

CERTIFICATION OF APPROVAL

**To Determine the Efficiency of Wormlike Micelle as Drag Reducing Agent (DRA)
for Flow Assurance**

by

Suria Melanie Binti Mohammad

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Approved by,

(Mr Iskandar Dzulkarnain)

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Abstract

In the oil and gas industry, drag reducing agent (DRA) is a necessity for reducing the frictional drag in oil pipeline conduits, oil well operations, and water flooding. DRAs are normally high molecular weight polymers with Polyacrylamide (PAM) as the typical DRA.

However, PAM is permanently mechanically degraded and this could reduce the drag reducing efficiency, giving technical problems to the pipeline and its operation. This paper discusses on the capability of wormlike micelle (WLM) to overcome the mechanical degradation by PAM. Unlike polymeric system, WLMs break and reform when subjected to turbulent flow.

The WLM system is a product of 3-(N,N-Dimethyloctadecylammonia) (TDPS), sodium dodecyl sulphate (SDS), and brine water (0.5M NaCl). The efficiency of WLM as a drag reducing agent (DRA) is done by comparing its performance with PAM. DRA were added to water flowing vertically and horizontally – whereby the pressure drop and flow rate play an important role to quantitatively evaluate their efficiency. The rheological behaviour of DRA, both as a function of viscosity and shear rate, was determined using a viscometer subjected to different surfactant ratios [$R=SDS/TDPS$], and polymer concentration. The shear thinning phenomenon was also studied.

As a result, WLM gives a higher drag reducing efficiency compared to PAM by 32.80%. This places a significant contribution to the oil distribution through pipelines as it reduces the frictional drag between the fluid and the pipe hence increase the pumpability if liquid. Hence, liquid throughput volume or flow rate is increased as less pressure is needed to push the oil in the pipeline. Pressure drop can be reduced, leading to lower operating expenditure, optimized oil distribution, and longer pipe life.

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Nomenclatures and Abbreviations

DRA	Drag reducing agent
PAM	Polyacrylamide
Re	Reynolds number
MDF	Mechanical degradation of flow
MAOP	Maximum allowable operating pressure
CAPEX	Capital expenditure
ppm	Parts per million
IUPAC	International Union of Pure and Applied Chemistry
p	Packing parameter
A	Surface area
<i>l</i>	Length
v	Volume
Cryo-TEM	Cryogenic Transmission Electron Microscopy
DR	Drag reduction
EOR	Enhanced Oil Recovery
RPM	Rotations per minute
TDPS	N-tetradecyl-N,N-dimethyl-3-ammonio-1-propanesulfonate
SDS	Sodium dodecyl sulphate
CaCl ₂	Calcium Chloride
ρ	Density
V	Velocity
D	Length
μ	Viscosity

CHAPTER 1

INTRODUCTION

1.1 Background of Study

DRAs are typically high molecular mass polymers, and this article would discuss on the mechanism on how wormlike micelle (WLM) can be used as such agents. There are experimental studies conducted so as to investigate and support the theory behind the drag reduction capability between WLM and PAM. In industrial applications, PAM which is commonly used as DRA will undergo thermal, chemical, and mechanical degradation.

Chemical degradation of PAM occurs when there is a change in the PAM property due to a chemical reaction with the PAM's surroundings i.e. oxidation process which tends to break the PAM molecule's double bonds. For thermal degradation, it is when the component of long chain backbone PAM begins to separate (molecular scission) due to temperature rise, hence changing the properties of PAM. Mechanical degradation is the extreme stretching and elongation of PAM molecules due to high shear stresses. This project focuses on the mechanism of mechanical degradation. Experimental methods of determination of DRA efficiency are outlined in this article whereby finally a connection between flow rate and drag reduction efficiency will be discussed.

In spite of many different positive applications, drag reduction provided by PAM has its disadvantage – mechanical degradation in flow takes place. Flow turbulence causes the polymeric chain providing drag reduction to undergo scission. It was reported that one successful application of drag reduction polymer was that in the Trans-Alaska Pipeline, where the target discharge of one million barrels per day was obtained without having to construct additional pumping stations (B.K. Berge, O. Solsvik,1996).

The performance of DRAs in water and/or hydrocarbon fluids depends on many parameters such as fluid viscosity, liquid and gas velocities, composition of the oil, pipe roughness, water cut, pipeline inclination, DRA concentration, type of DRA, shear degradation of DRA, and temperature, and even pH for aqueous DRAs. However for the purpose of this project, the author places a focus on certain variables in order to vary the flow type in the system and to find the optimum criteria for an efficient drag reduction system using WLM and PAM. The identified learning parameters are concentration, shear thinning, flow rate, throughput increase, and percentage of drag reducing efficiency.

