Investigation of Polymer Slug Viscosity in Porous Media

by

Amirruddin Ali Bin Sidek Ali

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

SEPTEMBER 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Investigation of Polymer Slug Viscosity in Porous Media

by

Amirruddin Ali Bin Sidek Ali

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

____
(DR. ISA M TAN)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2012

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.

AMIRRUDDIN ALI BIN SIDEK ALI

ABSTRACT

In order to maintain reservoir pressure and also to sweep out oil efficiently, water flooding became the standard practice in many reservoir formations. The efficiency of the water flood oil displacement mechanism as a result of an unfavorable mobility ratio was identified. Polymer solutions are designed to develop a favorable mobility ratio between injected polymer solution and the oil or water bank being displaced a head of the polymer. The purpose is to develop a more uniform volumetric sweep of the reservoir, both vertically and aerially. An experimental study has been conducted to examine the effects of a dilute aqueous solutions of a partially hydrolyzed polyacrylamide polymer, over a wide range of parameters. In general, the viscosity-shear rate relationship was found to obey the Newtonian behavior at low shear rates and a power-law behavior at high shear rates with the power indices from 0.2 to 0.6. However, adding an ionic species such as sodium chloride (NaCl), reduced the hydrodynamic size of the polymer molecule (physical change), changing the viscosity-shear rate relationship. The viscosity-shear rate relationship was found to be a strong function of cation type only at salt concentrations less than 2 wt%. The viscosity values showed that polymer solutions are more affected by the different molecular weight of polymer than the degree of hydrolysis used. The higher concentration of polymer will make the polymer solution viscosity increasing. The different pressure applied on the polymer solution will effect on the viscosity at the certain range. This study demonstrates the effect of several parameters to the polymer solution viscosity that significantly influencing the performance of chemical flooding in EOR.

ACKNOWLEDGEMENTS

The author wishes to take the opportunity to express his utmost gratitude to the individual that have taken the time and effort to assist the author in completing the project. Without the cooperation of these individuals, no doubt the author would have faced some minor complications throughout the course.

First and foremost the author's utmost gratitude goes to the author's supervisor, Dr. Isa M Tan. Without his guidance and patience, the author would not be succeeded to complete the project. To Muhammad Rehan Hasmet in Enhanced Oil Recovery Centre, UTP, for providing the author with all the initial information required to begin the project and continuously support during the lab work execution.

To all technicians in Chemical Engineering, and Petroleum Engineering Department, thank you for assisting the author in completing her project.

To all individuals that has helped the author in any way, but whose name is not mentioned here, the author thank you all. Special thanks especially to my family and friends. And to Allah, who made all things possible.

TABLE OF CONTENT

LIST OF FIGURES

Abbreviations and Nomenclatures:

EOR – Enhanced Oil Recovery

CEOR – Chemical Enhanced Oil Recovery

HPAM – Partially hydrolyzed polyacrylamide

NaCl – Sodium Chloride

HPHT – High Pressure High Temperature

ASP – Alkali and polymeric surfactant

MW – Molecular Weight

DOH – Degree of hydrolysis

λ – Mobility

K_i – Effective Permeability

μ_i – Fluid Viscosity

i – oil, water or gas

M – Mobility ratio

K_{rw} – Relative Permeability of the displacing fluid (e.g water)

μ_w – Displacing fluid Viscosity (e.g water)

K_{ro} – Relative Permeability of the displaced fluid (e.g oil)

μ_o – Displaced fluid Viscosity (e.g oil)

μ_i – Viscosity of fluid i

τ – Shear Stress

γ – Shear Rate

cP – centipoise

CHAPTER 1 INTRODUCTION

1.1 Background

In Malaysia and many other countries, most mature reservoirs are already waterflooded, or are being subjected to secondary and tertiary recovery processes. Recognizing the potential of EOR in the fields, the national oil company (PETRONAS) endorsed a comprehensive EOR screening in year. The screening study on seventy two reservoirs has identified almost a billion barrels of additional reserves can be achieved through EOR (Samsudin, Dorman, Husain, & Hamdan, 2005). The Chemical Enhanced Oil Recovery (CEOR) was identified as one of the key EOR processes that have good potential for field implementation to increase ultimate recovery in Malaysian oil fields.

One of the considerations for chemical flooding application is the addition of alkaline which has a detrimental effect on polymer performance and in many cases additional polymer is required to achieve the desired viscosity (Wang & Caudle, 1970). (Nasr-El-Din, Hawkins, & Green, 1991) documented that there was an exponential decrease in viscosity of the combined ASP solution with an increase in alkali concentration. A process that eliminates some of the existing problems is required and this project is proposing new formulation for ASP flooding that will mitigate the viscosity reduction. In this project, a new chemical formulation will be developed which consist of alkali and polymeric surfactant (ASP).

1.1.1 ASP Flooding

This process, as the name suggests, is a combination of the three processes namely alkaline, surfactant and polymer flooding in which the three slugs are used in sequence. Alternatively, the three fluids could be mixed together and injected as a single slug. The objective of the ASP flooding process is to reduce the amount of chemical consumed per unit volume of oil required (Ali & Thomas, Miscellar Flooding and ASP-Chemical

Methods for Enhanced Oil Recovery, 2001) and invariable a reduction in cost. Problem Statement

1.1.2 Problem Identification

For heavy oils , thermal processes have been used extensively whereas for light oils, chemical processes such as polymer flooding, caustic flooding, miscible flooding and surfactant-polymer flooding have attracted great interest. The degradation of polymer in porous media with current temperature, pressure, salinity condition of reservoir has decrease the effectiveness of the polymer as thicknening agent. The present project focuses to study on polymer viscosity to improve the areal sweep efficiecny for oil recovery and the fundamental aspects of the surfactant-polymer flooding process.

1.1.3 Significant of the Project

Through this project, we aim to investigate and identify the effects of different molecular weight and degree of partially hydrolyzed polyacrylamide polymer, over a wide range of temperature, pressure, salinity and hardness.

1.2 Objective

This study embarks on the following objectives:

1. To study the affect of polymer viscosity in specified conditions of temperature, pressure, salinity and shear rate
2. To measure polymer amounts and concentration required in Polymer solution formulation.
3. To screen and identify the suitable common polymer i.e. polyacrylamide and xanthan or combination of these polymer for the best effectiveness in reducing the mobility ratio.
4. To investigate for the optimal conditions that gives highest viscosity for Polymer solution formulation.

1.3 Scope of the Study

The main focus of this work is to find an optimum condition for partially hydrolyzed polyacrylamide slug that will mitigate the viscosity reduction.

1.4 Relevancy of the Project

Extensive research has been carried out to develop and refine the polymer flooding process. The rheological properties of polymer solutions such temperature, pressure, shear rate and the presence of chemical such: salts, alkali and surfactant will affect the viscosity of the polymer solution thus affect their effectiveness in mobility control. With the recent surge of interest in polymer flooding, new needs arise for more data on the viscosity properties.

CHAPTER 2 LITERATURE REVIEW

Generally, the addition of a very small amount of water-soluble, high molecular weight polymer to the displacing water can increase the apparent viscosity of the water and lower the mobility ratio (Ali, Thomas, Scoular, & Verkoczy, 2001).

2.1 Polymer in Industries and Classification

There are many water-soluble polymers with potential use in enhacend oil recovery applications. However, two most general polymer types used in the EOR process are a synthetic material, polyacrylamide, in its partially hydrolysed form (HPAM) and the biopolymer, xanthan (Sorbie, 1991). These kinds of polymers are extensively used in several industries as the thickening agents or as the parts of the manufacturing process.

2.2 Structure of a Polymer

The rheological properties of polymer solutions play an important role in determining their effectiveness. Depending on the process, polymers can encounter various chemical species, including: salts, alkalis, and surfactants. The presence of these chemicals together may significantly alter the chemical and physical nature of the polymer molecule and consequently, the viscosity of the polymer solution will change.

2.2.1 Partially hydrolyzed polyacrylamide (HPAM)

The chemical structure of partially hydrolyzed polyacrylamide is:

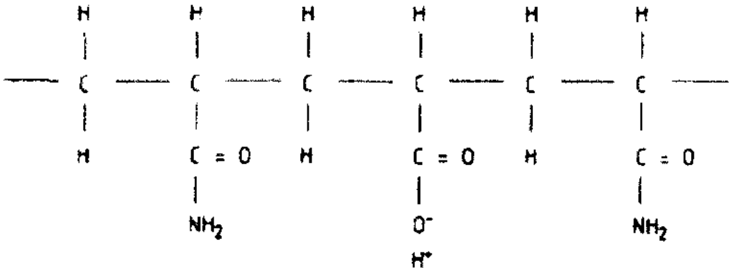


Figure 1: Chemical structure of HPAM (Littman, 1988)

The typical molecular weight of HPAM used in polymer flood is within the range of 2 - 20 x 10^6 g/mole. The viscosity-increasing feature is derived the repulsion between polymer molecules and between the segments of the same molecule. This repulsion causes the molecule to lengthen and snag on other molecule. This increase in viscosity causes the lower mobility of the polymer solution.

2.3 Polymer Flooding in Petroleum Reservoirs

Polymer flooding results from adding a polymer to the injected water in a waterflood to decrease its mobility (Lake, 1989). By adding a polymer to the water, the viscosity of that polymer solution increases which leads to significant decrease in the mobility ratio of the waterflood. The mobility ratio is the ratio of the displacing fluid mobility to the displaced fluid mobility. It is the primary factor that affects the areal sweep efficiency of a given well spacing and pattern of waterflood.

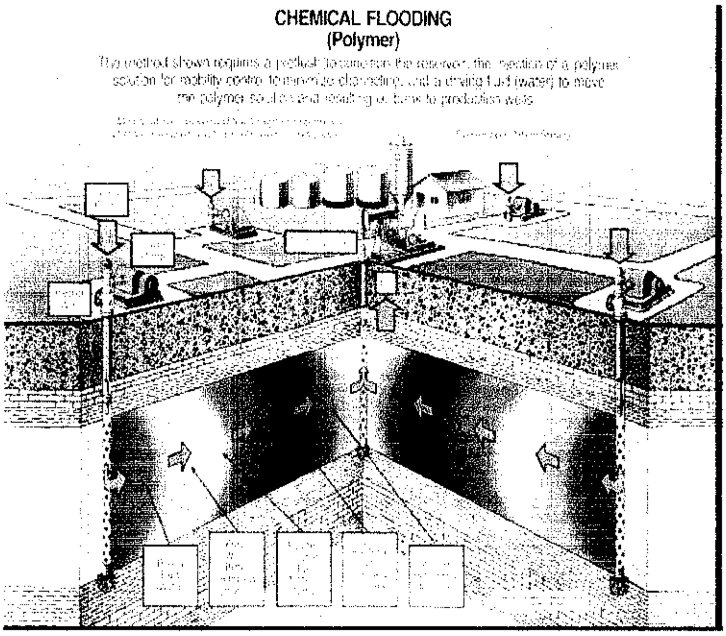


Figure 2: Polymer flooding process (Lindley, 2001)

Figure above demonstrates a typical polymer flood schematic (Lake, 1989). The polymer flood process usually starts with a pre-flush of low-salinity brine, followed by the flushed oil bank and the polymer solution. Fresh water or a lower concentration of polymer solution is usually used as a buffer to protect the polymer solution from backside contamination. These precautions are taken because of the significant sensitivity of conventional polymers to brine salinity and chemistry. The final step is injecting the chasing or driving water to push the polymer solution into the reservoir.

2.4 Improving the mobility ratio

For an EOR to be effective, the two important parameters that must be taken into consideration are the mobility ratio and the capillary number. Mobility of a fluid is defined as the ratio of the effective permeability to the viscosity of the fluid:

$$\lambda = \frac{K_i}{\mu_i}$$

Where

λ = Mobility

K_i= Effective Permeability

μ_i = Fluid Viscosity

i = oil, water or gas

While mobility ratio, M, is defined as the mobility of the displacing fluid divided by the mobility of the displaced fluid.

$$M = \frac{K_{rw}}{\mu_w} \Big/ \frac{K_{ro}}{\mu_o}$$

Where

M = Mobility ratio

K_{rw}= Relative Permeability of the displacing fluid (e.g water)

μ_w = Displacing fluid Viscosity (e.g water)

K_{ro}= Relative Permeability of the displaced fluid (e.g oil)

μ_o = Displaced fluid Viscosity (e.g oil)

For maximum displacement efficiency, M should be ≤ 1 for favorable mobility ratio. If $M>1$, then it means that the displacing fluid, for example, water in a waterflood moves more easily than the displaced fluid, for example, oil. This is unfavorable because the displacing fluid will flow past the displaced fluid given rise to a phenomenon called 'viscous fingering' where most of the oil is by-passed (Figure 2) (Torsæter, 2009). However, if M >1 and there is no viscous fingering, it means that more fluid will be injected to attain a given residual oil saturation in the pores. Thus, for effective displacement of fluid, the mobility ratio is very important.

In case of enhanced oil recovery, mobility ratio can be made smaller, in other words, 'improved' by one of the following ways;

- Lowering the viscosity of the displaced fluid, for example, oil
- Increasing the viscosity of displaced fluid
- Increasing the effective permeability to oil
- Decreasing the effective permeability to the displacing fluid.

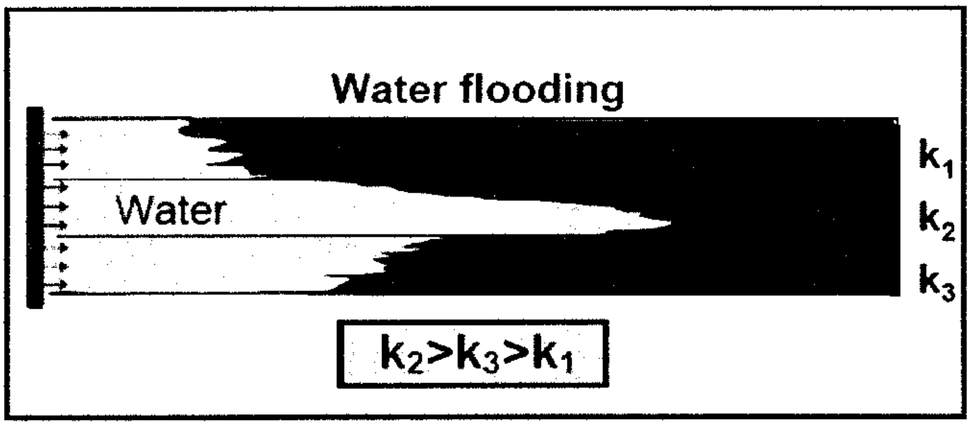


Figure 3: Fingering of water into the oil bank for mobility ratios greater than 1 (Lindley, 2001)

Polymer solutions used in EOR are normally behaved in shear thinning region. These solutions show Newtonian behavior at low shear rate, correspond to low flow rate, followed by region of shear thinning where the viscosity of fluid reduces, above. At very high shear rates correspond to high flow rate, polymer viscosity tends to show second Newtonian behavior just above the solvent viscosity.

