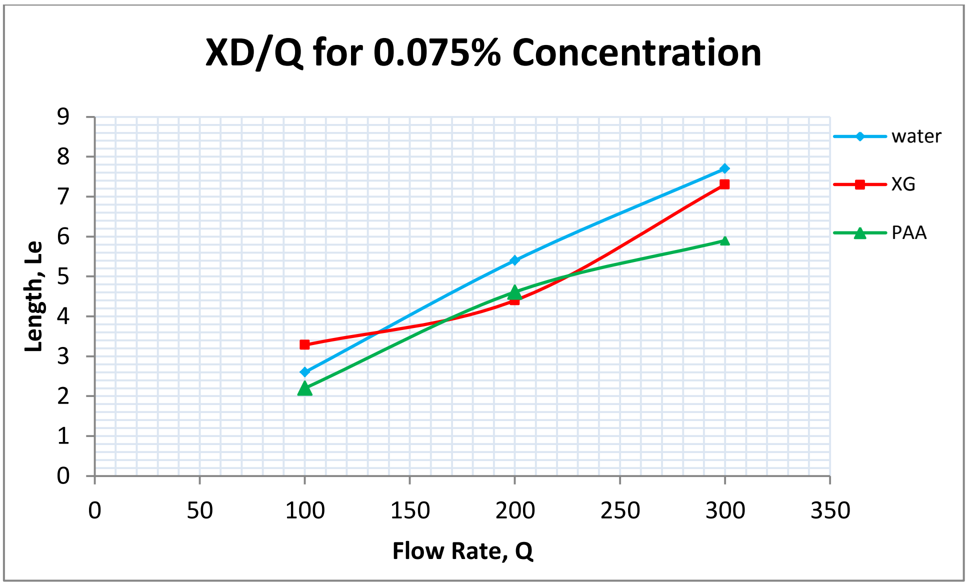

Figure 4.42: Graph of Length and Flow Rate of 0.075 % polymer concentration

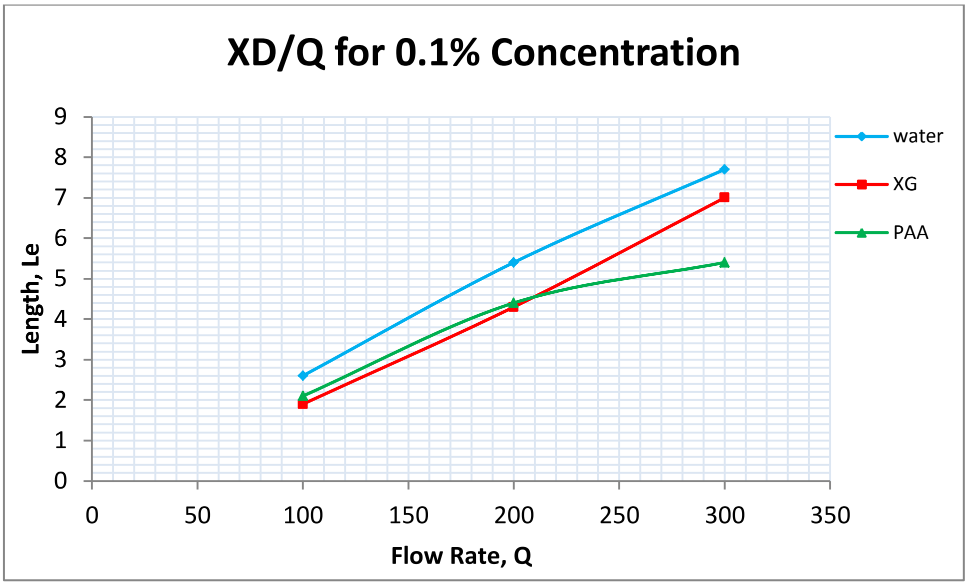

Figure 4.43: Graph of Length and Flow Rate of 0.1 % polymer concentration

Based on the results plotted above, it is shown that the flow rate does has an influence on the entrance length where the length keeps increasing with a higher flow rate and the opposite would take place otherwise. Hence, we have proven another theory from the literature studied.

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4.6 Discussion

From the flow loop experiment conducted throughout this study using water, xanthan gum and polyacrylamide has been used at various mass flow rates of 100 kg/min, 200 kg/min and 300 kg/min. Besides that the concentrations of the polymer also have been varied to 0.01 %, 0.025 %, 0.05 %, 0.075% and 0.1 %. The results that were produced did prove the theory for flow of fluids in a pipe. The objective of the study was to discover the entrance length of the polymer flows and identify the difference in the length whether is reduces or increases the entrance length. From the results of conducting the experiment with tap water, we noticed the difference of the results in terms of flow rate, pressure drop, velocity and the entrance length. All this results do relate to each other. We notice that for water flowing at 100 kg/min at a velocity of 0.3095 m/s the pressure drop as well as the Reynolds number and entrance length is smaller. As the mass flow rate is increased to 200 kg/min and 300 kg/min there is an increase in the velocity which is 0.6124 and 0.9291 respectively, pressure drop Reynolds number and entrance length. This results supports the theory that velocity is proportional to pressure drop whereby when the velocity is increased the pressure drop increases as well. This phenomenon occurs when any fluid that moves in a pipe; there is a collision between molecules because of the random movements of molecules which results in the decrease in the kinetic energy. This loss of kinetic energy is converted into some other form of energy. As we know from continuity equation; **A1 x V1 = A2 x V2** that, if the cross section of flow is not changing then velocity of fluid has to be same. Due to this reason, pressure energy is converted into kinetic energy to keep the velocity same. Hence we observe drop in pressure. When you increase the velocity of fluid, the collision between molecules increases resulting into greater loss of kinetic energy, in turn, a greater pressure drop would occur. Velocity is also known theoretically to be proportionate with the Reynolds number whereby proven using the equation;