1.2 Problem Statement

Mechanical degradation is a severe issue for PAM as once the molecules are degraded, PAM could not perform effectively to reduce the frictional fluidic drag in the pipeline. Hence, the liquid will experience difficulty to flow because of the drag present between liquid and pipewall. This will force the operators to increase the pump pressure located at the booster pump stations every few kilometers so that the liquid could flow better. These problems would cause a disadvantage to the power saving field as well as early pipe problems since as time goes by, the pipewall gets thinner due to corrosion. Hence by increasing the pump pressure, it would lead to pipe burst.

Due to this limitation of PAM, this project intends to do a research and study on alternative DRA – WLM, which has the potential to regain back its original molecular structure even after subjected to a high shear rate normally located at booster pumps. This means that the molecules does not break easily, hence it could still maintain its structure and drag reducing property. This break-and-reform behavior is typical of WLM as it is viscoelastic and hence is capable of becoming a better DRA.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The objectives of this present research are to:

- To experimentally study the drag reduction ability of WLM as a DRA.
- To measure the effectiveness of a WLM as compared to PAM.
- To investigate the most suitable procedures and systems in the formation of a WLM.
- To perform experimental study on the effects of DRA concentration on drag reduction efficiency.

1.3.2 Scope of Study

Basically, this study narrows down to the knowledge on rheology, which is the study of deformation of fluids, and fluid mechanics. The study of potentials of a WLM as DRA requires an experimental set up which could compare its drag reduction capabilities with PAM. There are manipulated and constant variables to be set up such as the following:

- WLM formation by surfactant system namely Sodium dodecyl sulphate (SDS), and N-tetradecyl-N,N-dimethyl-3-ammonio-1-propanesulfonate (TDPS).
- PAM is used because it is a typical DRA.
- Important parameters to be investigated for this experiment are concentration, shear thinning, flow rate, throughput increase, and drag reducing efficiency percentage.
- Water is used as the solvent.

There are also some boundaries for these studies due to equipment and human limitations such as:

- Conducting experiments in ambient temperature, 25 degrees Celsius.
- Limited to two types of surfactant system which is anionic and zwitterionic. Other systems are non-ionic and cationic.
- Equipment to study the growth of WLM with increasing concentration is not available or is insufficient i.e. Cryo-TEM.

1.4 Relevancy and Significance of Project

DRA's can reduce the frictional drag existing between pipe wall and fluid, hence help to reduce the pump energy consumption as well as increasing the flow capacity in transporting the liquids from one point to another. WLM have the tendency to maintain the throughput volume of the flowing fluid and also, one of its best properties is that it does not degrade as easily as PAM because of its "break-and-reform" property. Without a proper DRA, it would bring bad implication to the pipeline development such as reduced pipe life times and pipe failures. Having a good DRA that does not degrade easily can help to save energy by reducing circulation effect (eddy currents) that exists in turbulent flow. Therefore, operating cost can be saved by injecting WLM in pipeline system.

1.5 Feasibility of Project

To determine whether this project is feasible within the time frame, the author has applied the 5M's which is commonly being applied in any operating organizations. The 5M's are; materials, method, machine, money, and manpower. First of all, the materials are easy to obtain as they are either already available in the EOR lab or can be procured from the external suppliers. For method, there are a lot of journals and articles available by SPE or Science Direct. The methodology of this project's experiments is being made by referring to the previous studies done on PAM and WLM.

However certain modifications need to be done in accordance to the equipment limitations. For machine, most of the needed apparatus can be used at any time, depending on its availability. Viscometer for example, can be found in the Petroleum and Geoscience and Chemical block, while the turbulent pipe flow at Block I. In terms of money, every FYP students are funded by the University. For manpower, the author needs to manage some time between lab works, further research, as well as meetings with lecturers, and Msc students. In short, this project is feasible within the time frame because all the 5M's criteria can be met - with the proper time management.

CHAPTER 2

LITERATURE REVIEW

2.1 Fluid flow

In the fluid dynamics concept, there are three types of flow regime – laminar, transitional, and turbulent flow. However for the purpose for this project, attention is being focused on the laminar and turbulent flow. There are certain criteria which would characterise these two flow regimes which are explained throughout this paper.