2.5 Polymer Rheology

Rheology is the science of the deformation and flow of matter. When applied to polymer solution, rheology deals with the relationship between Shear Rate and Shear Stress. Shear rate is the change in fluid velocity divided by the gap or width of the channel through which the fluid moving in laminar flow whereas shear stress is the force per unit area required to move a fluid at a given shear rate. Viscosity is the resistance of fluid to flow or deform. In mathematical definition it is a fluid shear stress divided by corresponding shear rate.

$$\mu_i = \frac{\tau}{\gamma}$$

Where

μ_i = Viscosity of fluid i

τ = Shear Stress

γ = Shear Rate

Several models have been developed to give more understanding on different fluid in laminar flow. Some of the models are:

- Newtonian Model
- Bingham Plastic Model
- Power Law Model

Newtonian Model describes Newtonian fluid which the ratio of shear stress to shear rate is constant.

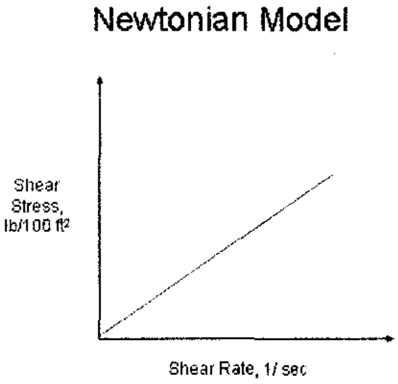


Figure 4: Graph of Newtonian Model. (Lindley, 2001)

For the non-Newtonian fluids, its ratio of shear stress and shear rate are not constant. The fluids contain solid particles of various sizes (normally larger than the fluid molecules) that form a structure resistant to flow.

Bingham Plastic Model is the most common model to describe non-Newtonian fluid. This model assumes that the shear rate is a straight line function of the shear stress. The point (on shear stress) where the shear rate is zero is called yield point or threshold stress. While the slope of shear stress and shear rate curve is called plastic viscosity.

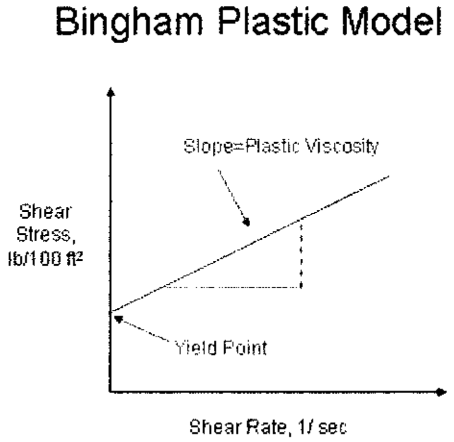


Figure 5: Graph of Bingham Plastic Model. (Lindley, 2001)

Another model to describe non-Newtonian fluid is Power Law Model. The shear rate and shear stress curve has the exponential equation.

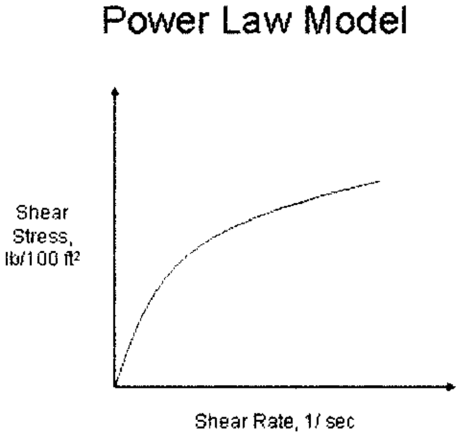


Figure 6: Graph of Power Law Model. (Lindley, 2001)

The most common relationship between shear rate and viscosity of non-Newtonian fluid is described by power law model (Bird et al., 1960):

$$\eta(\dot{\gamma}) = K\dot{\gamma}^{n-1}$$

Where

$\eta(\dot{\gamma})$ = Viscosity of fluid at $\dot{\gamma}$ shear rate.

$\dot{\gamma}$ = Shear rate.

K, n = Constant, for shear thinning material n is less than 1 while n is equal to 1 for Newtonian fluid.

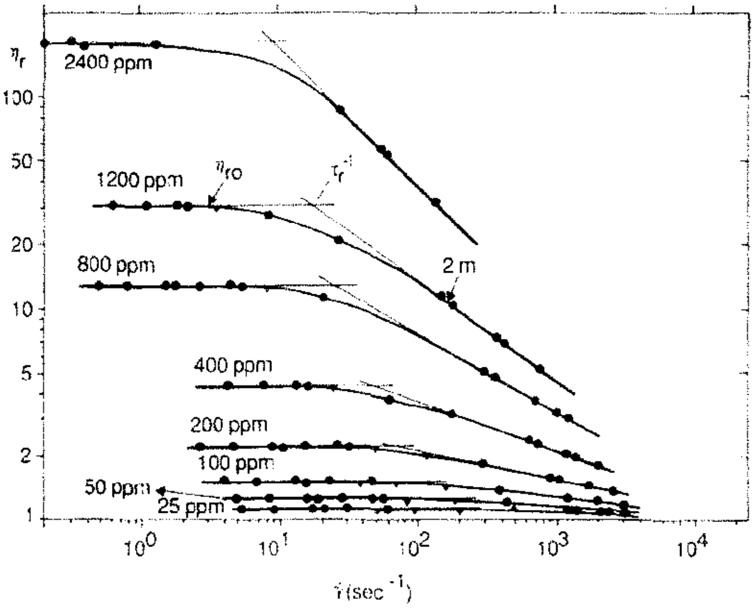


Figure 7: Viscosity versus shear rate of xanthan solution at a range of polymer concentration (after Chauveteau, 1982)

2.6 Viscosity Units

The SI unit of pressure, *p*, as well as shear of stress, is the Pascal (Pa) = Newtons per square meter [N=m2]. This is a small unit; a larger unit is the kilopascal (kPa) = 103 Pa. In the imperial (English) unit system, the common unit of pressure, *p*, as well as of shear stress, is lbf per square inch (psi). The conversion factors for pressure and stress are:

1 Pa = 1:4504 x 10-4 psi
1 kPa = 1:4504 x 10-1 psi

The SI units of kinematic viscosity, *v*, are [m2/s]. An additional cgs unit for absolute viscosity, m, is the poise [dyne-s/cm2]. The unit of dyne-seconds per square centimeter is the poise, while the centipoise (one hundredth of poise) has been widely used in bearing calculations, but now has been gradually replaced by SI units. The cgs unit for kinematic viscosity, n, is the stokes (St) [cm2/s]. A smaller unit is the centistokes (cSt), cSt = 10^{-2} stokes. The unit cSt is equivalent to [mm2/s].

2.7 Factors that Affect the Efficiency of Polymer Viscosity

2.4.1 Slug Size

A review by (Wang & Caudle, 1970) on the feasibility of using polymer for mobility control of surfactant-polymer (SP) and alkali-surfactant-polymer (ASP) in EOR process shown generally that it is better to use a high viscosity, small size slug in flooding a homogenous formation, while stratified reservoirs do better with the use a large diluted slug. It is found that the there exist an optimum slug size for a given amount of thickening chemical depending upon the oil viscosity and degree of permeability stratification.

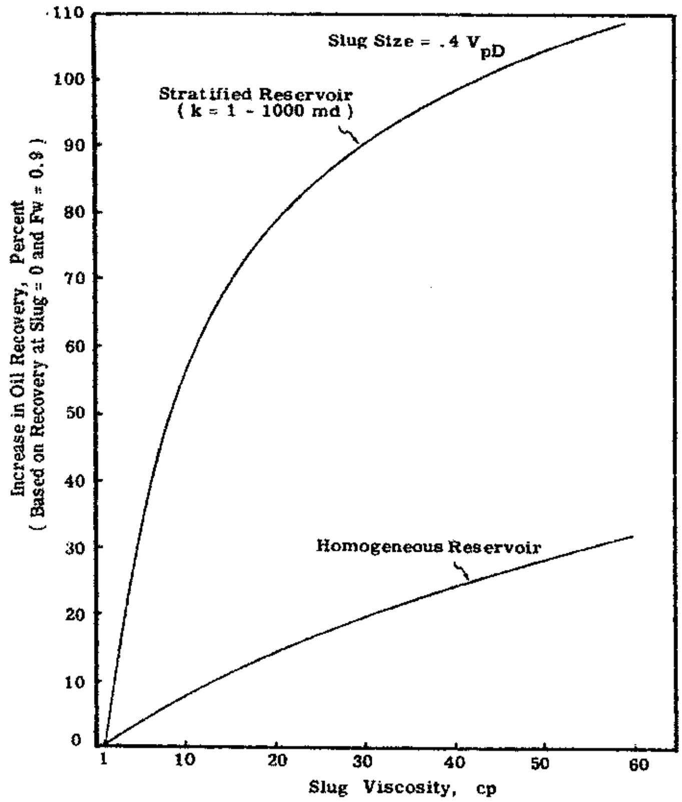


Figure 8: Oil Recovery Increment as a function of Slug viscosity (Wang & Caudle, 1970)

2.4.2 Temperature

(Nouri & Root, 1971) experimented data indicates that polymer solution viscosity and its shear dependence decrease with increasing sodium chloride concentration. The solution viscosity is increased as the molecular weight and polymer concentration increased. However when the affect of temperature tested, it indicates that, depending upon the nature of polymer, the degree of hydrolysis, concentration and its molecular weight, the theological behavior of each solution, due to the temperature rise, was found to be uniquely different from the others which led to the rejection of the previously reported concept (Mungan, Smith, & Thompson, 1966) that the decerease in the viscosity of the polymer solution is due only to the decrease in the viscosity of water as the temperature increased.

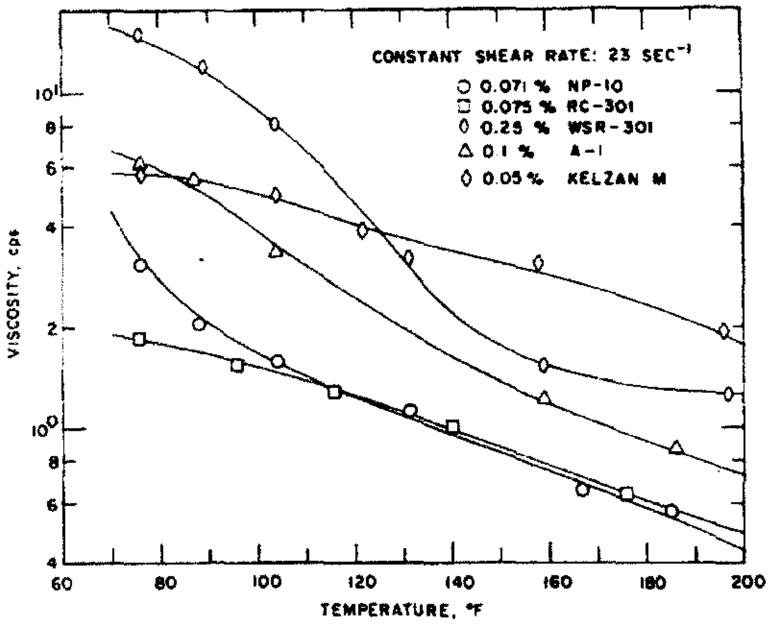


Figure 9: Effect of temperature on polymer solution viscosity (Nouri & Root, 1971)

2.4.3 Alkali and Surfactant

(Krumrine & Falcone, 1983) reported the viscosity performance of polymers can be improved by the presence of surfactants and alkalis especially for extremely unfavorable mobility ratios it is almost imperative that alkali and polymer be injected together in the same slug. The sodium silicates appear to protect the PAM polymers better in the presence of hardness than the other alkalis. Thus the recovery of crude oil should be increased both in rate an in total amount by injection of surfactant, polymer and alkali in a manner that mixes them to take advantage of demonstrated synergisms.

2.4.4 Salinity and Hardness

(Nasr-El-Din, Hawkins, & Green, 1991) also cover the review of affect of surfactant, alkali, sodium chloride and cation type on viscosity of ASP slug with consideration of the shear thinning region only. Adding a non-ionic species had an insignificant effect on the viscosity-shear rate relationship. However, adding an ionic species, (sodium chloride, calcium chloride, or an anionic surfactant) reduced the hydrodynamic size of the polymer molecule (physical change), changing the viscosity-shear rate relationship.

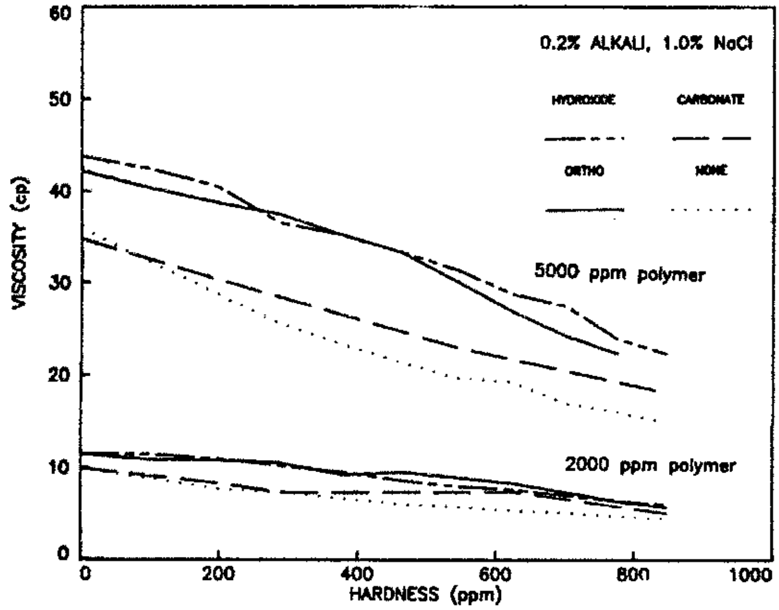


Figure 10(a): Polyacrylamide viscosity vs. hardness as affected by low alkali levels (Krumrine & Falcone, 1983)

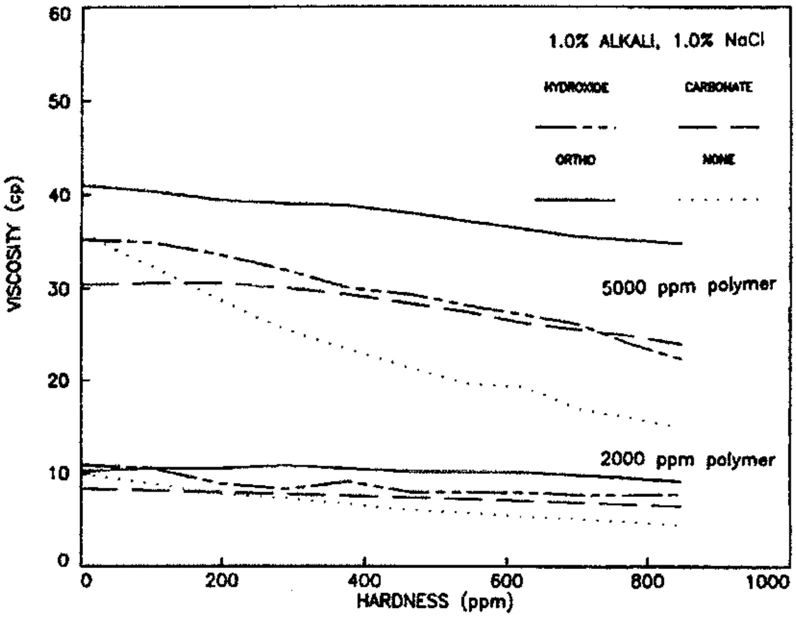


Figure 10(b): Polyacrylamide viscosity vs. hardness as affected by high alkali levels (Krumrine & Falcone, 1983)