Equation 11: $$Re = \frac{\rho V D}{\mu}$$

The following formula also proves that the viscosity of the fluid is proportionate to the Reynolds number where if the viscosity increases the Reynolds number would as well increase and vice versa. The objective of this experiment is to determine the entrance length of polymer addition in fluids which is where Xanthan Gum and Polyacrylamide was added using the various concentrations as mentioned above. From the results of Xanthan Gum additions, we can see a common pattern in the change of the entrance length. The change in the entrance length may not be significant however the results show a significant trend. From the theory studied, there are several reasons this occurs. Firstly, by increasing the concentration of Xanthan Gum from 0.01 to 0.1, the viscosity of the fluid is as well increased as we can observe from the viscosity difference that resulted from the results of the rheometer experiment. This shows Xanthan Gum polymer gives an effect on the viscosity as proven in the theory states that it increases the viscosity by adding a small amount close to 1 %. Therefore by adding the viscosity to the fluid the velocity would also increase as the drag reduces. This occurs because the friction among the molecules is reduced hence creating a larger pressure drop as stated above. Hence, this also increases the Reynolds number as can be seen from the results above where it decreases with increased viscosity. This whole phenomenon gives an effect to the entrance length by applying the theory and formula in general for Newtonian flow;

Equation 10: $X_D/D = 4.4Re^{1/6}$ **(for turbulent flow)**

From the results of the entrance length for Xanthan Gum at 100 kg/min mass flow rate we can see the difference where from the concentration of 0.01 %, we get an entrance length close to as the results of water. This indicates the slight increase in its viscosity which has given effect to the entrance length. As the concentration is increased to 0.025, 0.05, 0.075 and 0.1 we monitor the difference of the entrance length to reduce even more significantly from 1.8 to 1.0 meters. The similar situation occurs at 200 kg/min and 300 kg/min flow rate for Xanthan Gum polymers as well. For the concentration of 0.075 %, we observe the results to be out of range. This might have happened due to some errors.

Among the errors that would have occurred are the possibility of air bubbles in the fluid which caused the reading to fluctuate as air bubbles can be compressed. Another error that might have occurred is the possibility that the concentration mixture could have been wrongly done or the reading misinterpreted which is both human errors. Therefore as we can conclude by using the equation for entrance length above, as the Reynolds number is decreased the entrance length would as well be reduced hence the transition from laminar to turbulent would be faster allowing the overall development length to reduce. The similar effects are observed with the mass flow rate of 200 kg/min where with thickness of 0.01 to 0.1 % the entrance length is reduced by 0.9 meters and 300 kg/min, the entrance length is reduced by 1.0 meters. The pattern observed from here comparing all the three flow rates is that at higher flow rates the effect becomes more minimal.

As for the results on the entrance length of Polyacrylamide polymer, similar effects occur as the results of Xanthan Gum except that due to its higher viscosity which is 0.002244(0.01%), 0.003016(0.025%), 0.004462(0.05%), 0.00609 (0.075%) and 0.007563(0.1%) compared to Xanthan Gum of viscosities 0.001785(0.01%), 0.002418(0.025%), 0.003964(0.05%), 0.005193(0.075%) and 0.006963(0.1%), the velocity is increased from by 0.0005 m/s (100kg/min), 0.001 (200 kg/min) and 0.01 (300 kg/min) compared to Xanthan Gum of 0.0002 (100 kg/min), 0.0004 (200 kg/min) and 0.0004 (300 kg/min) hence causing a much higher pressure drop as proven in the results section in the previous subtopic. Therefore, this results in a shorter entrance length.

Therefore by comparing both the polymers we can say that polyacrylamide would provide better effects compared to the use of Xanthan Gum. Furthermore, along conducting the experiment Polyacrylamide is also proven to have a longer run duration compared to Xanthan Gum because Xanthan Gum is synthesized from cabbage, which is an organic material whereby it has the tendency to biologically degrade which in turn decreases its viscosity therefore it spoils and its viscosity effect decreases. Whereby, polyacrylamide which is formed chemically from acrylamide subunits has very late decay time. However both has its benefits and uses in different fields as stated in theory therefore both polymers provide benefits to the development length of fluids.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Literature review has highlighted the importance of the different fluid properties of polymer flows and shown the importance of the work of numerous researchers in this field. However, there was not much published work on the study of turbulent entrance length in pipe flow. Several researchers have developed empirical equations to characterize the entrance length of turbulent Newtonian flow however, little has been done to characterize the entrance length of turbulent Non-Newtonian flow, and therefore the conclusion of this study is expected to provide future researchers with an experimental solution for characterizing the entrance length of turbulent Non-Newtonian flow. Before initiating our experiment we also have identified the steps required in order to run the study, which could prove vital for the experiments to be conducted then. In our methodology we have discussed the steps in getting familiar with the flow loop and the additional apparatus required. Therefore, our experiments could be conducted with complete understanding of the phenomena occurring in the flow as well as the ability to analyze the result. From the results obtained, we could identify the difference of polymer addition in comparison to plain tap water. Our experiment results indicated a difference in the entrance length with Xanthan Gum and Polyacrylamide polymers addition. The entrance length was taken to be the point where the pressure difference becomes constant or a very slight difference. This is the point where the fluid has developed whereby from laminar to turbulent and is proven from the theory of the textbook and reference. [23] Besides that from the study we can also conclude that the addition of polymer provides significant difference in the entrance length whereby as the concentration of polymer is higher the entrance length reduces. This concept has been proven experimentally and tallies with the literature where a higher viscosity results in an increase of velocity because of drag reduction where the friction among molecules id reduced giving a higher pressure drop so as a higher Reynolds Number. Hence, the transition from laminar to turbulence is increased. [19]. In conclusion, this experimental study was a success as the results proved above that polymer does effect the entrance length of fluid therefore in other words, higher viscosity reduces the entrance length of the fluid.

5.2 Future Work

For the future work of this study, it has been identified that there is room for improvement where necessary improvements and modifications could be made in order to increase the quality as well as the productivity of the research. Among the few measures that could be taken are:

- Use a wider variety of polymer of different properties where the results would be more accurate to the theory when compared whereby a wider set of results could be studied.
- Use higher concentration variance to get better results where the changes are more visible.
- To implement more accurate measuring devices whereby the data collected would be more precise and accurate. Besides that a standard polymer mixing method should also be implemented to reduce losses during mixing and accurate measurement of materials.
- Implement a cheaper and suitable polymer which required a very small amount to increase the viscosity greatly as well as also having a longer degradation time where its viscosity remains constant for a longer period.