2.1.1 Laminar flow

Laminar flows have uniform velocity that is $\partial V / \partial t = 0$. Laminar flow is a stable, smooth parallel flows which do not encounter disruption between flow layer, as shown in Figure 1. The resistance to flow will be independent of the pipe wall roughness. The Reynolds Number of laminar flow is below than 2100 (Holman, J.P., 2002) which can be calculated by the following formula:

$$\text{Re} = \frac{\rho V D}{\mu}$$

whereby; ρ = density
 V = velocity
 D = length
 μ = viscosity

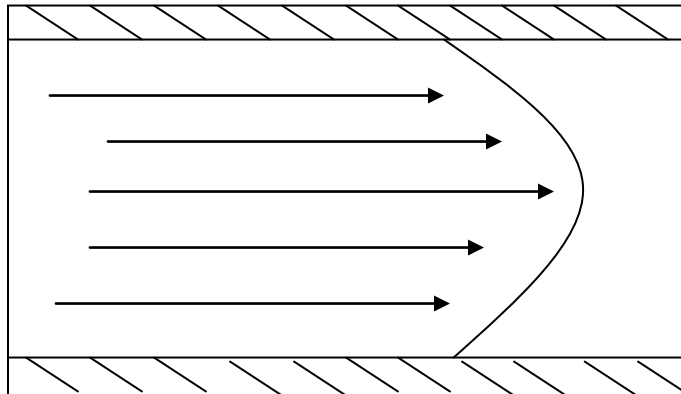


Figure 1 Laminar Flow Mechanism

2.1.2. Turbulent flow

The problems start to occur when flows momentum convert their energy in time of period from high momentum diffusion and low momentum convection to low momentum diffusion and high momentum convection. This phenomenon is called turbulent. Turbulence occurs when the Reynolds number is greater than 4000 with eddy currents present causing an unstable, chaotic flow (Holman, J.P., 2002). The flow is not streamlined – there are a lot of swirling eddies in the fluid as shown in Figure 2 below.

When fluids motion increases due to momentum convection (which is responsible for transporting energy and molecules trough pipes), it causes in an increase various velocity of fluid motion. In addition, there are also molecules that tend to become stagnant at their origin place which is influenced by inertia. Inertia is the resistance of molecules has to a change in its state of motion. Therefore, the static molecules will forms boundary layers between pipe wall and the molecules of solvents.

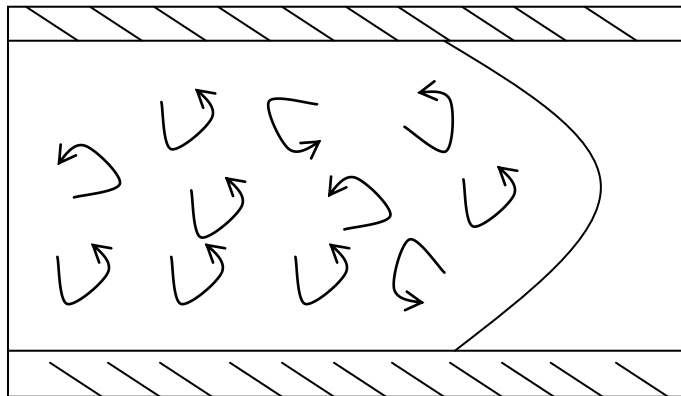


Figure 2 Turbulent Flow Mechanism

In turbulent flows, the friction at the pipe wall will lead to frictional drag hence the decrease in flow speed. There will be high tendencies for the molecules to form vortices in the fluid. Thus, energy will be loss due to formation of vortices and numerous small eddies.

2.2. Working mechanism of DRA to reduce turbulence

Drag reduction is defined as the reduction of skin friction in turbulent flow below that of solvent alone (J.L. Lumley, 1969). This phenomenon, also termed as Tom's effect has been shown to have an effect when certain additives are mixed into a flowing fluid. These additives can be either natural or synthetic-produced, such as guar gum, surfactants, fibers, and even wood pulp. They are commonly regarded as Drag Reducing Agents (DRA) because they can perform the primary function of reducing drag in a turbulent flowing fluid which has led to their applications in a variety of fields such as fire-fighting operations, ship-building industries, and biomedical purposes.

This paper focuses on investigating the potentials of WLM as a DRA in the oil industry. Actually, there are a lot other commercial polymers that are used as DRA such as PAM, however due to their properties which are permanently mechanically degraded, the WLM is being studied as they have the potential to eliminate this limitation by PAM. Despite their differences, the main objective to achieve from this project is none other than to reduce frictional pressure drop caused by turbulence in a pipeline. As a result, the operating pressure can be reduced while keeping the same flow rate with the throughput volume of fluid increased at the end of the line.

Basically the mechanism of how DRA works to reduce turbulence can be explained by the following steps:

1. DRA molecules are injected into a flowing liquid which is undergoing turbulence.
2. The molecules undergo chain stretching and elongation that interacts with eddies in the flow.
3. This will alter the whole energy balance of flowing fluid by dampening the small eddies in the turbulence.
4. Dampening of turbulence would result in the reduction in frictional drag, lowering the rate of pressure drop and increase in throughput volume.