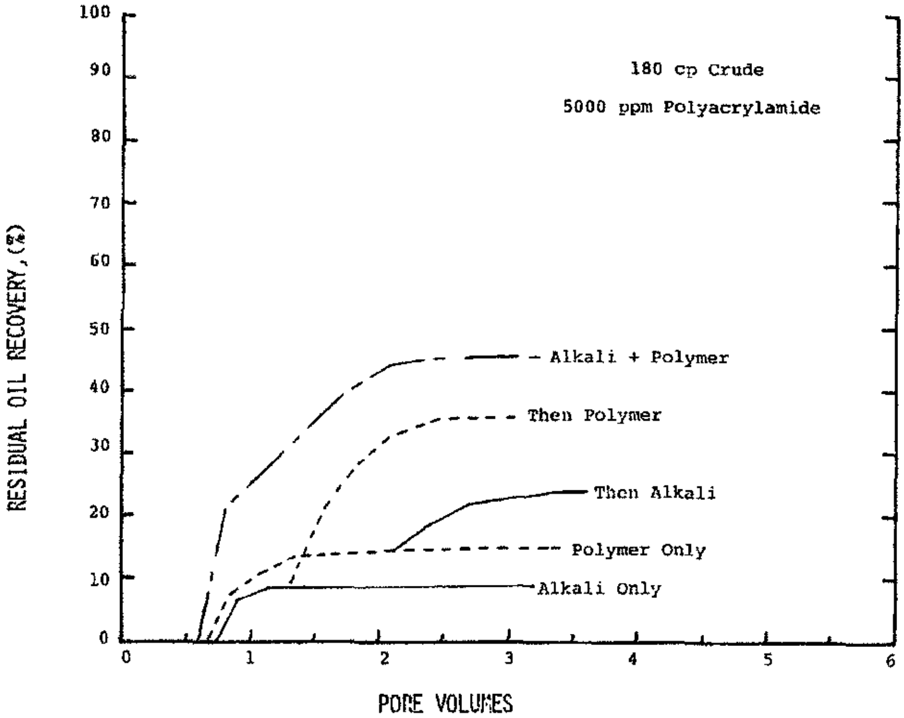


Figure 11: Comparison of polyacrylamide/orthosilicate recovery results for a highly viscous crude. (Krumrine & Falcone, 1983)

2.4.5 Surfactant

The addition of anionic surfactants at low concentrations slightly decreased alkali/polymer solutions viscosity. However, a significant viscosity enhancement for alkali/polymer solutions was observed at higher surfactant concentrations and over a narrow range of alkali concentrations (Nasr-El-Din, Hawkins, & Green, 1991). The surfactant-polymer incompatibility can lead to a phase separation of a surfactant and polymer even in the absence of oil. In the presence of oil, the formation of middle phase microemulsion is promoted by the presence of polymer in the aqueous phase. The surfactant-polymer incompatibility is explained in terms of excluded volume effects and the maximization of solvent for polymer molecules (Fayers, 1981, pp. 1-14).

2.4.6 Alkali

The effect of alkalis on the viscosity of polymer solutions was complex as they affected the polymer chain both physically (charge shielding) and chemically (hydrolysis). For alkali/polymer solutions, the viscosity was found to be a function of alkali type, concentration and time after initial mixing. The effect of these parameters on the viscosity of alkali/polymer solutions diminished by adding NaCI (Nasr-El-Din, Hawkins, & Green, 1991).

2.4.7 Polymer rheology

In another work, (Han, Wang, & Xu, 1995) investigated the viscoelastic behavior of HPAM solution in porous media and its effects on displacement efficiency. He presented a method to determine the values of first critical velocity (or critical viscoelastic velocity), Vce which the straining flow occurs and the second critical velocity (or critical transit velocity) Vcr which the rheological behaviour of HPAM solution transits from pseudoplastic to dilatants behaviour. The viscoelastic property of polymer play important role in improving oil displacement efficiency. Polymer flood displacement efficiency reaches it maximum when the viscoelastic property of polymer solution is brought into full play.

(Lee Kim et al. 2009) gave a correlation for viscosity considering shear thinning and shear thickening behavior and its dependence on temperature and polymer concentration and concluded that steady shear viscosity of polymer solution depends strongly not only on the shear rate but also on the variables such as polymer concentrations, salinity, hardness and temperature.

2.8 Factors for polymer retention in porous media

Polymer adsorption, mechanical entrapment and hydrodynamic retention are three main retention mechanisms of polymer retention through porous media.

Polymer adsorption

The interaction between the polymer molecules and solid surface causes polymer molecules to be bounded to the surface of the solid mainly by physical adsorption.

Basically the polymer sits on the surface of the rock, and the larger the surface area available the higher the levels of adsorption. Rocks with lower permeability have higher surface available in the porous media. Therefore the adsorption may be more in the rock with low permeability. In the rock with very low permeability, polymer may not be able to inter and adsorption will reduce. Adsorption cannot be avoided since it is between polymer rock surface and solvent. Therefore main work has been done on adsorption by many workers.

Mechanical entrapment

Retention by mechanical entrapment is occurs when larger polymer molecules trap in narrow flow channels (Willhite, 1977). Assuming porous media as a complex pore structure with large interconnected networks giving lots of possible routes which connects inlet and outlet of the core. As polymer solution passes through this complex connected network, molecules may go through any available routes and if the rout be narrow enough, polymer molecule will trap and block the rout. And probably cause more trapping at the upstream of blockage. As a consequence of this process, concentration of effluent will reach to input concentration after many pore volume of injection. And if the number of entrapment locations exceeds the critical number the core would block eventually.

Mechanical entrapment is a more likely mechanism for polymer retention for lower permeability cores where the pore sizes are small and chance of polymer molecules to be trapped is very high.

This has been studied by several workers. There are a very few workers studied retention in present of residual oil phase and most of the works has been done on water-wet cores.

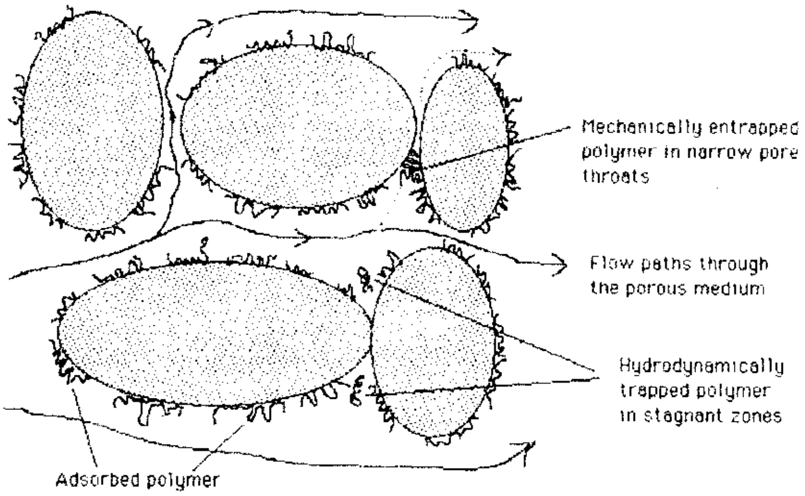


Figure 12: Schematic diagram of polymer retention mechanisms in porous media (after Sorbie, 1991)

Hydrodynamic retention

It has been observed that after reaching full concentration of input in effluent at constant rate, the total level of retention changed when fluid flow was adjusted to new value (Chauveteau, 1974). Although the mechanism of hydrodynamic retention is not firmly established, there is a good explanation for that. As illustrated in Figure 12, hydrodynamic drag force traps some of the polymer molecules temporarily in stagnant flow regions. In such region it may be possible to exceed the polymer stream concentration. When flow rate stops, these molecules may introduce into main stream channels and increase the concentration. When the flow starts again the effluent concentration shows a peak.

Porous media is a complex network of channels and pore sizes in microscopic scale. Therefore both molecular structure of polymer and pore structure play very important role in determining rheological behavior.

There are two observations for polymer behavior in porous media. Some workers (Chauveteau and Zaitan, 1981) found that polymer has lower apparent viscosity than bulk viscosity in low shear rate. The polymer concentrations were used by these workers was less than unity (Sorbie, 1991). Other workers (Cannella et al, 1988) which used polymer concentration more than one, have shown apparent viscosity more than bulk viscosity in low shear rate.

Since HPAM has flexible coil structure shows elastic behavior. Chauveteau described the flow of HPAM in geometries varying from the very simple pure shear, through to complex mixed flow in porous media. In pure shear flows, HPAM behavior is just a shear thinning. In porous media, high flow rate applies high shear force on polymer molecule and causes the shape of polymer molecule to deform. The molecule tends to elongate passing through pore throats and channels which increases molecular size and consequently apparent viscosity increases. When the polymer molecule has been fully stretched, the force maybe large enough to break the molecule chain causing mechanical degradation. The depredated polymer has lower viscosity due to smaller size comparing with original molecule and apparent viscosity decrease.

CHAPTER 3 METHODOLOGY

3.1 Description of Methodology

The experimental part of this work is to study the bulk rheology properties of HPAM by investigating several factors that affecting the viscosity of the polymer solution.

1) Several types of polymers (HPAM) were selected which consist of different molecular weight (MW) and degree of hydrolysis (DOH).

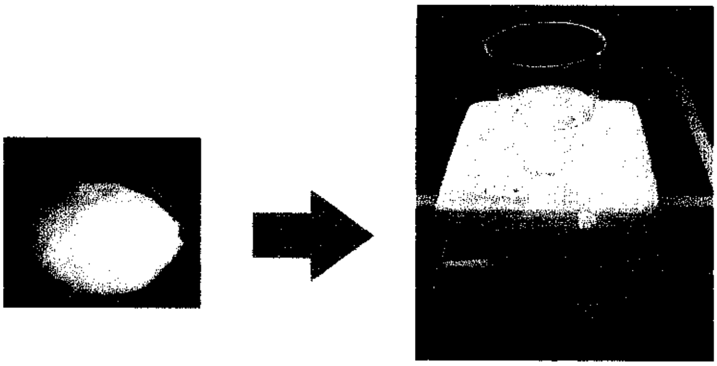


Figure 13: Polyacrylamide in solid and polymer solution.

2) 2 g of pure HPAM is accurately weighs and quantitatively transferred and diluted with distilled water in a 250 ml volumetric flask. The solution is being stirred for 30 hours to make sure all the polymer diluted into the solution and to ensure for complete hydration. This solution is then called stock solution.

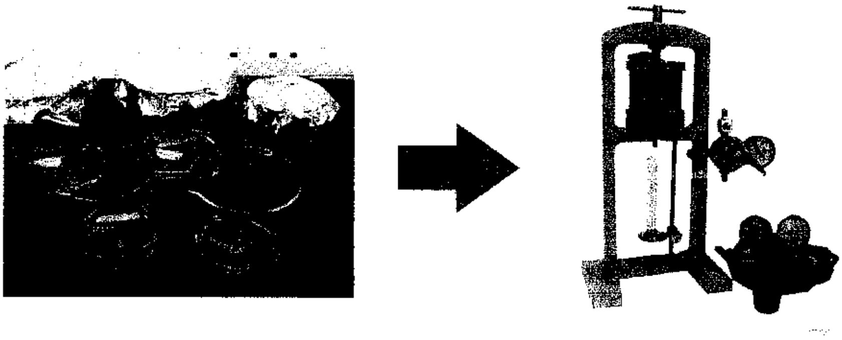


Figure 14: Polymer solution filtration process.

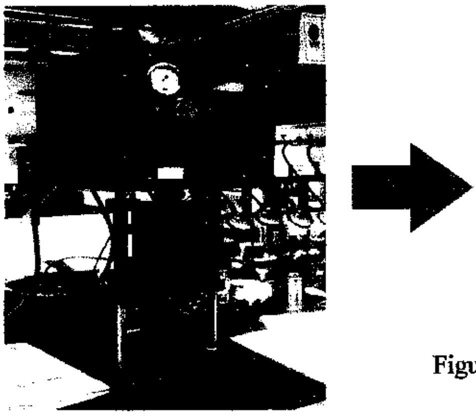
3) Each polymer solutions have been filtered using low filter press paper by applying with 20 psi across the filter. The time taken to flow for each 10 ml is recorded. Each time taken for first 10 ml until the last 10 ml must be equal. This is to ensure that the solution is homogenous.
4) Each polymer type has been diluted into five polymer concentrations which are 1000ppm, 2000ppm, 2500ppm, 3000ppm, and 4000ppm.
5) The calculation below shows on how to prepare 4000ppm stock solution of HPAM

$$Concentration = \frac{g\ solute}{g\ solution}$$

$$4000\ ppm = \frac{g\ HPAM}{0.25\ L}$$

$$g\ HPAM = 1\ g\ HPAM$$

6) Four dilutions solution has been prepared and named by A, B, C, D and E
7) The concentration of HPAM in every diluted solution will be calculated.
8) The bulk viscosities of these diluted solutions are measured as a function of the applied shear rate ranging from 1.0 s-1 up to 1000 s-1.
9) All bulk viscosities were measured using Offite Model 1100 HPHT Viscometer.
10) Measurements were conducted at various pressure and concentration.
11) B1 Bob type sample is selected for the test with amount fluid required of 42mL.
12) Polymer viscosities were measured both at increasing and decreasing shear rate.



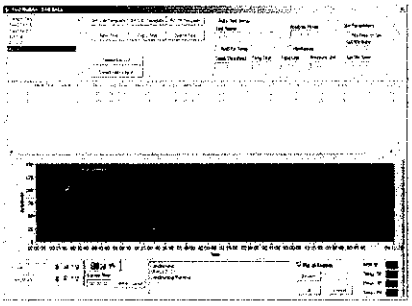


Figure 15: OFFITE 1100 HPHT Viscometer

13) Step 3 to 12 is repeated for the other 4 HPAM with different molecular weight and % of hydrolyzed.

14) Step 3 to 13 is repeated for 4wt % and 6 wt % of brine solution NaCl and hardness of 2 wt% of MgCl and 2 wt % of $CaCl_2$

15) All the data of viscosity versus shear rate has been analyzed and plotted by using OriginPro 8.5.1.