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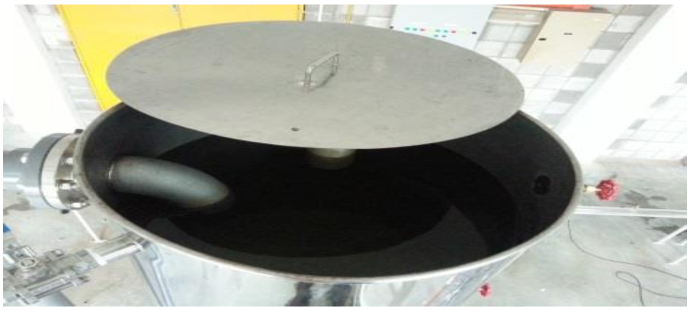
APPENDICES

Appendix 1

1. Image of Polymer Flow Loop Test Rig

2. Images of procedures of experiment

2.1 Flow loop tank for storing water and mixing polymers



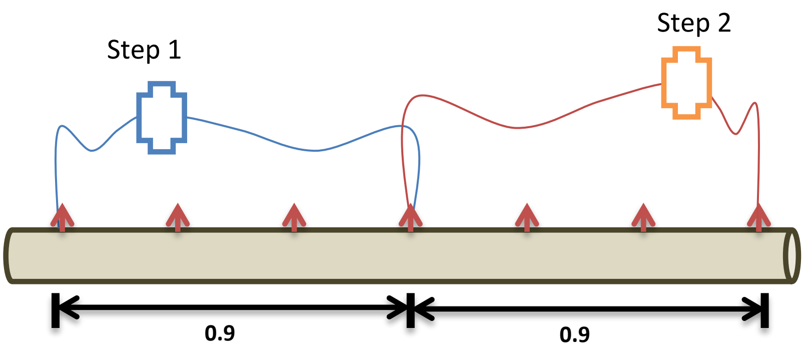
2.2 Control panel of flow loop used to control flow rate and power on/off

2.3 Valve along pipeline to measure pressure drop

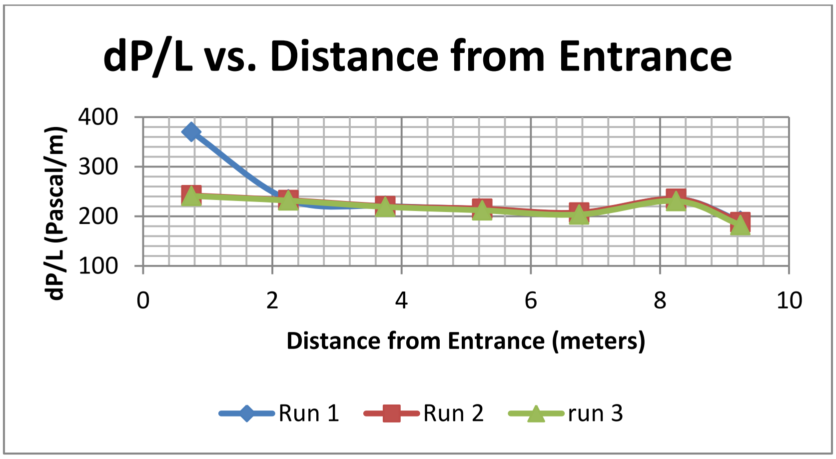
2.4 Pressure transducer to measure pressure drop along test tube

2.5 Data results of flow experiment on computer

3. Procedure of measuring the pressure of the test loop



4. Example of Data Collected and Analyzed by graph



5. Raw data average from experiment runs

5.1 Tap Water

Flow rate of 100 m/s

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperatur e	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	99.84722222	99.99305556	26	997	34.1770625	0.787971163
Point 2	0.9	0.9	99.82608696	99.98550725	26	997	28.31608696	0.652843116
Point 3	0.9	1.8	99.86764706	100	26	997	23.09508824	0.53247009
Point 4	0.9	2.7	99.92957746	100	26	997	27.08049296	0.62435581
Point 5	0.9	3.6	99.90909091	100	26	997	27.70539394	0.638763249
Point 6	0.9	4.5	99.56179775	99.85393258	26	997	30.11480899	0.694313652
Point 7	0.9	5.4	99.69117647	99.97058824	26	997.0294118	21.45764706	0.494717974
Point 8	0.9	6.3	99.73015873	99.98412698	26	997.031746	25.63496825	0.591028435
Point 9	0.9	7.2	99.73846154	99.95384615	26	997.1230769	26.43366154	0.609442752
Point10	0.45	8.1	99.70422535	99.95774648	26	997.3098592	11.34022535	0.522910391

Appendix 4

Flow rate of 200 m/s

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	27	997	133.8610769	3.086241495
Point 2	0.9	0.9	200	200	27	997	131.2454194	3.025936058
Point 3	0.9	1.8	200	200	27	997	104.0680476	2.399346653
Point 4	0.9	2.7	200	200	27	997	117.8095556	2.716164754
Point 5	0.9	3.6	200	200	27	997	107.1990968	2.471534732
Point 6	0.9	4.5	200	200	27	997	106.4375238	2.453976243
Point 7	0.9	5.4	200	200	27	997	97.29341935	2.243153835
Point 8	0.9	6.3	200	200	27	997.015873	124.3472063	2.866893923
Point 9	0.9	7.2	200	200	27	997.0634921	111.9816508	2.581799171
Point 10	0.45	8.1	200	200	27	997.031746	50.55453968	2.331125996