5. This chain stretching occurs only under high shear rates, meaning when a fluid is in turbulence.

The following Figure 3 demonstrates how the DRA acts in a turbulent flow:

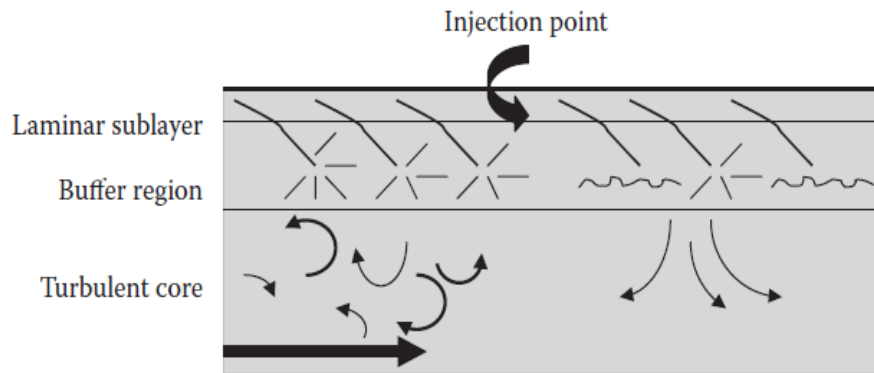


Figure 3 Injection of DRA to reduce the fluidic turbulence (source from B.A. Jubran, et al., 2005)

The figure above demonstrates how injecting a DRA can help suppress the turbulence in a pipeline which is caused by the energy burst. A theory states that the turbulent flow in a pipeline has three parts; laminar sublayer, buffer region, and turbulent core (A.A. Hamouda, 2005).

The centre of the pipe, which is the turbulent core holds the most chaotic flow which is the eddy current. Nearest to the pipe wall is the laminar sublayer where the fluid moves laterally in sheets. In between the two parts, is the buffer region where turbulence is firstly created. First of all, a portion of the laminar sublayer called “streak” travels into the buffer region. Here, the streak begins to vortex and oscillate, moving quicker as it throws fluid into the flow core.

This ejection of fluid into the turbulent core is called the “turbulent burst”. The growth of streak to the formation of turbulent core causes the waste in flow energy, hence inefficiency of fluid transportation not just across the pipeline, but also hoses and other conduits in which liquids flow can be achieved. DRA interfere with the bursting process and reduce the turbulence by absorbing the energy in the streak before most of the

energy is loss to the turbulent core. Thus, turbulence burst can be reduced and less friction is loss in the pipes, generating a lower pumping pressure in the pipelines. It can be stated that the DRA polymers are most active in the buffer region (A.A. Hamouda, 2005).

DRAs can also decrease the cost of pumping fluids, the cost of equipment used to pump fluids, and the possibility of enabling the use of a smaller pipe diameter for a given flow capacity. The drag reduction levels may reach 80% under laboratory conditions (Ezrahi, S 2006). The role of drag reducers to reducing the pumping energy costs lies in its interaction of the polymer chain with the small vortices created within the turbulent flow. Currently, by injecting a high molecular weight polymer can help by balancing the transient molecular interactions in such dynamic system where the micelles continuously breaks and reforms within a finite time scale.

This project aims to evaluate and compare the effectiveness of both PAM and WLM. The tests require three important equipments namely the Viscometer, Vertical flow system, and Horizontal flow system. These apparatus will be described in the experimental section of the paper with their respective parameters to measure.

2.3. Case studies of DRA

Drag reduction agent can be classified in three different categories which are high and low molecular weight polymers, cationic-zwitterionic-anionic surfactants and fibers (Myska *et al.*, 2001). Many researches have proven this efficiency of additives in their investigations. There differ in terms of their molecular structure and properties.

Normally, it is necessary to inject the PAM downstream pipeline pumps to avoid the early mechanical degradation that occurs within a pump. The extent of drag reduction induced by a homologous series of polymers in a given pipe is a universal function of concentration, flow rate and molecular weight. The maximum drag reduction possible is limited by an asymptote that is independent of polymer and pipe diameter. Warholic et

al. performed a study in 1999 on the effect of different polymer concentrations on the drag reduction. He injected polymer solutions within a range of 50ppm to 200wppm and flow rates, from 0.7 to 30 L min⁻¹; whereby the end result was a drag reduction range of 10-69% was achieved.