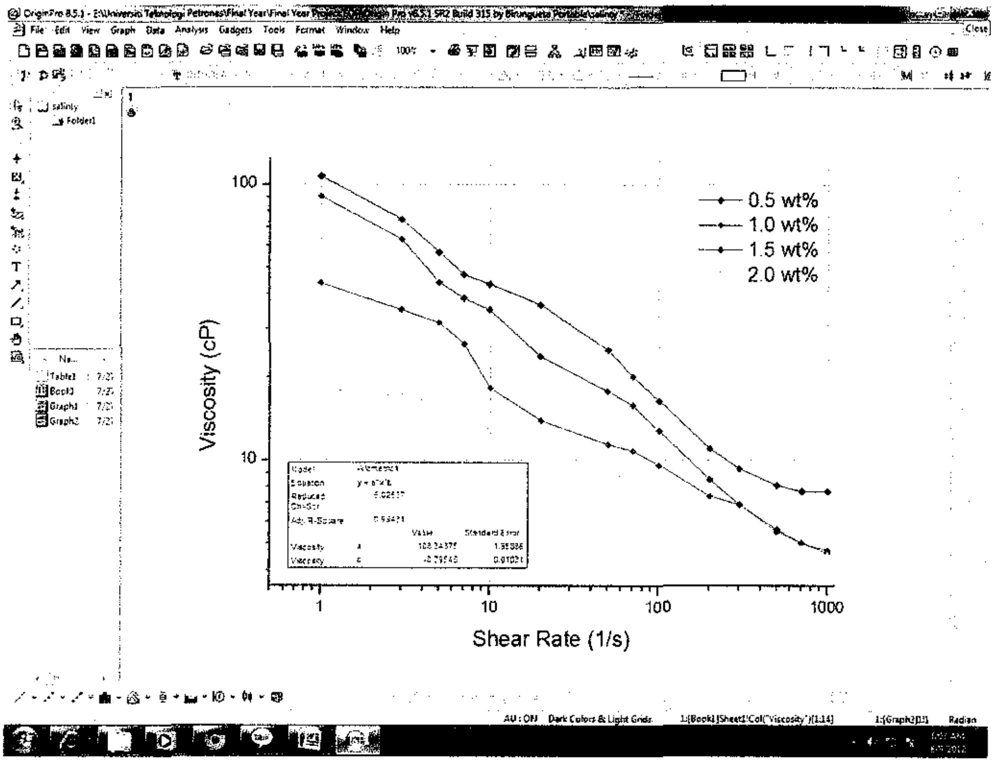


Figure 16: Analysis using OriginPro 8.5.1

16) As early reported research, unlike water the polymer solution should behave as one of the non-newtonion fluid which the fluid viscosity changed with the shear rate.

17) In these cases the data were fitted using power-law model. The apparent viscosity for a power-law fluid is $\eta(\gamma)$= $K\dot{\gamma}^{n-1}$ where K & n are the power law parameters. For a Newtonian fluid, n-1 and k is the fluid viscosity.

Polymer Type(SNF)	Molecular Weight , x 10^6 g/mol	Degree of hydrolysis, %	Salinity/ Pressure/ Temp.	Viscosity at Concentration (ppm)				
				1000	2000	2500	3000	4000
3630	**20**	**30**		Result as per graph plotted in result and discussion section.				
3430	**12**	**30**						
3330	**8**	**30**						
1630	**20**	**20**						

Figure 17: Table of viscosity test experiment in a wide range of parameters.

3.2 Gantt Charts of Research Activities

No.	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Project Work Continues	■	■	■	■	■	■	■	Mid-Semester Break								
2	Submission of Progress Report									●							
3	Project Work Continues									■	■	■	■	■			
4	Pre-EDX												●				
5	Submission of Draft Report													●			
6	Submission of Dissertation (soft bound)														●		
7	Submission of Technical Paper														●		
8	Oral Presentation															●	
9	Submission of Project Dissertation (Hard Bound)																●

Figure 18: Gantt Charts

3.3 Tool, Equipment and Material

- Offite 1100 Viscometer, Heater and Stirrer, Analytical Weight, Partially Hydrolyzed Polyacrylamide, Brine (Sodium Chloride).

CHAPTER 4 RESULT AND DISCUSSION

4.1 Analysis on the effect of different molecular weight (MW) and degree of hydrolysis (DOH) on viscosity of polymer solution

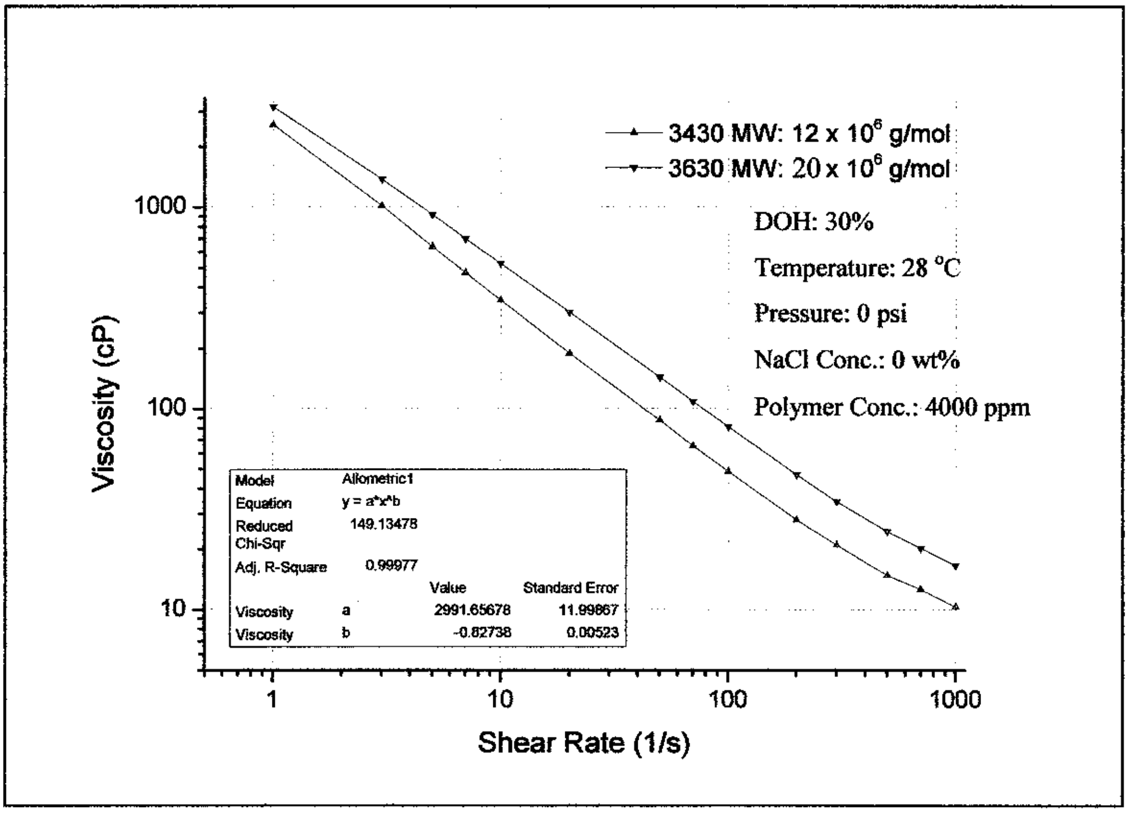
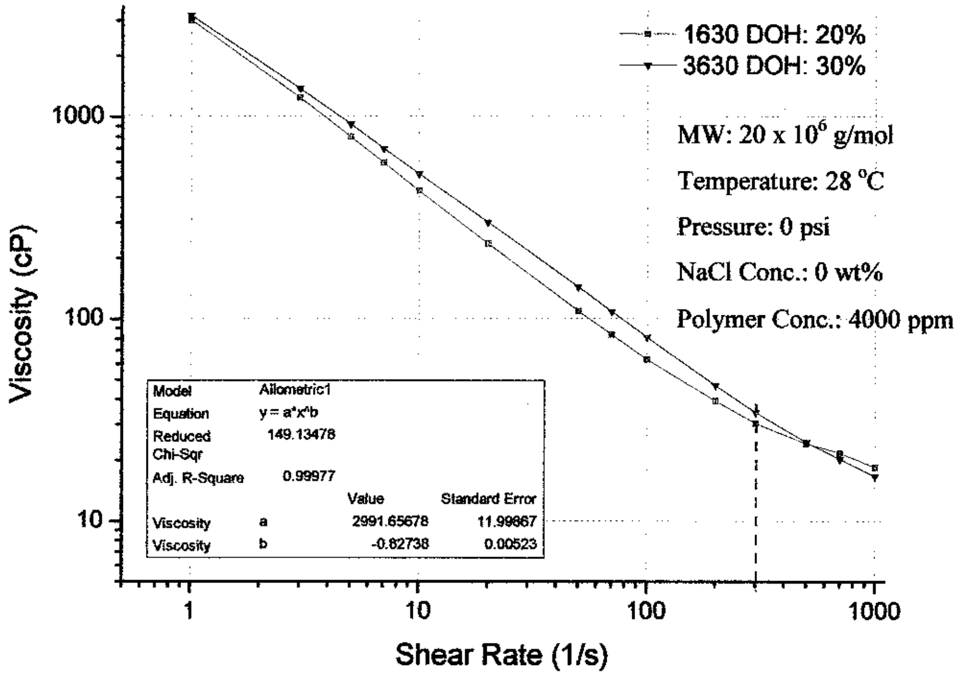


Figure 19: Effect of Molecular Weight on Polymer Solution Viscosity

The graph plotted was based on the values taken from the original raw data generated from Orcada (Offite 1100 Viscometer Software). Based on figure 19 and figure 20 it was found that both increasing in molecular weight and degree of hydrolysis will make the viscosity of the solution higher. However, the effect of increasing in molecular weight is more significant than the increasing in degree of hydrolysis. Thus, it is better to select the higher molecular weight polymer than higher degree of hydrolysis.

The other parameters such as degree of hydrolysis, temperature, pressure, salinity and polymer concentration are made constant during experiment of molecular weight effect on polymer solution.



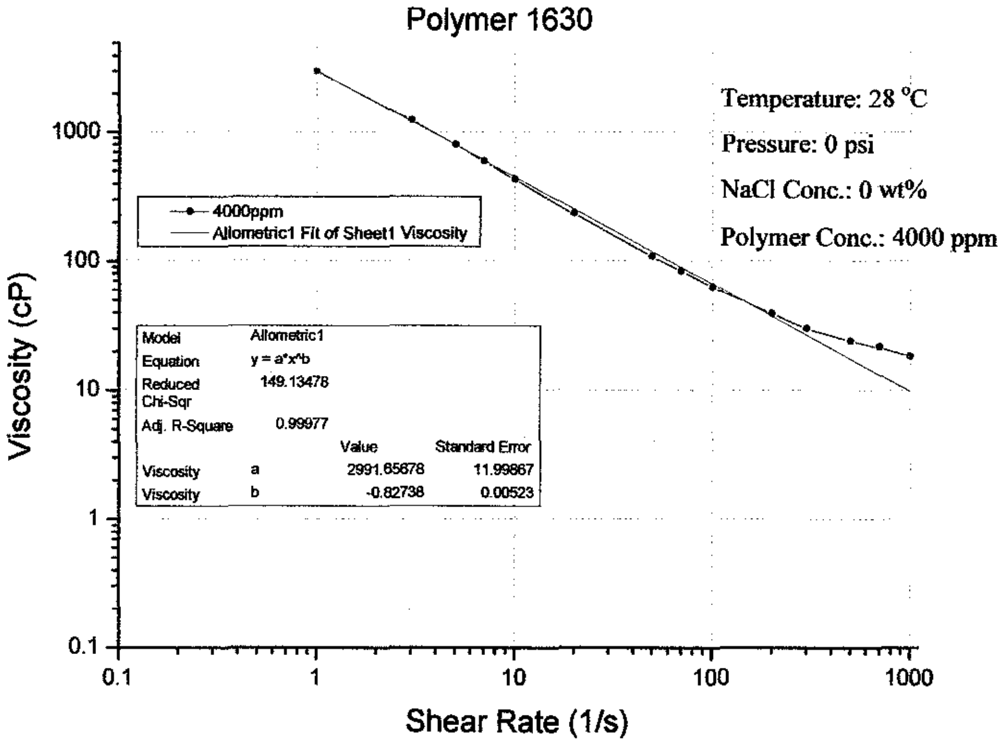
Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	149.13478		
Adj. R-Square	0.99977		
		Value	Standard Error
Viscosity	a	2991.65678	11.99667
Viscosity	b	-0.82738	0.00523

Figure 20: Effect of Degree of Hydrolysis on Polymer Solution Viscosity

Solution viscosity is increased as the molecular weight and polymer concentration increased. However at shear rate of $120s^{-1}$ rheological behaviour of HPAM solution shows that it transits from pseudoplastic to dilatants behaviour. The viscoelastic property of polymer play important role in improving oil displacement efficiency. Polymer flood displacement efficiency reaches it maximum when the viscoelastic property of polymer solution is brought into full play.

The viscosity-increasing feature is derived the repulsion between polymer molecules and between the segments of the same molecule. This repulsion causes the molecule to lengthen and snag on other molecule.

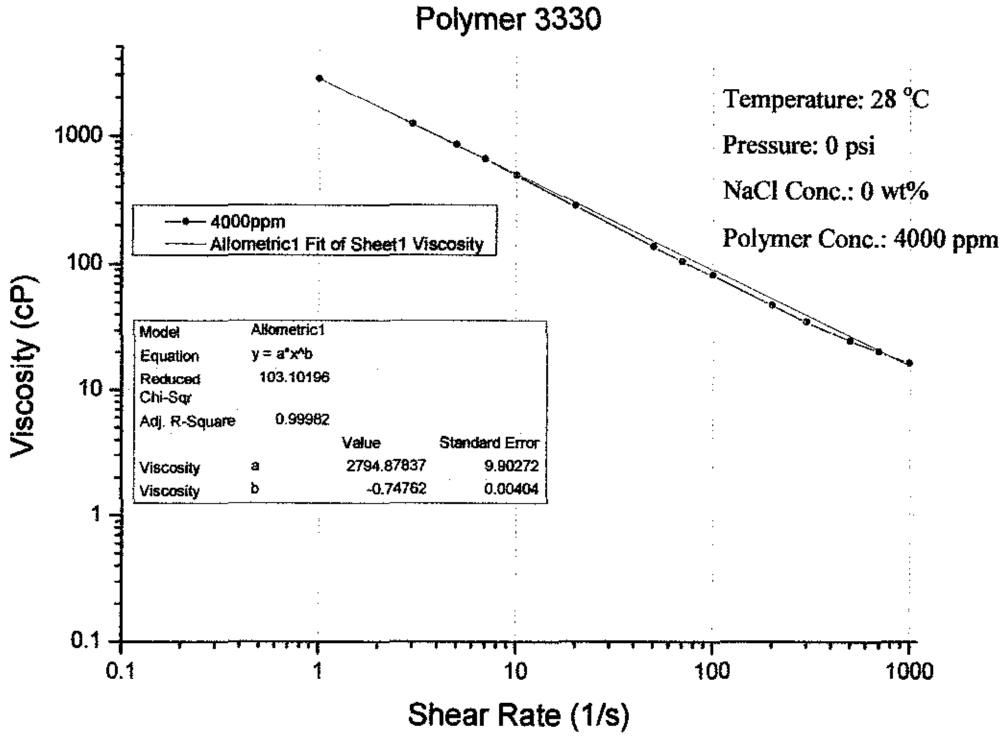
The following graph plotted in single log-log plot showed that the viscosity data distribution within the power law equation $\eta(\gamma)= K\dot{\gamma}^{n-1}$ where K is constant equal to (a) and n is constant equal to (b+1). The red line showed the power law equation fitting while the line with dotted showed the experimental data. It is found that all polymer solution viscosity obey the power law with the power indices from 0.2 to 0.6. The value of adjusted R^2 which near to 99% to proved it obey the power law.



Temperature: 28 °C
Pressure: 0 psi
NaCl Conc.: 0 wt%
Polymer Conc.: 4000 ppm

Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	149.13478		
Adj. R-Square	0.99977		
		Value	Standard Error
Viscosity	a	2991.65678	11.99867
Viscosity	b	-0.82738	0.00523

Figure 21: Expected Power Law Regression line for Polymer 1630.