Flow rate of 300 m/s

Point/Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	299.9846154	300.0307692	26	997	254.7716308	5.873901488
Point 2	0.9	0.9	299.4776119	300	26	997	264.3726567	6.095258474
Point 3	0.9	1.8	299.0285714	300	26	997	218.7120857	5.042528643
Point 4	0.9	2.7	299	300	26	997	236.8896364	5.461622173
Point 5	0.9	3.6	299	300	26	997	212.7238235	4.904465931
Point 6	0.9	4.5	299.7272727	300	26	997	211.0174848	4.865125344
Point 7	0.9	5.4	299.9705882	300	26	997	197.9443824	4.563717705
Point 8	0.9	6.3	299.9848485	300	26	997	255.1203333	5.881941018
Point 9	0.9	7.2	300	300	26	997	224.9474394	5.186288186
Point 10	0.45	8.1	300	300.0615385	26	997	89.4822	4.126123667

5.2 Xanthan Gum mixture of 0.01 %

Flow Rate of 100 kg/m

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	**Density**	**Pressure Drop**	Shear Stress
Point 1	0.9	0	100	100.2631579	27	997	32.84667105	0.757298249
Point 2	0.9	0.9	100.0128205	100.2051282	27	997	31.21512821	0.719682123
Point 3	0.9	1.8	100	100.29	27	997	28.07348	0.647249678
Point 4	0.9	2.7	100	100.202381	27	997	26.60790476	0.613460026
Point 5	0.9	3.6	100.0196078	100.3235294	27	997	26.14035294	0.602680359
Point 6	0.9	4.5	100.0512821	100.3717949	27	997	26.02125641	0.599934523
Point 7	0.9	5.4	100	100.3076923	27	997	25.73246154	0.593276197
Point 8	0.9	6.3	100.0512821	100.4615385	27	997	27.99602564	0.645463924
Point 9	0.9	7.2	100.0240964	100.3373494	27	997	25.32461446	0.583873056
Point 10	0.45	8.1	100.0808081	100.5252525	27	997	8.216151515	0.378855875

Appendix 5

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	199	199.4972067	26	997	117.442933	2.707712066
Point 2	0.9	0.9	199	199.4025974	26	997	118.5409351	2.733027115
Point 3	0.9	1.8	199	199.3246753	26	997	101.9464286	2.350431548
Point 4	0.9	2.7	199	200	26	997.063	109.6992125	2.529176288
Point 5	0.9	3.6	199.0113636	200	26	997.114	103.0461364	2.375785923
Point 6	0.9	4.5	199.0117647	200	26	997.318	99.41868235	2.292152954
Point 7	0.9	5.4	199	200	26	997.718	93.68391026	2.159934598
Point 8	0.9	6.3	199.1976744	200	26	997.884	117.8786279	2.717757254
Point 9	0.9	7.2	199.379562	200	26	997.993	105.1669489	2.424682433
Point 10	0.45	8.1	199.4615385	200	26	998	44.17723077	2.037061197

Flow Rate of 300 kg/min

Point/ Section	Lengt h	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300.124183	26	997.986	250.2089869	5.768707198
Point 2	0.9	0.9	299.8571429	300	26	998	255.0640909	5.880644318
Point 3	0.9	1.8	299.5	300	26	998	215.7184024	4.973507611
Point 4	0.9	2.7	299.244186	300	26	998	234.7997907	5.413439619
Point 5	0.9	3.6	299.25	300	26	998	219.2001071	5.053780247
Point 6	0.9	4.5	299.1833333	300	26	998	208.5627833	4.808530837
Point 7	0.9	5.4	299	300	26	998	198.5696506	4.578133611
Point 8	0.9	6.3	299.0126582	300	26	998	252.5546456	5.822787662
Point 9	0.9	7.2	299.0625	300	26	998	219.65075	5.064170069
Point 10	0.45	8.1	299.0102041	300	26	998	93.38611224	4.306137398

5.3 Xanthan Gum mixture 0f 0.025 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100.7179487	101	29	996	32.10332051	0.74015989
Point 2	0.9	0.9	100.7102804	101	29	996	35.20176636	0.81159628
Point 3	0.9	1.8	100.7051282	101	29	996	33.4355	0.770874028
Point 4	0.9	2.7	100.5641026	100.974359	29	996	32.53571795	0.750129053
Point 5	0.9	3.6	100.6296296	100.9753086	29	996	34.71103704	0.800282243
Point 6	0.9	4.5	100.625	100.975	29	996	30.88865	0.712154986
Point 7	0.9	5.4	100.5584416	100.987013	29	996	25.48132468	0.587486097
Point 8	0.9	6.3	100.5384615	100.9487179	29	996	24.06769231	0.554894017
Point 9	0.9	7.2	100.4415584	100.9350649	29	996	30.90136364	0.712448106
Point 10	0.45	8.1	100.4642857	100.9761905	29	996	2.9785	0.137341944

Appendix 6

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	201	29	996	120.0381818	2.767546969
Point 2	0.9	0.9	200	201	29	996.025641	124.8325	2.878082639
Point 3	0.9	1.8	200	201	28.58974359	996.1923077	97.69674359	2.252452699
Point 4	0.9	2.7	200	201	28	996.6233766	115.3571299	2.659622717
Point 5	0.9	3.6	200	201	28	997	107.1179405	2.469663628
Point 6	0.9	4.5	200	201	28	997	97.44819737	2.246722328
Point 7	0.9	5.4	200	201	28	997	101.8051948	2.347175325
Point 8	0.9	6.3	200	201	28	997	114.958961	2.650442712
Point 9	0.9	7.2	200	201	28	997	111.7816883	2.577188925
Point 10	0.45	8.1	200	201	28	997	38.62909091	1.781230303

Flow Rate of 300 kg/m

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	299	300	28	997	250.5850533	5.777377618
Point 2	0.9	0.9	299	300	28	997	254.9024868	5.876918446
Point 3	0.9	1.8	299	300	28	997	215.7047432	4.97319269
Point 4	0.9	2.7	299	300	28	997	236.17748	5.445203011
Point 5	0.9	3.6	299	300	28	997	219.7668125	5.066845955
Point 6	0.9	4.5	299	300	28	997	202.000026	4.657222822
Point 7	0.9	5.4	299	300	28	997	198.1874875	4.569322628
Point 8	0.9	6.3	299	300	28	997	256.1362338	5.905363168
Point 9	0.9	7.2	299	300	28	997	225.2279067	5.192754516
Point 10	0.45	8.1	299.9210526	300.2763158	28	997	87.81827632	4.049398297