Some of the DRAs have proven to benefit in the oil and gas field because of their tendency to dampen the eddy current in turbulent flow even when they are injected at low concentrations. When injected at high concentrations, a change in the physical behavior of fluid flow can be observed whereby more interfacial waves present can be dampened. Therefore, the frictional drag between pipe wall and fluid can be reduced.

This investigation was done by T. Al-Wahaibi et al. in 2007, and they also observed that the presence of polymer reduces the two-phase pressure gradient and this effect becomes more obvious as the water velocity increase. This further proves that DRAs work better in turbulent flow instead of laminar flow because the DRA molecules collide more with each other, forming polymeric chains which are elongated due to shear thinning.

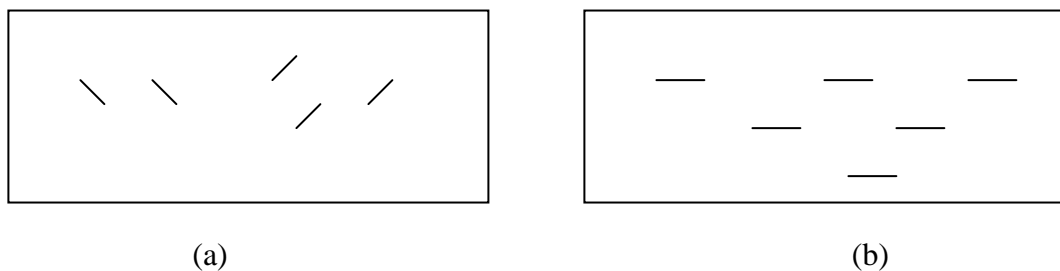


Figure 4 DRA molecules alignment in (a) laminar flow (b) turbulent flow

The above figure 4 demonstrates how the DRA alignment is configured in both laminar and turbulent flow. The difference is resulted from the properties of the polymer whereby it elongates under an increasing stress rate. However, H.A. Abdul Bari et Al conducted an experiment in 2010 to a significant finding whereby the efficiency of DRA will reach a maximum point at a certain Reynolds number and any further increase in the Reynolds number will result in reduced efficiency, as shown in Figure 5 below.

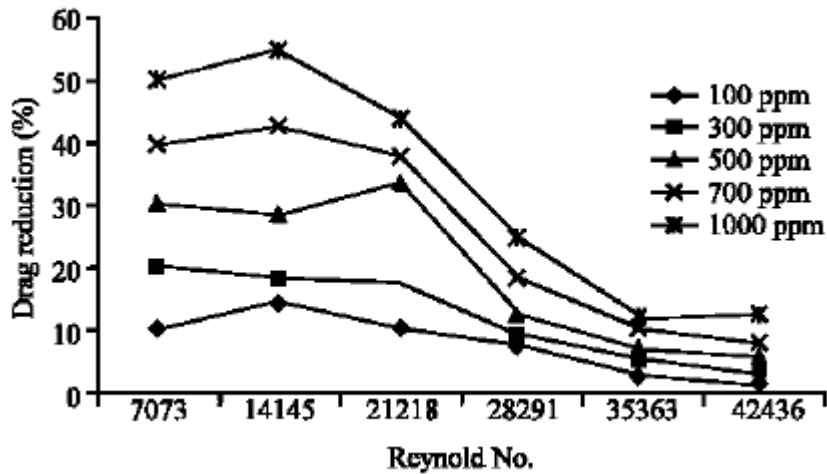


Figure 5 Effect of Reynolds number on percentage of drag reduction with different concentration (source from H.A. Abdul Bari, et al., 2010)

Following the above finding is another research by B.K. Berge et al. in 1996 has pointed out that the shear stress present in turbulent flow degrades the dissolved high molecular weight polymer, thus reducing the overall performance accordingly. Considering the overall performance of a drag reducer additive, the following characteristics of a product are important – fast dissolution rate, slow degradation, and low sensitivity in the cloud point temperature range. In 2008, H.A. Al-Anazi et al. concluded from their experiment that polymer degradation reduces the drag-reducing effect of a flowing system and it is also mentioned in another research paper that polymer solutions are strongly affected by mechanical degradation, which possibly results in a shorter lifetime of drag reduction effectiveness thus it is crucial to study the effect of degradation in the drag reduction efficiency (A. Kamel et al., 2009).