Temperature: 28 °C
Pressure: 0 psi
NaCl Conc.: 0 wt%
Polymer Conc.: 4000 ppm

Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	103.10196		
Adj. R-Square	0.99982		
		Value	Standard Error
Viscosity	a	2794.87837	9.90272
Viscosity	b	-0.74762	0.00404

Figure 22: Expected Power Law Regression line for Polymer 3330.

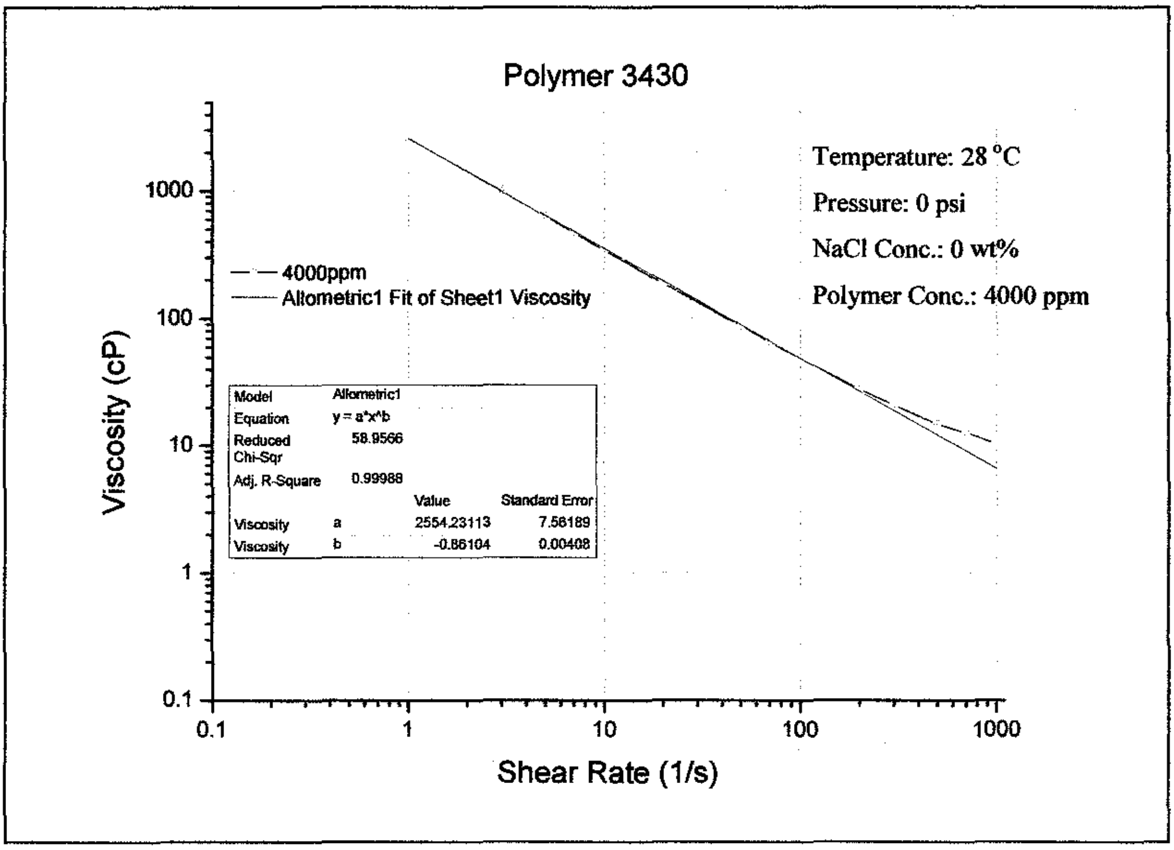


Figure 23: Expected Power Law Regression line for Polymer 3430.

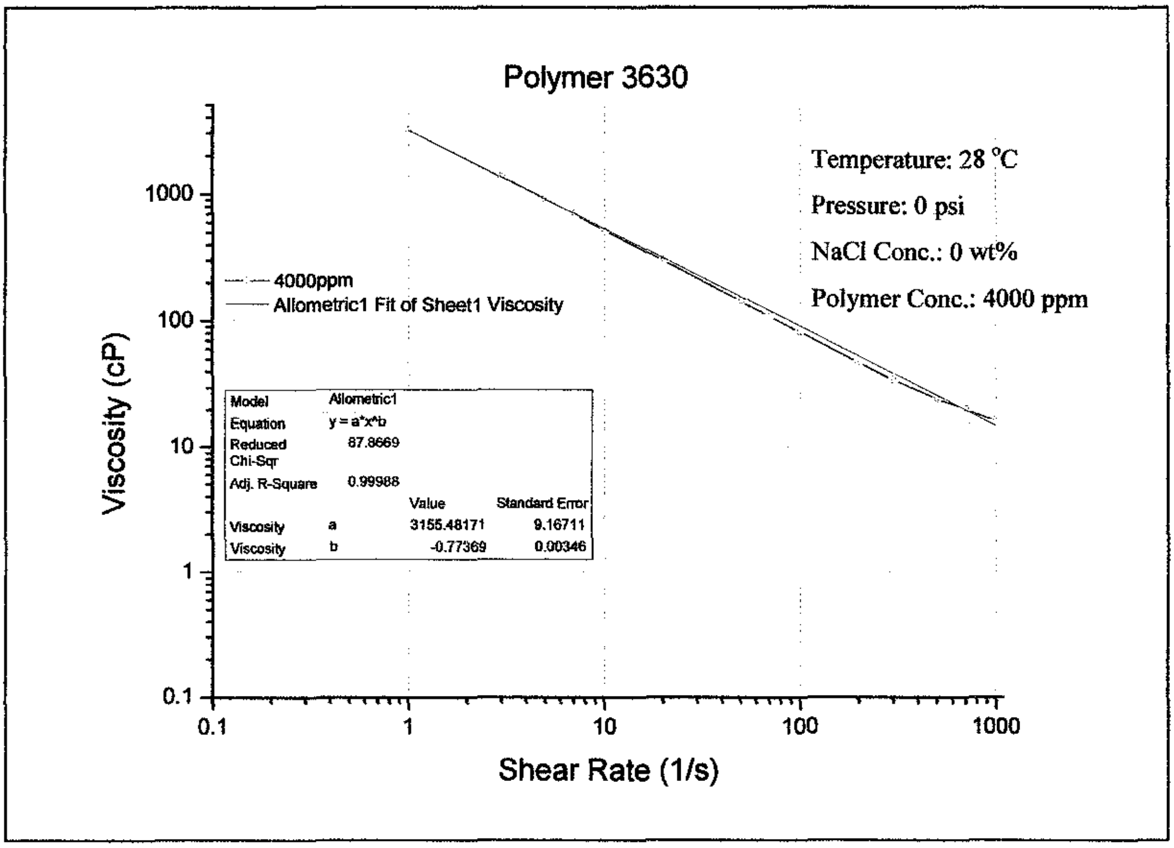
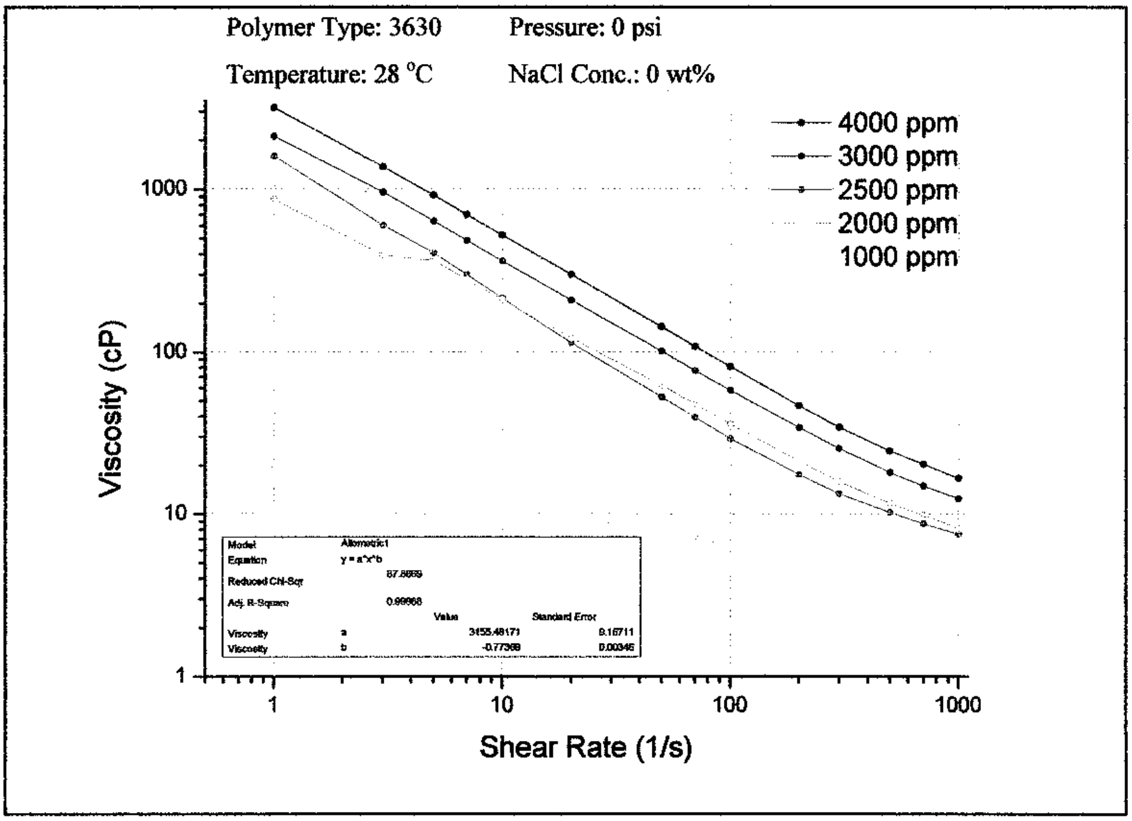


Figure 24: Expected Power Law Regression line for Polymer 3630.

4.2 Analysis on the effect of different Polymer Concentration on the viscosity of polymer solution

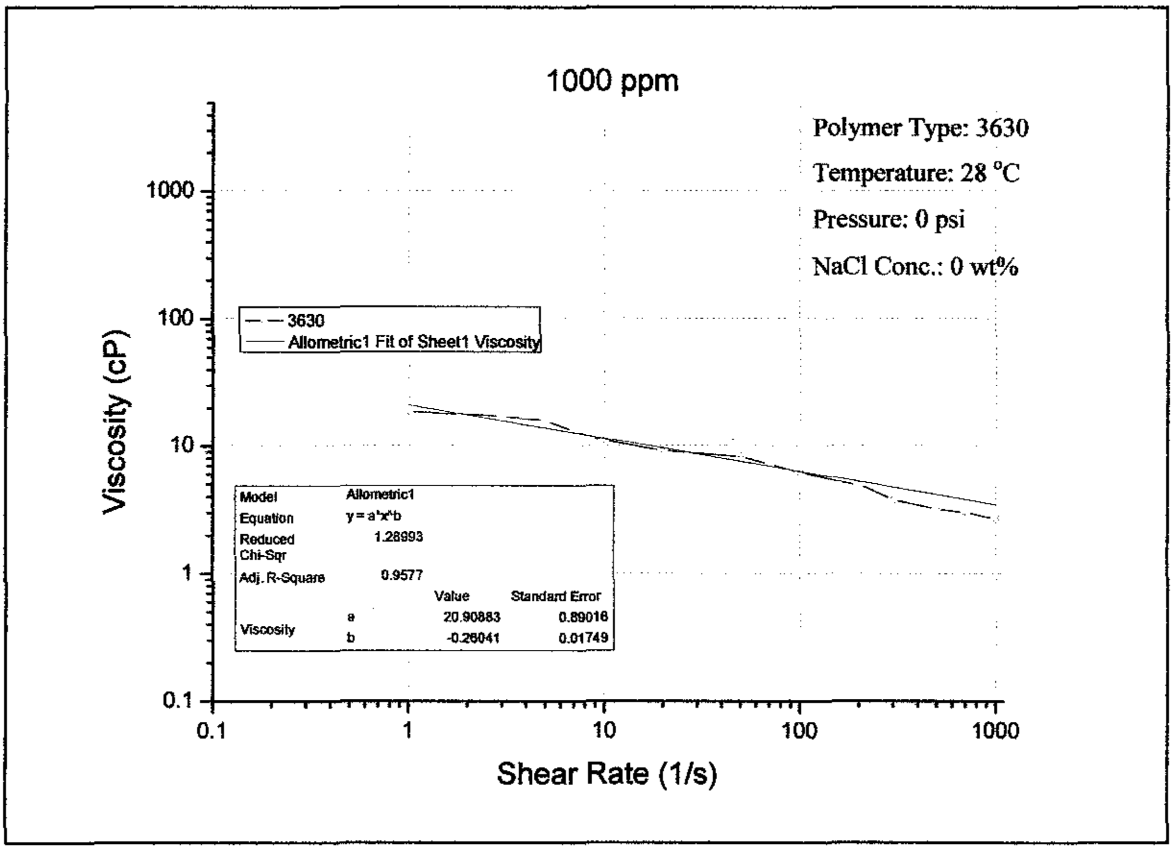


Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	87.8869		
Adj. R-Square	0.99968		
		Value	Standard Error
Viscosity	a	3155.48171	9.16711
Viscosity	b	-0.77368	0.00346

Figure 25: Effect of Polymer Concentration on Polymer Solution Viscosity

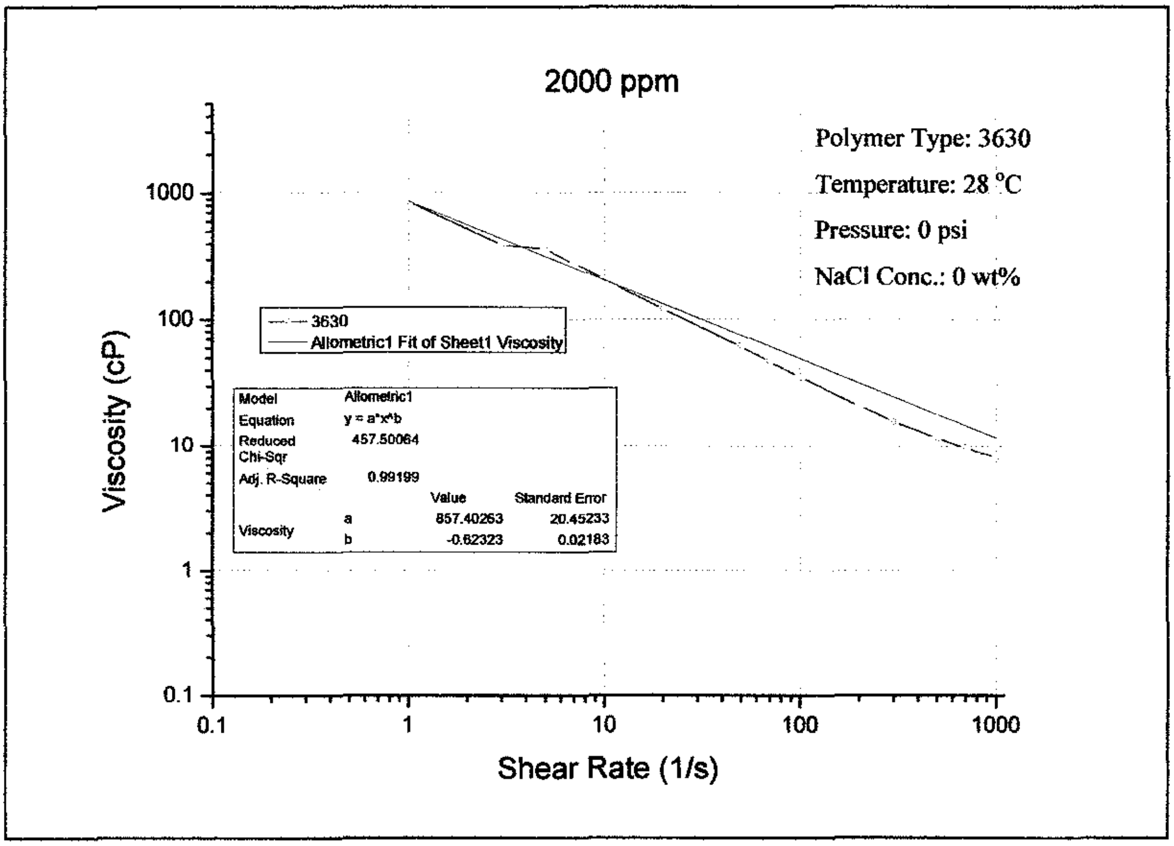
Based on the graph plotted above it was found that the increasing polymer concentration will make the viscosity of the solution higher in both type of polymer. It is obvious that below the concentration of 2000 ppm, a large amount of viscosity is dropped. Thus depend on the need, it is recommended to have the minimum concentration use within the range of 2000 ppm to 2500 ppm.