5.4 Xanthan Gum mixture of 0.05 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100	100.0208333	23	999	32.72397917	0.75446952
Point 2	0.9	0.9	100.0120482	100.0240964	23	999	32.6096506	0.751833611
Point 3	0.9	1.8	100	100.0128205	22.92307692	999	29.05212821	0.669812956
Point 4	0.9	2.7	100	100	22	999	33.04668966	0.761909789
Point 5	0.9	3.6	100	100.0126582	22	999	28.19422785	0.650033587
Point 6	0.9	4.5	100.0114943	100.0229885	22	999	29.65045977	0.683607822
Point 7	0.9	5.4	100.0123457	100.0246914	22	999	27.27046914	0.628735816
Point 8	0.9	6.3	100	100.0126582	22	999	34.23301266	0.789261125
Point 9	0.9	7.2	100	100	22	999	30.99876623	0.714693777
Point 10	0.45	8.1	100	100	22	999	11.51159551	0.53081246

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	22	999	123.2463974	2.841514162
Point 2	0.9	0.9	200	200	22	999	124.744369	2.87605073
Point 3	0.9	1.8	200	200	22	999	107.2563735	2.472855278
Point 4	0.9	2.7	200	200	22	999	116.3307792	2.682070743
Point 5	0.9	3.6	200	200	22	999	108.638297	2.504716292
Point 6	0.9	4.5	200	200	22	999	106.206275	2.448644674
Point 7	0.9	5.4	200	200	22	999	100.3049425	2.312586174
Point 8	0.9	6.3	200	200	22	999	124.4400118	2.869033605
Point 9	0.9	7.2	200	200	22	999	110.7648372	2.553744858
Point 10	0.45	8.1	200	200	22	999	46.53662069	2.145855287

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300	22	999	261.8192585	6.03638846
Point 2	0.9	0.9	300	300	22	999	265.9382353	6.131353758
Point 3	0.9	1.8	299.98	300	22	999	223.51464	5.1532542
Point 4	0.9	2.7	300	300	22	999	242.5621538	5.592405213
Point 5	0.9	3.6	300	300	22	999	226.191141	5.214962418
Point 6	0.9	4.5	299.9886364	300	22	999	216.7223068	4.996653185
Point 7	0.9	5.4	299.9873418	300	22	999	208.2725949	4.801840382
Point 8	0.9	6.3	300	300	22	999	260.6658718	6.009796489
Point 9	0.9	7.2	300	300	22	999	227.25075	5.239392292
Point 10	0.45	8.1	300	300	22	999	98.28047436	4.531821873

5.5 Xanthan Gum mixture of 0.075 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100	100.1343284	29	997	40.44586567	0.932501903
Point 2	0.9	0.9	100	100.1744186	29	997	29.57955814	0.681973146
Point 3	0.9	1.8	100	100.1594203	29	997	22.12136232	0.510020298
Point 4	0.9	2.7	100.0147059	100.2352941	29	997	26.97980882	0.622034481
Point 5	0.9	3.6	99.984375	100.25	28.984375	997	29.00978125	0.668836623
Point 6	0.9	4.5	100.0151515	100.2424242	28.36363636	997	27.61027273	0.636570177
Point 7	0.9	5.4	100	100.28125	28	997	25.90239063	0.597194006
Point 8	0.9	6.3	100.0163934	100.3114754	28	997	27.13781967	0.625677509
Point 9	0.9	7.2	100	100.2903226	28	997	26.04585484	0.600501653
Point 10	0.45	8.1	100	100.2676056	28	997	7.361323944	0.339438826

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200.2403101	28	997	112.7822248	2.60025685
Point 2	0.9	0.9	200	200.0615385	28	997	121.8764308	2.809928821
Point 3	0.9	1.8	200	200	28	997	100.1786197	2.309673732
Point 4	0.9	2.7	200	200.119403	28	997	115.5205522	2.663390509
Point 5	0.9	3.6	200	200.2089552	28	997	104.2509552	2.403563689
Point 6	0.9	4.5	200	200.4788732	28	997	104.2218451	2.40289254
Point 7	0.9	5.4	200	200.6056338	28	997	94.70160563	2.18339813
Point 8	0.9	6.3	200	200.6338028	28	997	118.6180563	2.734805187
Point 9	0.9	7.2	200	200.75	28	997	104.1748889	2.401809939
Point 10	0.45	8.1	200	200.8157895	28	997	52.30017105	2.411618998

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	299.4603175	300.0634921	28	997	250.3476984	5.771905269
Point 2	0.9	0.9	299	300	28	997	251.4954203	5.798366635
Point 3	0.9	1.8	299	300	28	997	211.0338592	4.865502865
Point 4	0.9	2.7	299	300	28	997	227.7459714	5.250809896
Point 5	0.9	3.6	299	300	28	997	218.8627042	5.046001236
Point 6	0.9	4.5	299	300	28	997	196.9429014	4.540628005
Point 7	0.9	5.4	299	300	28	997	195.5422121	4.508334335
Point 8	0.9	6.3	299	300	28	997	246.1192143	5.674415219
Point 9	0.9	7.2	299	300	28	997	220.4009231	5.081465727
Point 10	0.45	8.1	299	300	28	997	94.24386364	4.345689268