2.4. Polymeric DRA, POLYACRYLAMIDE (PAM)

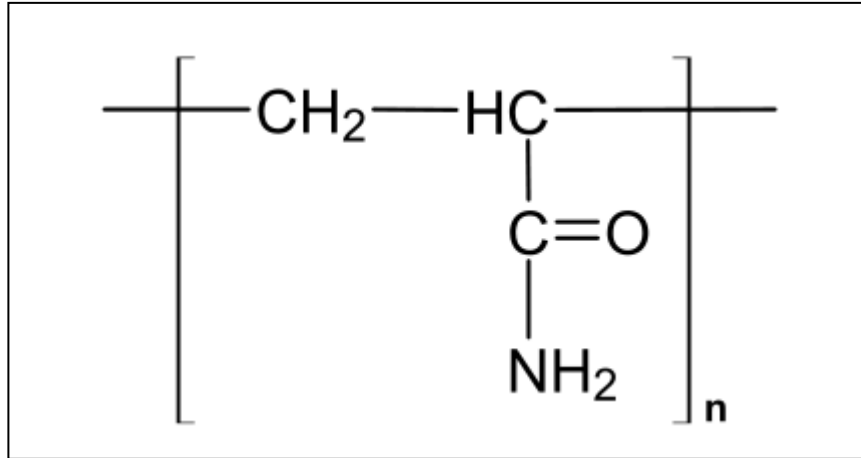


Figure 6 Chemical structure of PAM (source from Merck Index, 1960)

Polyacrylamide (IUPAC poly(2-propenamide) or poly(1-carbamoylethylene)) is a polymer (-CH₂CHCONH₂-) formed from acrylamide subunits, as shown in Figure 6. Polyacrylamide is not toxic. However, unpolymerized acrylamide, which is a neurotoxin, can be present in very small amounts in the polymerized acrylamide (Daughlon, Christian G., 1988), therefore it is recommended to handle it with caution.

PAM is an example of a water-soluble polymer with an acrylic group (B.L. Rivas et al., 2003). Al-Sarkhi and Hanratty found a significant point in 2001 through their experiment whereby when a concentrated solution of a co-polymer of PAM and sodium acrylate were injected into an air-water flow in a 9.53 cm pipe changed an annular pattern to a stratified pattern by destroying the disturbance waves in the liquid film. This occurred with mixed concentrations of 10-15ppm. Drag reductions of 48% were realized. In a subsequent study in a 2.54cm, they have again obtained similar results and observed drag reductions as large as 63%.

There were a few studies done on the investigation of PAM properties – one of them is its yield stress of PAM solution decreases with increasing temperature and decreases with increasing concentration (M.H. Yang, 2000). Another research has stated that mechanical degradation effect increases with decreasing concentration of PAM in the

solution (C.W.Morris, 1978). According to Maxwell system, there are two important terms – G' for the elastic (storage) modulus, G'' for the viscous(loss) modulus, and λ for fluid relaxation time (Jian-Hai, et. Al, 2001). Both G' and G'' will increase with the surfactant concentration, which changes the packing arrangement. In the meantime, λ will reduce with increasing surfactant concentration, indicating that the PAM molecule gets more elastic and shorter recovery time. However PAM still comes with limitations; its drag reducing capability reduced due to its low resistance to shear degradation and hence, the study on WLM is conducted.

2.5 Wormlike Micelle (WLM)

Surfactants in solution will spontaneously form supramolecular aggregates (when above the critical micellar concentration, cmc), and the micellar morphology covers a large range of shapes and sizes (Israelachvili, J. N. et al., 1976). Normally in solutions with low surfactant concentration and without other cosolutes, the aggregates in the fluid will form spherical structures.

However, with an increasing concentration of the surfactant will result in the formation of long and flexible cylindrical micelles, usually called as WLMs (Ezrahi S. et al., 2006).The WLMs have been studied for various type of surfactants in recently years, and new applications have been found in different areas from oil fields, drag reducing agents in district heating systems, home and personal care products to templates for asymmetric and aligned nanostructures.