Sometime, in order to reduce the polymer cost in EOR application, lower concentration is used, but this will effect on the effectiveness of the polymer flooding itself. Thus it is better to select the optimum concentration for polymer solution considering the minimum required polymer viscosity in the polymer flooding application.



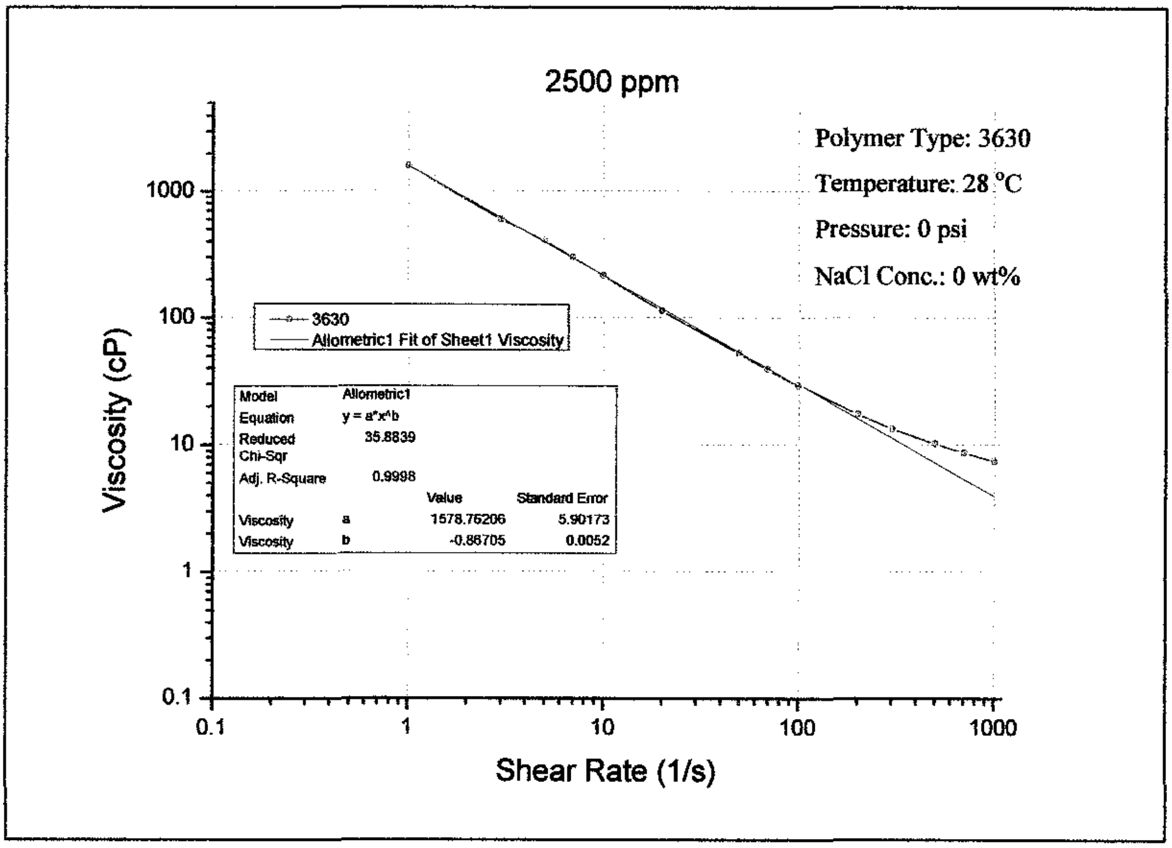
Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	1.28993		
Adj. R-Square	0.9577		
		Value	Standard Error
Viscosity	a	20.90883	0.89016
	b	-0.26041	0.01749

Figure 26: Expected Power Law Regression line for 1000 ppm.



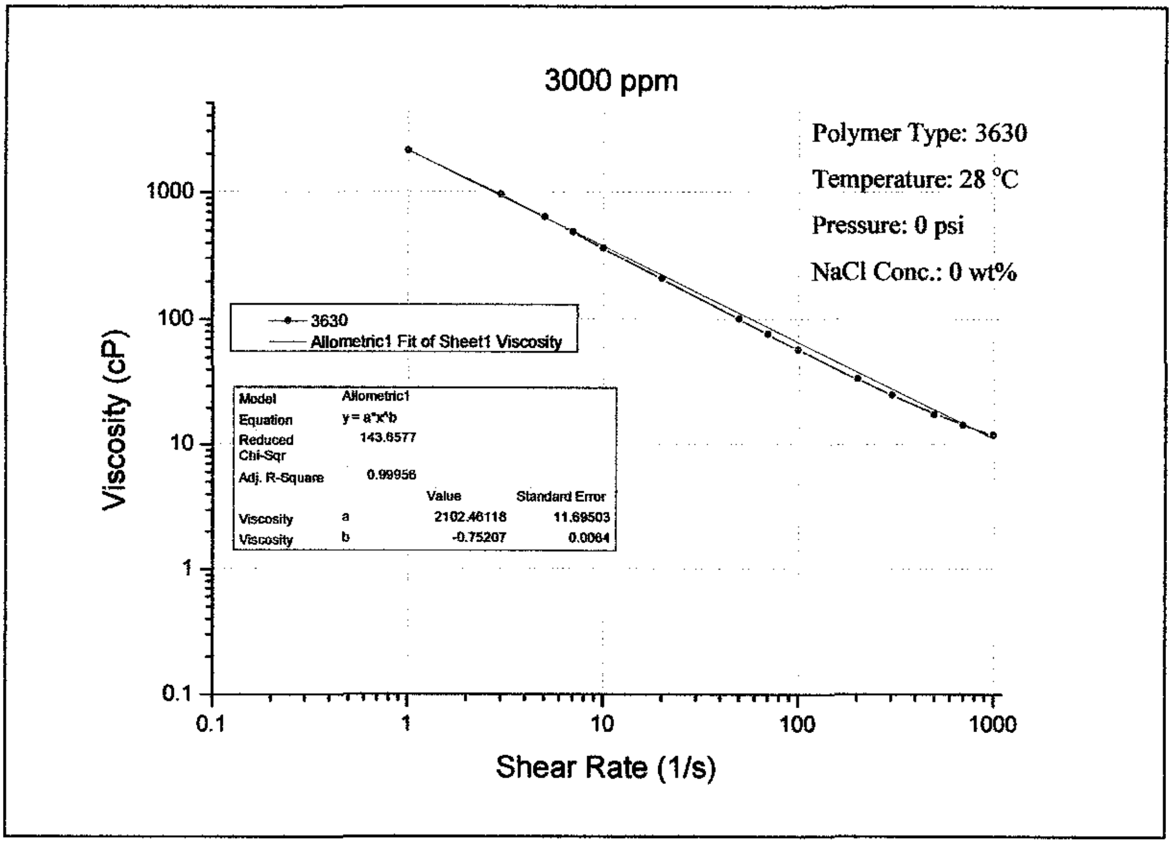
Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	457.50064		
Adj. R-Square	0.99199		
		Value	Standard Error
Viscosity	a	857.40263	20.45233
	b	-0.62323	0.02183

Figure 27: Expected Power Law Regression line 2000 ppm.



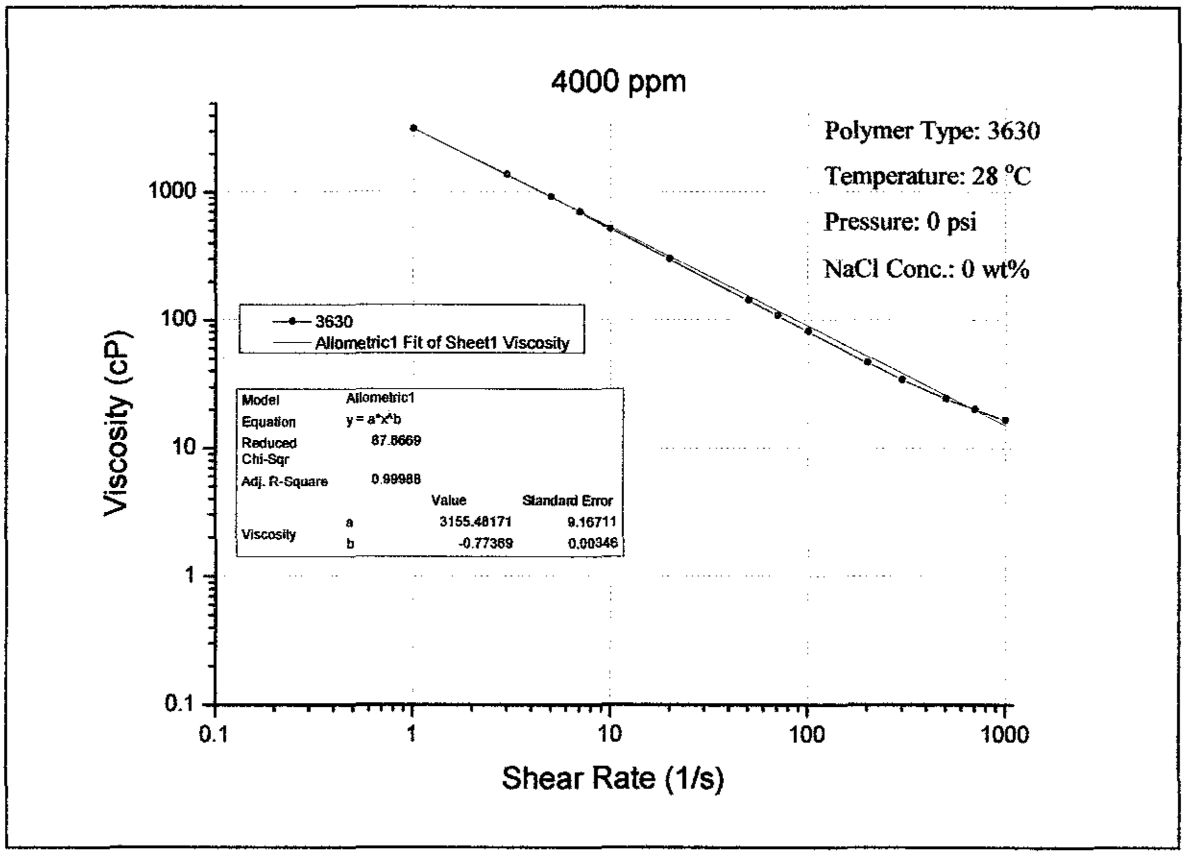
Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	35.8839		
Adj. R-Square	0.9998		
		Value	Standard Error
Viscosity	a	1578.76206	5.90173
Viscosity	b	-0.86705	0.0052

Figure 28: Expected Power Law Regression line for 2500 ppm.



Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	143.6577		
Adj. R-Square	0.99956		
		Value	Standard Error
Viscosity	a	2102.46118	11.69503
Viscosity	b	-0.75207	0.0064

Figure 29: Expected Power Law Regression line 3000 ppm.



Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	87.8669		
Adj. R-Square	0.99988		
		Value	Standard Error
Viscosity	a	3155.48171	9.16711
	b	-0.77369	0.00346

Figure 30: Expected Power Law Regression line for 4000 ppm

4.3 Analysis on the effect of different Salinity concentration on the viscosity of polymer solution

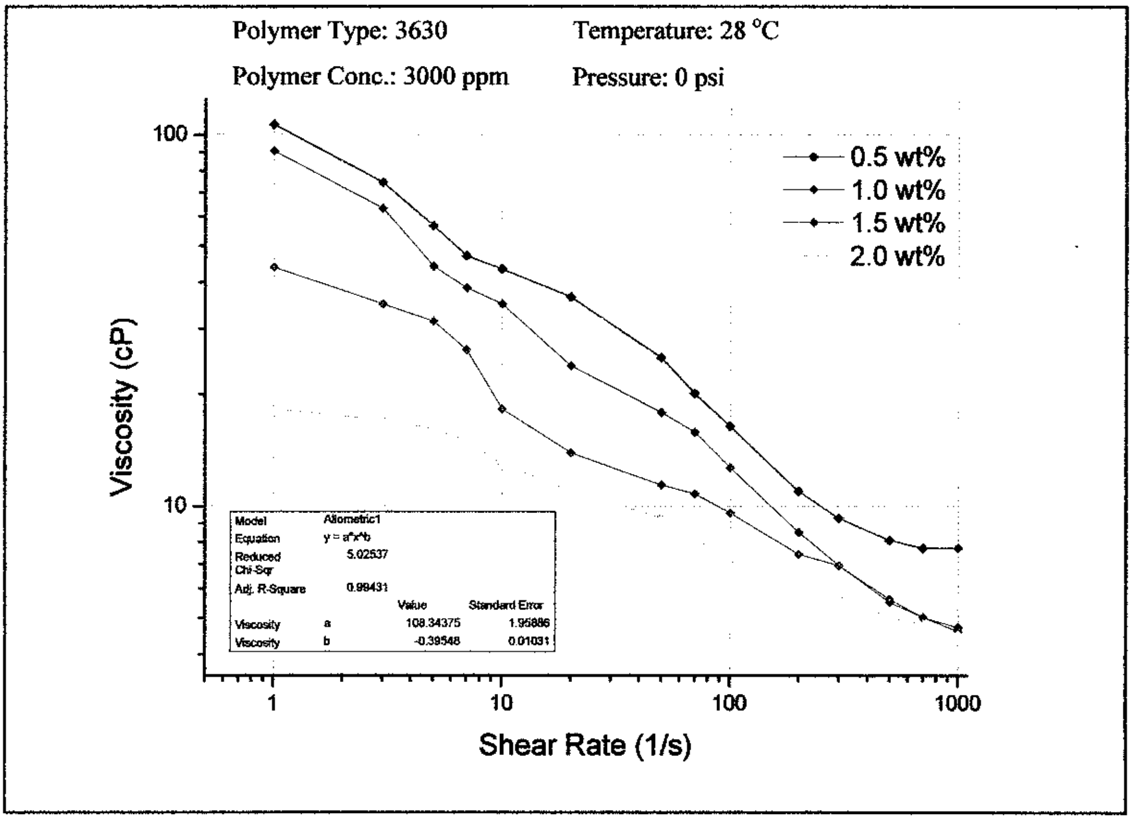


Figure 31: Effect of Salinity (NaCl) Concentration on Polymer Solution Viscosity

Based on the graph plotted above it was found that the increasing of salinity (NaCl) concentration will make the viscosity of the solution decrease. It is obvious that above the concentration of 1.5 wt %, the viscosity is dropped. Thus the polymer solution viscosity is only good when the solution is below 2 wt%.