5.6 Xanthan Gum mixture of 0.1 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	99.98795181	99.96385542	20	1000	34.69391566	0.7998875
Point 2	0.9	0.9	99.98795181	99.93975904	20	1000	35.07983133	0.808785
Point 3	0.9	1.8	99.9625	99.925	20	1000	31.53325	0.727016597
Point 4	0.9	2.7	99.98765432	99.9382716	20	1000	37.28050617	0.859522781
Point 5	0.9	3.6	99.95061728	99.87654321	20	1000	33.13692593	0.763990237
Point 6	0.9	4.5	99.95061728	99.90123457	20	1000	31.94138272	0.736426324
Point 7	0.9	5.4	99.90243902	99.82926829	20	1000	31.07196341	0.716381379
Point 8	0.9	6.3	99.95454545	99.92045455	20	1000	33.96622727	0.78311024
Point 9	0.9	7.2	99.93975904	99.91566265	20	1000	30.753	0.7090275
Point 10	0.45	8.1	99.96103896	99.92207792	20	1000	12.48945455	0.575902626

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	20	1000	126.0004286	2.905009882
Point 2	0.9	0.9	200	200	20	1000	126.9894045	2.92781127
Point 3	0.9	1.8	200	200	20	1000	107.4941412	2.478337144
Point 4	0.9	2.7	200	200	20	1000	117.5178701	2.709439783
Point 5	0.9	3.6	200	200	20	1000	110.1752683	2.540152019
Point 6	0.9	4.5	200	200	20	1000	106.1135443	2.446506716
Point 7	0.9	5.4	200	200	20	1000	102.9672169	2.37396639
Point 8	0.9	6.3	200	200	20	1000	126.5906625	2.918618052
Point 9	0.9	7.2	200	200	20	1000	112.6282152	2.596706073
Point 10	0.45	8.1	200	200	20	1000	48.43828205	2.233543006

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300	20	1000	264.2599412	6.092659755
Point 2	0.9	0.9	300	299.8988764	20	1000	267.8427079	6.175262432
Point 3	0.9	1.8	299.987013	299.7402597	20	1000	225.2118312	5.192383886
Point 4	0.9	2.7	299.8791209	299.5714286	20.14285714	1000	244.5213077	5.637574594
Point 5	0.9	3.6	299.8478261	299.423913	20.63043478	1000	231.5268804	5.337980854
Point 6	0.9	4.5	299.7843137	299.372549	20.99019608	1000	220.8872451	5.092678151
Point 7	0.9	5.4	299.8961039	299.4155844	21	1000	211.3814675	4.873517167
Point 8	0.9	6.3	299.6516854	299.2808989	21	1000	264.4409888	6.096833908
Point 9	0.9	7.2	299.6282051	299.2051282	21	1000	231.3237051	5.333296534
Point 10	0.45	8.1	299.5930233	299.1627907	21	1000	100.3932558	4.629244573

5.7 Polyacrylamide mixture of 0.01 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100.0344828	100.0344828	21	999	24.77833333	0.571278241
Point 2	0.9	0.9	100.0560748	100.0841121	21	999	23.98128037	0.552901742
Point 3	0.9	1.8	100.0555556	100.0777778	21	999	20.825	0.480131944
Point 4	0.9	2.7	100	100.0106383	21	999	19.86835106	0.458075872
Point 5	0.9	3.6	100	100.012987	21	999	20.82990909	0.480245126
Point 6	0.9	4.5	100.0283688	100.0496454	21	999	19.25560993	0.443948784
Point 7	0.9	5.4	100.019802	100.039604	21	999	20.20886139	0.465926526
Point 8	0.9	6.3	100.0506329	100.0506329	21	999	22.89832911	0.527933699
Point 9	0.9	7.2	100.0875	100.1375	21	999	21.2464625	0.489848997
Point 10	0.45	8.1	100.0365854	100.0487805	21	999	9.338426829	0.430605237

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	21	999	67.3898375	1.553710142
Point 2	0.9	0.9	200	200	21	999	71.74764151	1.654181735
Point 3	0.9	1.8	200	200	21	999	52.1562375	1.202491031
Point 4	0.9	2.7	200	200	21	999	64.38715054	1.484481526
Point 5	0.9	3.6	200	200	21	999	60.40098795	1.392578333
Point 6	0.9	4.5	200	200	21	999	58.0222375	1.33773492
Point 7	0.9	5.4	200	200	21	999	55.52197531	1.280089986
Point 8	0.9	6.3	200	200	21	999	69.99520408	1.613778316
Point 9	0.9	7.2	200	200	21	999	56.17187209	1.295073718
Point 10	0.45	8.1	200	200	21	999	34.22902198	1.578338236

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300	21	999	125.633443	2.896548825
Point 2	0.9	0.9	300	300	21	999	141.7503837	3.268133846
Point 3	0.9	1.8	299.9878049	300	21	999	95.79532927	2.208614536
Point 4	0.9	2.7	300	300	21	999	119.1832346	2.747835687
Point 5	0.9	3.6	299.9873418	300	21	999	104.8144304	2.416554923
Point 6	0.9	4.5	300	300	21	999	103.0336854	2.375498858
Point 7	0.9	5.4	300	300	21	999	97.534775	2.248718424
Point 8	0.9	6.3	300	300	21	999	134.2155949	3.094415105
Point 9	0.9	7.2	299.9913793	300	21	999	99.34641379	2.290486762
Point 10	0.45	8.1	300	300	21	999	54.62	2.518588889

5.8 Polyacrylamide mixture of 0.025 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100	100	21	999	36.95556989	0.852031195
Point 2	0.9	0.9	100.010989	100.010989	21	999	36.64215385	0.844805214
Point 3	0.9	1.8	100	100	21	999	26.9390641	0.621095089
Point 4	0.9	2.7	100.0258621	100.0344828	21	999	25.92296552	0.597668372
Point 5	0.9	3.6	100.0215054	100.0215054	21	999	23.59344086	0.543959886
Point 6	0.9	4.5	100.0458015	100.0687023	21	999	24.53985496	0.565779989
Point 7	0.9	5.4	100.0520833	100.0729167	21	999	20.07291667	0.462792245
Point 8	0.9	6.3	100.0825688	100.1100917	21	999	22.04444037	0.50824682
Point 9	0.9	7.2	100.0721649	100.1134021	21	999	20.40497938	0.470448136
Point 10	0.45	8.1	100.1333333	100.2190476	21	999	9.107733333	0.419967704