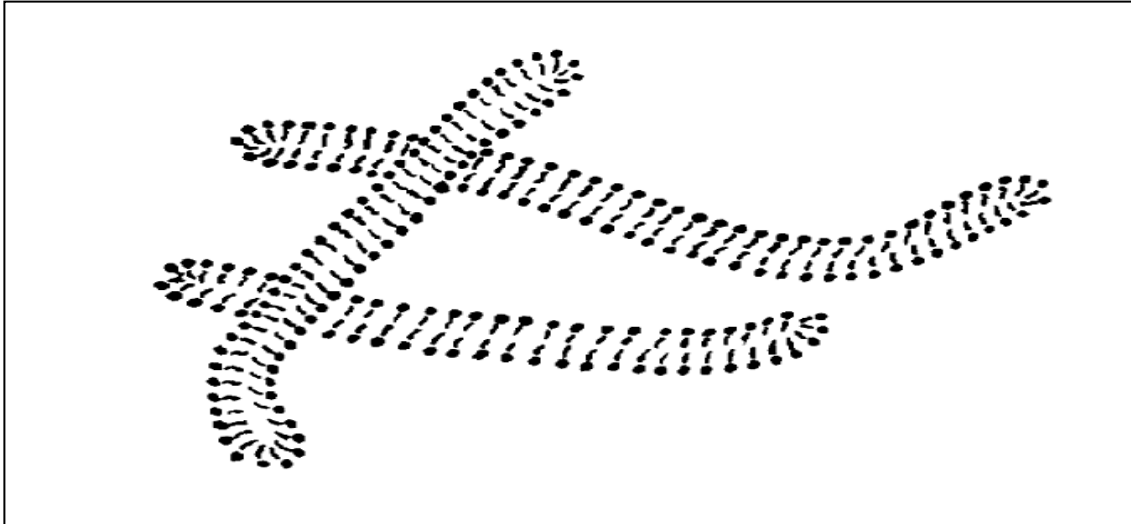


Figure 7 Schematic illustration of an entangled WLM network (source from J.Yang, 2002)

Figure 7 shows the illustration on the structure of the entangled WLM. As seen in the diagram, the wormlike structure is formed by the aggregation of charged heads and hydrophobic tails. Micelles tend toward elongated structures when the packing parameter, $p=v/Al$, of the surfactant increases towards $p=1/2$, where v is the volume of the hydrophobic part of the surfactant, A is the surface area occupied by the surfactant head group and l is the extended length of the hydrophobic portion (as shown in Fig 8).

Micelles are considered rod-like if the length of the micelle is short compared to its persistence length (the length over which it is rigid), and worm- or thread-like when the overall length, or contour length, is much greater than its persistence length (Walker, L, 2001). An analogy is drawn between worm-like micellar systems and polyelectrolytes, although micelles have the additional ability to break and reform, gaining the moniker 'equilibrium polymers'.

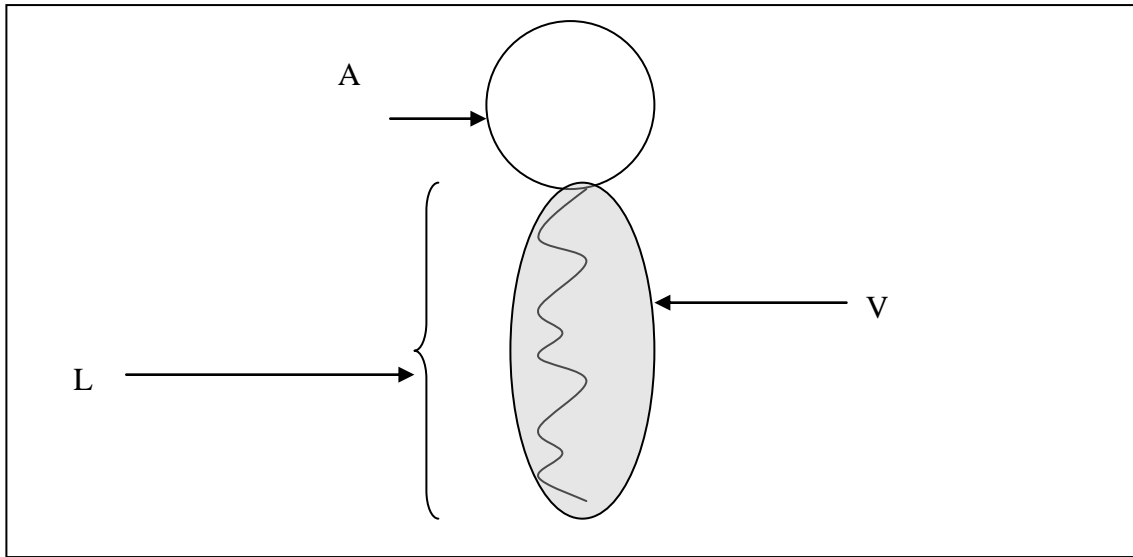


Figure 8 Schematic diagram of a surfactant molecule

A series of surfactants with various counterion concentrations have been shown to form WLM. They can be cationic, anionic, zwitterionic, or non-ionic surfactants. Cationic surfactant mixed with counterion is the most widely studied surfactant in both theory and practical applications (Candau SJ., 2001).

Throughout this project, the formation of WLMs would be as a function of surfactant/salt concentration, $R = [\text{SDS}] / [\text{TDPS}]$ subjected under various shear stress and rate; with the temperature being held constant throughout the study. This is done to investigate the best type of surfactant to use that could generate good WLM formation. Normally, microstructure of WLM can be direct visualized experimentally by cryo-TEM and determined by dynamic light scattering. The experimental study will be discussed further on in this document.