The effect of NaCI on the flow curves of polymer solutions can be explained as follows: the partially hydrolyzed polyacrylamide chain is stretched in water because of the repulsive forces between the negative charges (carboxylate groups) on the chain. This means that the hydraulic radius of the polymer chain is large in the water and consequently polymer solution viscosity is high.

As the concentration of the sodium ions in solution is increased, the repulsive forces within the polymer chain decrease, due to charge screening effects, and the chain coils up. This change in the polymer conformation causes the hydraulic radius of the chain to decrease and the degree of polymer chain entanglement to diminish. Both factors cause the polymer solution viscosity to decrease.

Also, the reduction in the polymer chain size, due to the charge shielding, would increase the critical shear rate. Hence the Newtonian behavior can be seen over a wider range of shear rates as the salt concentration is increased.

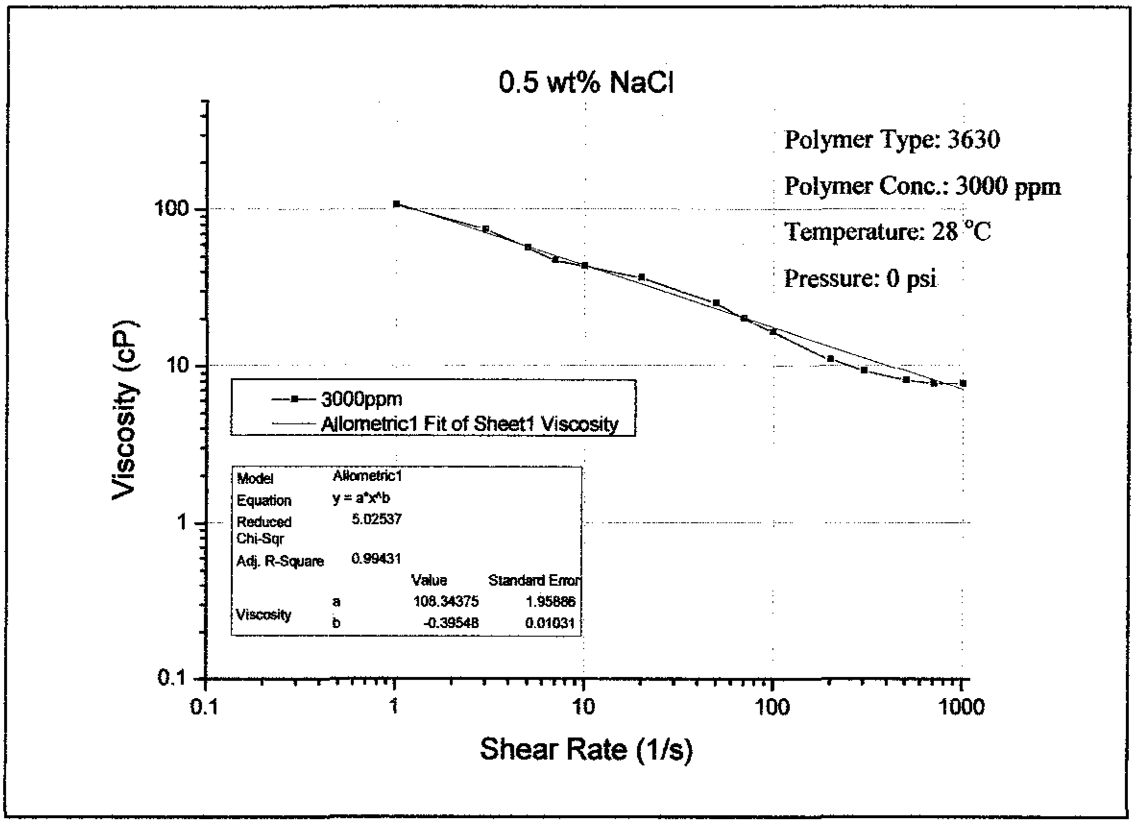


Figure 32: Expected Power Law Regression line for 0.5 wt% NaCl.

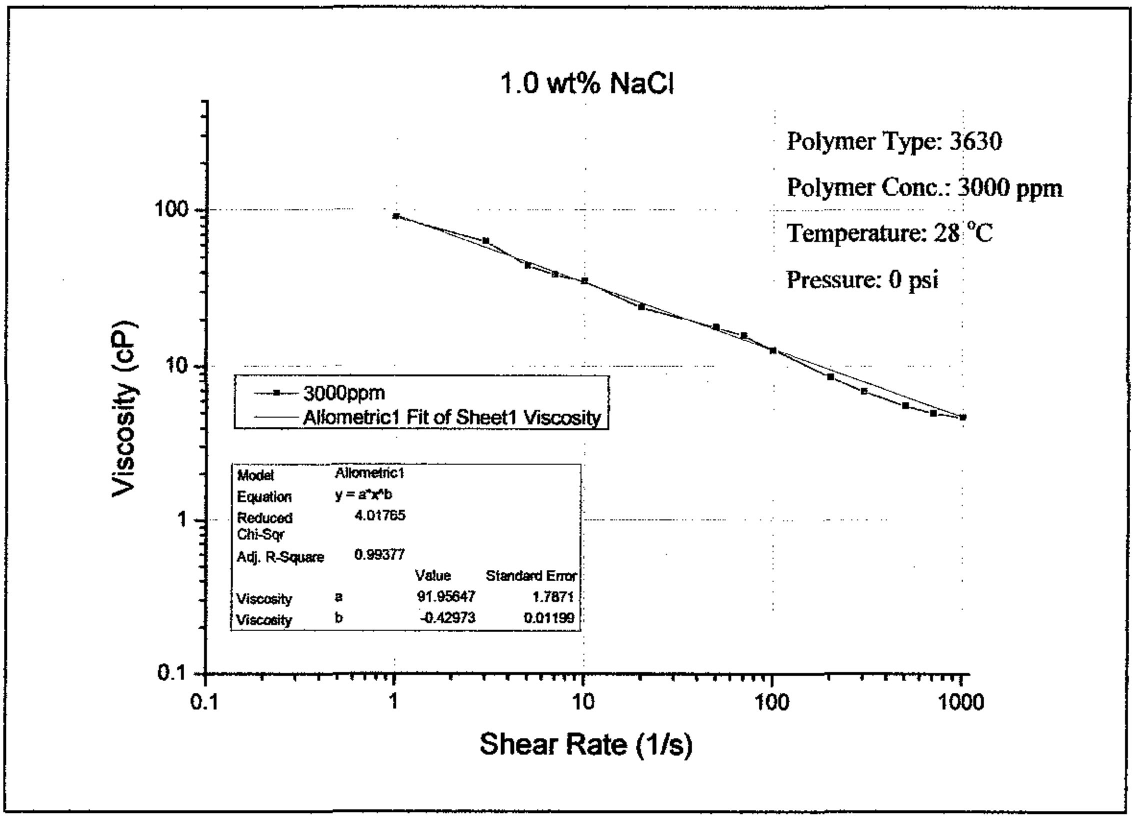


Figure 33: Expected Power Law Regression line for 1.0 wt% NaCl.

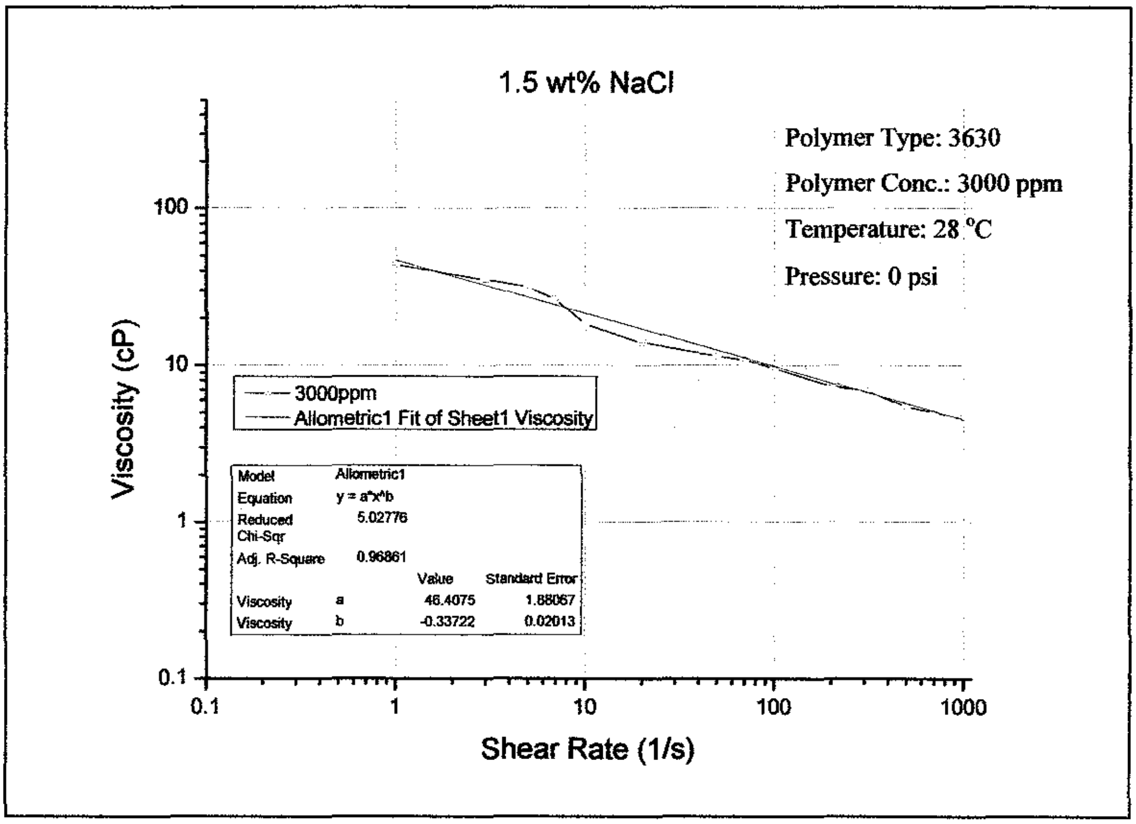


Figure 34: Expected Power Law Regression line for 1.5 wt% NaCl.

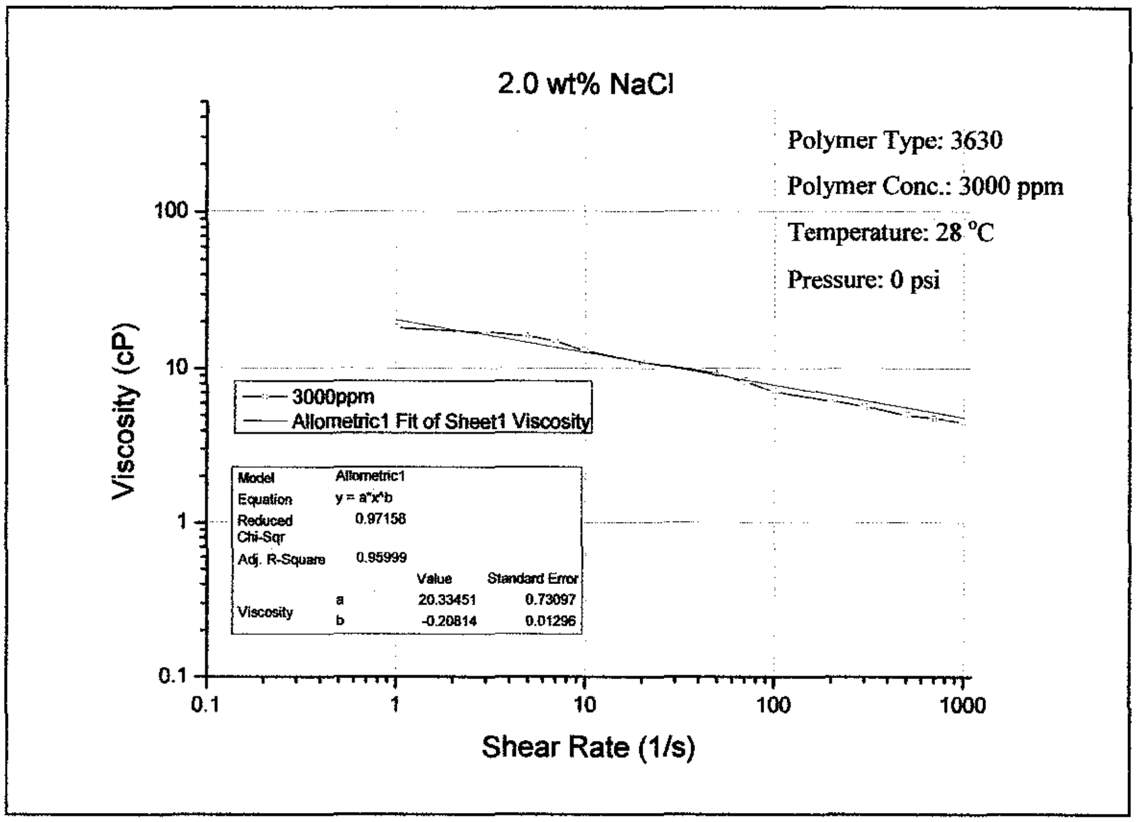
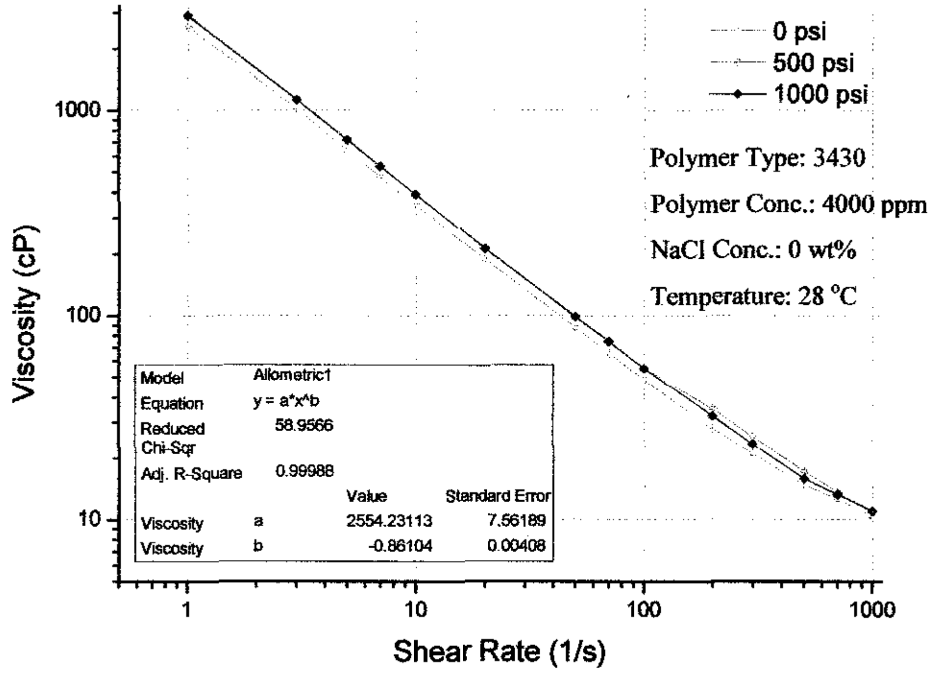


Figure 35: Expected Power Law Regression line for 2.0 wt% NaCl.