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	21	1000	82.1597125	1.894237816
Point 2	0.9	0.9	200	200	21	1000	75.1945	1.733650972
Point 3	0.9	1.8	200	200	21	1000	59.18440244	1.364529278
Point 4	0.9	2.7	200	200	21	999.9130435	59.10291304	1.362650495
Point 5	0.9	3.6	200	200	21	999.9493671	56.88598734	1.311538041
Point 6	0.9	4.5	200	200	21	999.0625	47.9277375	1.105000615
Point 7	0.9	5.4	200	200	21	999.0185185	52.6504537	1.21388546
Point 8	0.9	6.3	200	200	21	999	58.81147778	1.355931293
Point 9	0.9	7.2	200	200	21	999	53.36084946	1.230264029
Point 10	0.45	8.1	200	200	21	999	26.67871127	1.23018502

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	299.1898734	299.4936709	21	999	141.602443	3.264722991
Point 2	0.9	0.9	299	299	21	999	146.9455755	3.38791188
Point 3	0.9	1.8	299	299	21	999	110.2459712	2.541782114
Point 4	0.9	2.7	299	299	21	999	112.5324671	2.594498547
Point 5	0.9	3.6	299	299	21	999	109.5097311	2.524807689
Point 6	0.9	4.5	299.5802469	299.9135802	22	999	93.46991358	2.155000785
Point 7	0.9	5.4	299	299.0677966	22	999	101.5167034	2.340523995
Point 8	0.9	6.3	299	299	22	999	119.13666	2.746761883
Point 9	0.9	7.2	299	299	22	999	101.5483333	2.34125324
Point 10	0.45	8.1	299	299	22	999	52.36817391	2.414754686

5.9 Polyacrylamide mixture of 0.05 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	99.54545455	99.98701299	28	997	55.86119481	1.28791088
Point 2	0.9	0.9	99.58333333	100	27.14285714	997	43.60525	1.005343264
Point 3	0.9	1.8	99.72727273	100	27	997	30.93590909	0.713244571
Point 4	0.9	2.7	99.78947368	100	27	997	40.22322368	0.927368768
Point 5	0.9	3.6	99.80519481	100	27	997	45.3262987	1.045022998
Point 6	0.9	4.5	99.85526316	100	27	997	37.37127632	0.861615537
Point 7	0.9	5.4	99.88461538	100	27	997	36.55005128	0.842681738
Point 8	0.9	6.3	99.87096774	100	27	997	40.92713978	0.943597945
Point 9	0.9	7.2	99.8877551	100	27	997	44.90242857	1.035250436
Point 10	0.45	8.1	99.91262136	100	27	997	27.52607767	1.269258026

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	27	997	134.0698814	3.091055599
Point 2	0.9	0.9	200	200	27	997	120.6403976	2.781431389
Point 3	0.9	1.8	200	200	27	997	97.8692987	2.256431053
Point 4	0.9	2.7	200	200	27	997.0120482	92.6136988	2.135260278
Point 5	0.9	3.6	200	200	27	997.0804598	87.35377011	2.0139897
Point 6	0.9	4.5	200	200	26.86075949	997.3544304	77.76263291	1.792860703
Point 7	0.9	5.4	200	200	26.02631579	997.6578947	73.20636842	1.687813494
Point 8	0.9	6.3	200	200	26	997.974026	76.67041558	1.767679026
Point 9	0.9	7.2	200	200	26	998	70.89261538	1.634468632
Point 10	0.45	8.1	200	200	26	997.987013	36.65912987	1.690393211

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	299.5170068	300	26	997.9863946	188.6677143	4.349838969
Point 2	0.9	0.9	299.05	300	26	998	174.64122	4.02645035
Point 3	0.9	1.8	299	300	26	997.9888889	108.5048667	2.501639982
Point 4	0.9	2.7	299	300	26	998	135.6445269	3.127359926
Point 5	0.9	3.6	299	300	26	998	127.043593	2.929060616
Point 6	0.9	4.5	299.0606061	300	26	998	102.883202	2.372029379
Point 7	0.9	5.4	299.1184211	300	26	998	113.9403684	2.626958494
Point 8	0.9	6.3	299.1904762	300	26	998	113.6260714	2.619712202
Point 9	0.9	7.2	299.3205128	300	26	998	111.4767564	2.57015855
Point 10	0.45	8.1	299.6883117	300	26	998	56.91806494	2.624555217

5.10 Polyacrylamide mixture of 0.075 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100	100	25	998	88.549	2.041546389
Point 2	0.9	0.9	100	100	25	998	75.15730172	1.732793345
Point 3	0.9	1.8	100	100	25	998	70.13181818	1.61692803
Point 4	0.9	2.7	100	100	25	998	66.56691026	1.534737098
Point 5	0.9	3.6	100	100	25	998	67.269975	1.550946646
Point 6	0.9	4.5	100	100	25	998	69.70570886	1.607103843
Point 7	0.9	5.4	100	100.011236	25	998	68.85353933	1.587456601
Point 8	0.9	6.3	100	100	25	998	78.62386585	1.812716907
Point 9	0.9	7.2	100	100	25	998	68.8765375	1.587986837
Point 10	0.45	8.1	100	100	25	998	38.66831429	1.783038937

Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	25	998	148.8528188	3.431884433
Point 2	0.9	0.9	199.975	200	25	998	151.3570625	3.489621163
Point 3	0.9	1.8	200	200	25	998	118.7997051	2.738993201
Point 4	0.9	2.7	200	200	25	998	113.7592593	2.622782923
Point 5	0.9	3.6	200	200	25	998	106.6738629	2.459425172
Point 6	0.9	4.5	200	200	25	998	106.6478659	2.458825797
Point 7	0.9	5.4	200	200	25	998	103.3304368	2.382340626
Point 8	0.9	6.3	200	200	25	998	107.5577564	2.479803828
Point 9	0.9	7.2	200	200	25	998	97.06976623	2.237997388
Point 10	0.45	8.1	200	200	25	998	45.73541304	2.108910712

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300	25	998	210.4093224	4.851103822
Point 2	0.9	0.9	300	300	25	998	207.6201169	4.78679714
Point 3	0.9	1.8	300	300	25	998	164.5144103	3.792971126
Point 4	0.9	2.7	300	300	25	998	157.0513077	3.62090515
Point 5	0.9	3.6	300	300	25	998	149.0483117	3.436391631
Point 6	0.9	4.5	300	300	25	998	134.1858442	3.093729186
Point 7	0.9	5.4	300	300	25	998	134.2796883	3.095892814
Point 8	0.9	6.3	300	300	25	998	141.3620106	3.259179689
Point 9	0.9	7.2	300	300	25	998	134.8668646	3.109430489
Point 10	0.45	8.1	300	300	25	998	68.35475325	3.151913622

5.11 Polyacrylamide mixture of 0.1 %

Flow Rate of 100 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	100	100	21	1000	120.723703	2.783352041
Point 2	0.9	0.9	100	100	21	1000	102.8838485	2.372044285
Point 3	0.9	1.8	100	100	21	1000	100.4974773	2.317025171
Point 4	0.9	2.7	100	100	21	1000	93.91339474	2.16522549
Point 5	0.9	3.6	100	100	21	1000	94.26982222	2.173443123
Point 6	0.9	4.5	100	100	21	1000	94.87835714	2.187473234
Point 7	0.9	5.4	100	100	21	1000	93.37730864	2.152865727
Point 8	0.9	6.3	100	100	21	1000	98.111725	2.262020326
Point 9	0.9	7.2	100	100	21	1000	97.33123333	2.244025657
Point 10	0.45	8.1	100	100	21	1000	47.6794026	2.198550231

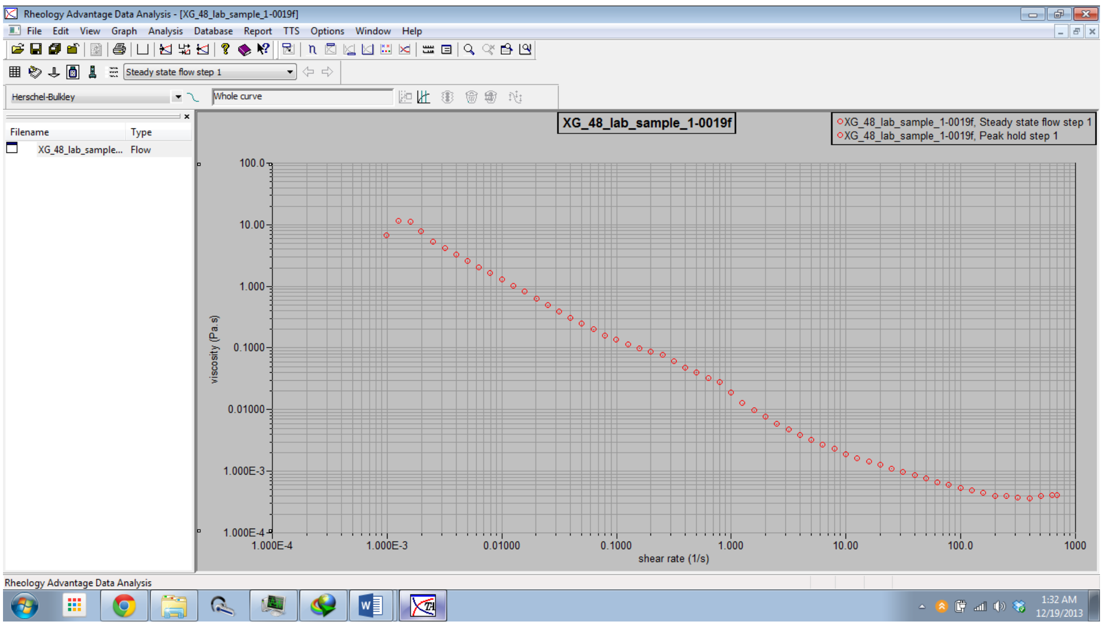
Flow Rate of 200 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	200	200	21	999.9892473	183.6011505	4.233026525
Point 2	0.9	0.9	200	200	21	999.9876543	173.1523951	3.992124665
Point 3	0.9	1.8	200	200	21	999.9411765	153.4261294	3.53732465
Point 4	0.9	2.7	200	200	21	999.7631579	150.6554474	3.473445037
Point 5	0.9	3.6	200	200	21	999.6153846	139.587359	3.21826411
Point 6	0.9	4.5	200	200	21	999.5057471	138.014069	3.181991035
Point 7	0.9	5.4	200	200	21	999.3536585	135.0247927	3.113071609
Point 8	0.9	6.3	200	200	21	999.0512821	142.6226026	3.288243338
Point 9	0.9	7.2	200	200	21	999.1153846	138.0268974	3.182286801
Point 10	0.45	8.1	200	200	21	999.0344828	68.60344828	3.163381226

Flow Rate of 300 kg/min

Point/ Section	Length	Distance	Mass Flow rate	Volume Flow Rate	Temperature	Density	Pressure Drop	Shear Stress
Point 1	0.9	0	300	300	21	999	270.3501951	6.233073943
Point 2	0.9	0.9	299.9764706	300	21	999	252.9558941	5.83203867
Point 3	0.9	1.8	300	300	21	999	214.1043176	4.936293989
Point 4	0.9	2.7	299.8536585	299.9634146	21	999	207.2663537	4.778640933
Point 5	0.9	3.6	299.9375	300	21.0375	999	189.8417875	4.376907878
Point 6	0.9	4.5	299.6883117	299.9220779	21.96103896	999	179.3981299	4.13612355
Point 7	0.9	5.4	299.8837209	299.9767442	22	999	174.2787093	4.018092464
Point 8	0.9	6.3	299.978022	300	22	999	186.4378571	4.298428372
Point 9	0.9	7.2	300	300	22	999	170.9344624	3.940988994
Point 10	0.45	8.1	300	300	22	999	87.46488889	4.03310321

6. Sample results of rheometer in order to get viscosity of fluid



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