4.4 Analysis on the effect of different Pressure on the viscosity of polymer solution



Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	58.9566		
Adj. R-Square	0.99988		
		Value	Standard Error
Viscosity	a	2554.23113	7.56189
Viscosity	b	-0.86104	0.00408

Figure 36: Effect of Pressure on Polymer Solution Viscosity

Based on the graph plotted above it was found that the increasing pressure applied will make the viscosity of the solution increase. The effect of the pressure was not much within 0 to 500 psi and almost same after the pressure applied above 500 psi. Thus, pressure is not a big concern compared to other parameter such as salinity, molecular weight, degree of hydrolysis and polymer concentration.

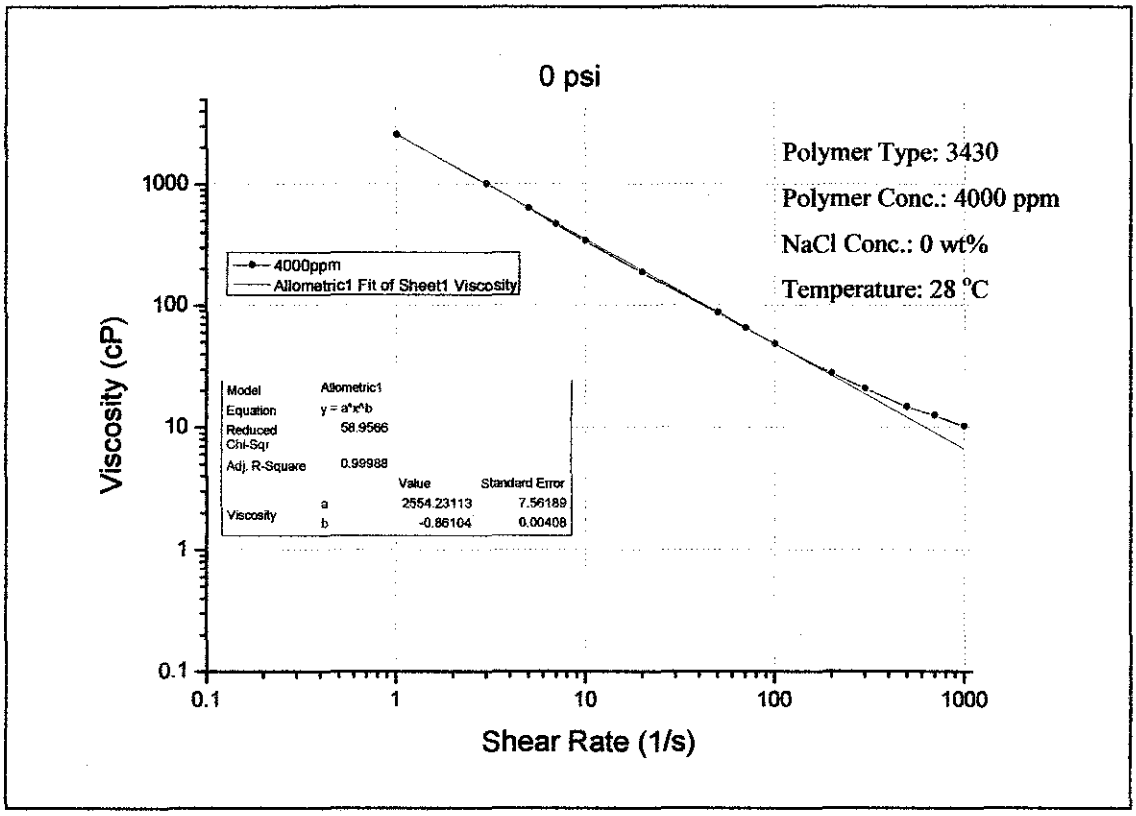


Figure 37: Expected Power Law Regression line for 0 psi.

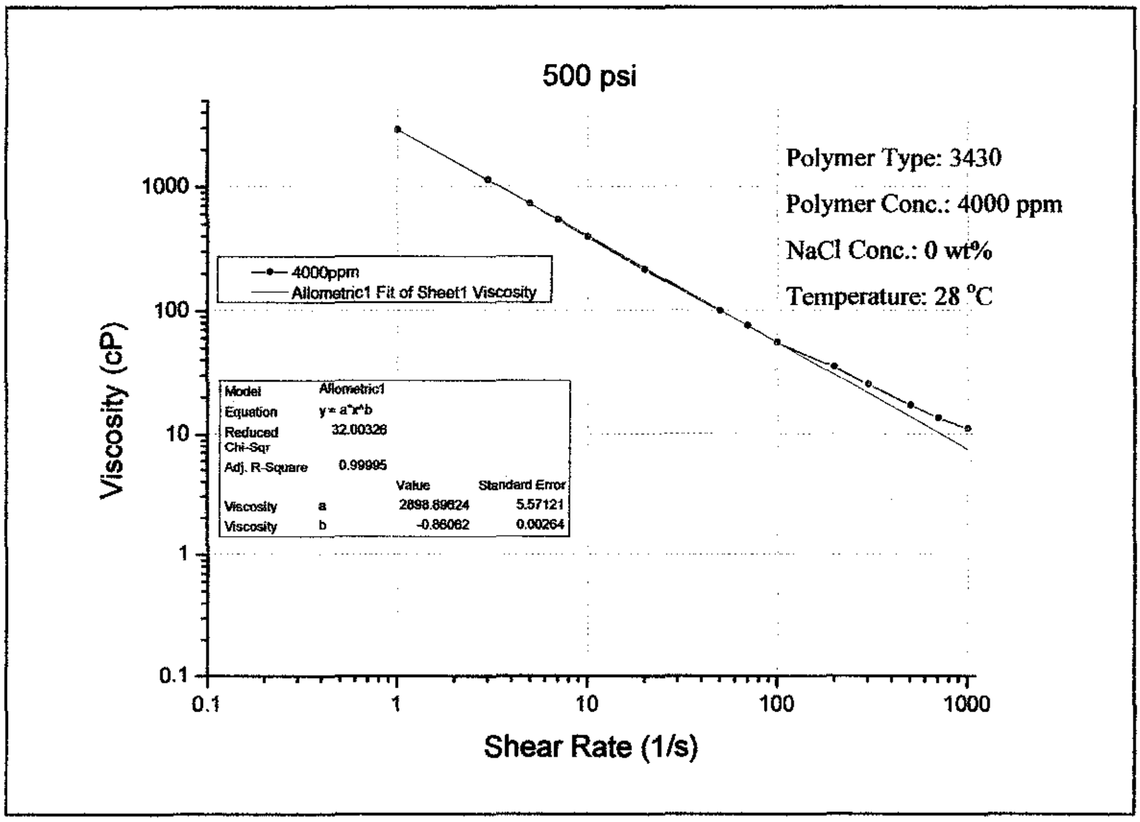


Figure 38: Expected Power Law Regression line for 500 psi.

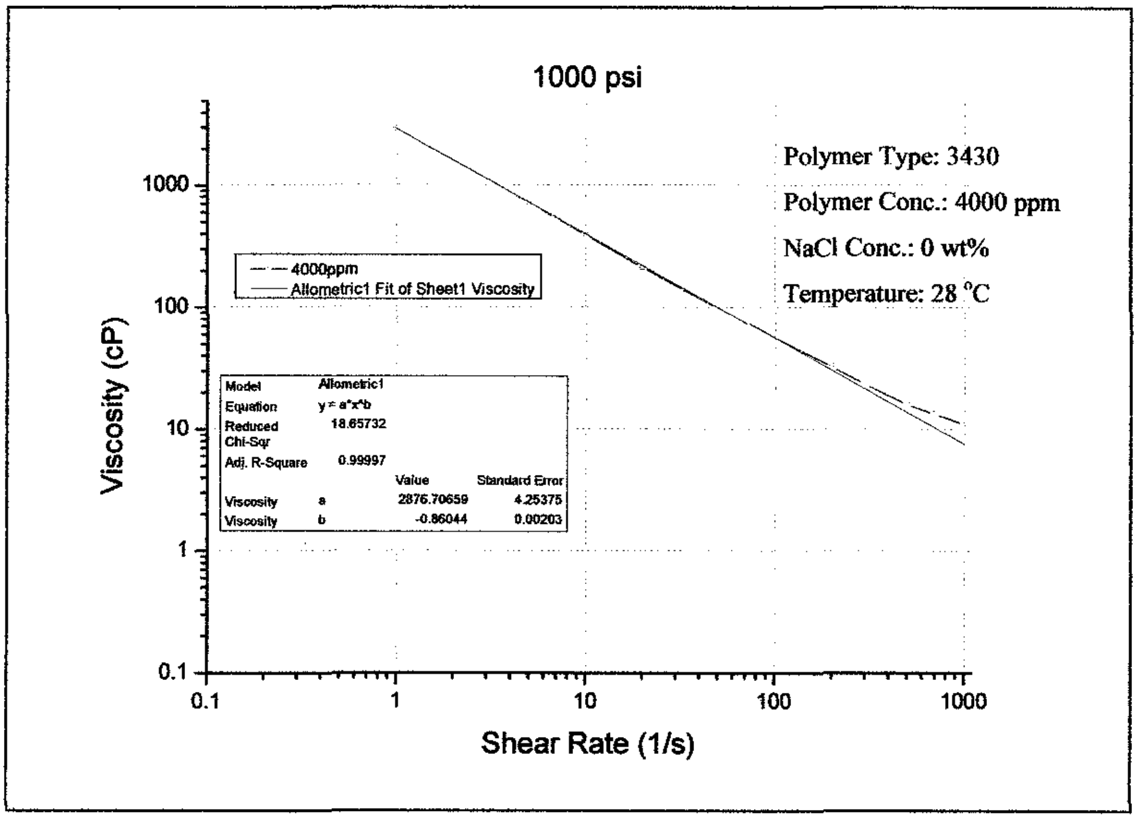


Figure 39: Expected Power Law Regression line for 1000 psi.

CHAPTER 5 CONCLUSION AND RECOMENDATION

In general, the viscosity of polymer solution decreased with increasing shear rate, showing shear thinning behavior and obeying the power-law with the power indices from 0.2 to 0.6. The viscosity values showed that polymer solutions are more affected by the different molecular weight of polymer than the degree of hydrolysis used. The higher concentration of polymer will make the polymer solution viscosity increasing. The different pressure applied on the polymer solution will effect on the viscosity at the certain range. The higher concentration of salinity will make the polymer solution viscosity decreasing.

RECOMMENDATIONS AND FUTURE WORKS

1. To get an accurate result of viscosity, it is recommended to prepare all solution at the same time, so the other factor or time effect on polymer solution could be made constant.

2. The viscosity experiment could be tested with other different parameters such as temperature, monovalent cations, and divalent cations to give a wide data to support the viscosity study. These parameters have their significant effect on the viscosity of polymer solution especially temperature of polymer solution.

3. Besides kinematic viscosity test, a real field application test should be conducted using core flooding test. The core flooding test will provide the data on the polymer retention time from breakthrough time with pore volume of sandstone.

4. A joint venture should be done between Petronas Carigali Sdn. Bhd. (PCSB) and UTP EOR Research Centre for future research work in providing laboratory data to field application of polymer flooding to meet the current requirement of the Malaysia oil field.

CHAPTER 6 BIBLIOGRAPHY

Ali, S. M., & Thomas, S. (2001, February). Miscellar Flooding and ASP-Chemical Methods for Enhanced Oil Recovery. *JCPT, Volume 40, No. 2, University of Albera* .

Ali, S. M., Thomas, S., Scoular, J. R., & Verkoczy. (2001, March). Chemical Methods for Heavy Oil Recovery. *JCPT, Volume 40, No.3, Pear Canada Limited, Saskatchewan Research Council* .

Fayers, F. J. (1981). Enhanced Oil Recovery. AMSTERDAM - OXFORD - NEW YORK: Elsevier Scientific Publishing Company.

Hamdan, Dorman, M., Husain, N., & Ibrahim, D. a. (2005; 5-7 April). Enhanced oil recovery in Malaysia: making it a reality. *presented at Asia Pacific oil and gas conference and exhibition*, (p. Paper SPE 93329). Jakarta.

Han, X.-Q., Wang, W.-Y., & Xu, Y. (1995, November 14-17). The Viscoelastic Behaviour of HPAM Solutions in Porous Media and It's Effects on Displacement Efficiency. *Society of Petroleum Engineers* , p. 30013.

Krumrine, P. H., & Falcone, J. S. (1983). Surfactant, Polymer, and Alkali Interactions in Chemical Flooding Processes. *Society of Petroleum Engineers* , 11778.

Lake, L. (1989). Enhanced Oil Recovery. Prentice Hall, NJ.

Lindley, J. (2001). *Chemical flooding (polymer)*. Retrieved from http://www.netl.doe.gov

Littman, J. (1988). Polymer Flooding: Developments in Petroleum Science. *Elsevier Amsterdam* , p. vol 24.

Mungan, N., Smith, F. W., & Thompson, J. L. (1966). Some Aspects of Polymer Floods. *Society of Petroleum Engineers* , 1143-1150.

Nasr-El-Din, H. A., Hawkins, B. F., & Green, K. A. (1991). Viscosity Behaviour of Alkaline, Surfactant, Polyacrylamide Solution Used for Enhanced Oil Recovery. *Society of Petroleum Engineers* , 21028.

Nouri, H. H., & Root, P. J. (1971). A Study of Polymer Solution Rheology, Flow Behaviour, and Oil Displacement Processes. *Society of Petroleum Engineers* , SPE 3523.

Samsudin, Dorman, Y., Husain, N., & Hamdan, M. K. (2005). Enhanced oil recovery in Malaysia: making it a reality (Part II). *Paper SPE* (p. 95931). Kuala Lumpur: presented at international improved oil recovery conference in Asia Pacific.

Sorbie, K. (1991). Polymer Improved Oil Recovery. Blackie, Glasgow - London.

Torsæter, P. O. (2009). Heavy Oil Production methods. *lecture notes on unconventional reservoirs* . Norwegian University of Science and Technology.

Wang, G. C., & Caudle, B. H. (1970). Effects of Polymer Concentrations, Slug Size and Permeability Stratification in Viscous Waterfloods. *Society of Petroleum Engineers* , SPE 2927.