Entangled WLMs increase the viscosity of fluids like polymer. Under shear, these WLMs can break and re-form. Hence, it was sometimes called ‘living polymer’. The association structure can also be molecularly stimulated (Maillet JB, 1999). The main aim of this project is to investigate how the WLM is a better DRA as compared to the PAM performance.

Table 1 Difference between WLM and PAM

Criteria	WLM	PAM
Raw material	Surfactant and salt	High molecular weight polymer
Scission	Can continuously break and re-form after undergo scission – maintain ability to promote DR. (Magid LJ et al., 1998).	Results in irreversible alteration – reduced DR efficiency.
Degradability	Does not degrade easily due to its rapid recovery rate.	Degrades easily especially by mechanical degradation i.e. when sample passes through pumps.

WLM has a lot of potential as a DRA, with the primary advantage of a higher DR efficiency while eliminating or reducing the unwanted side effects (mechanical degradation) of using PAM. Not only WLM can be applied in EOR i.e. water flooding, its application can actually go further up to the transportation pipe line as the drag between the fluids and pipe wall causes substantial pressure drops along such pipelines as the fluids flow.

Therefore with the practicality of WLM as DRA, pressure losses can be compensated without the extra costs of installing pump stations which are spaced along the pipelines to boost the pressure of the flowing fluids to maintain original throughput volume. Not only that, having WLMs as DRA does not require any maintenance programs as the pipe are not pressurized above its safety limits as compared to then when using PAM as the DRA.

As the year goes by, the maximum allowable operating pressure (MAOP) will have to be reduced. In terms of application DRA in the field, it is reasonable to say that the reason behind the restriction in MAOP is that over time the pipeline will corrode no matter the amount of work that has been done to prevent such cases (i.e. regular pigging, cathodic

protection, injecting corrosion inhibitors, etc). As the wall thickness reduces due to corrosion, MAOP will have to be reduced to prevent pipeline rupture. Among the options to overcome this matter is by:

- Replace the line (however with an increase in CAPEX).
- Reduce operating pressure and hence reducing flow restriction.
- Inject DRA (equal flow at lower pressure hence lower cost).

Hence, by implementing the latter option it can help to decrease the drag in oil pipeline and thus the pressure need not be increased to push the liquid to flow due to drag. In addition, the performance of WLM as DRA would theoretically be better than PAM due to its stated reasons previously.

2.6 Rationale for using WLM as DRA

In terms of raw cost, although the WLM is more expensive than PAM, operational-wise WLM is more cost-effective. This is due to the fact that once PAM molecules go through high shear rate pumps, its structure will be altered permanently. This results in a reduced drag reducing efficiency – hence more PAM is pumped at most booster stations to replace those degraded forms.

However unlike the WLM, its special viscoelastic property facilitates its shear degradation process whereby the molecules break, and then reform to its original molecular structure after scission. With this, less WLM is needed to be injected to replace those which have been degraded. By means of reducing the amount to be injected, the operational cost could therefore be reduced. It is actually the concept of quality versus quantity – small amount of WLM to be injected for the long run versus multiple additions of PAM throughout the pipe line.

CHAPTER 3

METHODOLOGY

3.1 Project activities

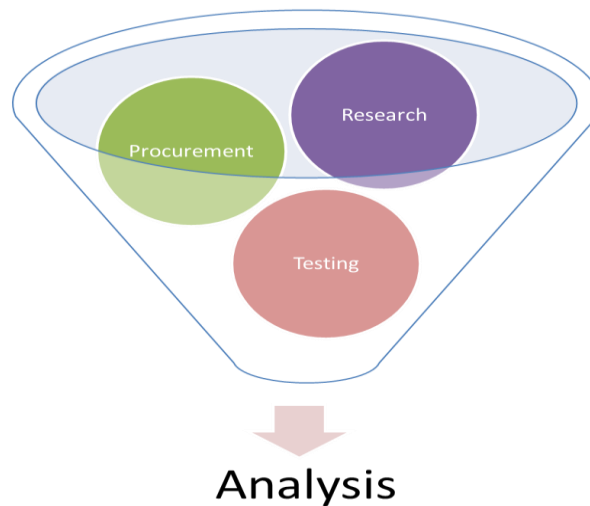


Figure 9 Schematic diagram of project activities

Figure 9 shows the general main activities that have been conducted for this research. Further details of the activities will be elaborated in the Gantt chart provided later in this following report. Basically, this project is divided into 4 main activities; research, procurement, testing, and analysis. Research comprises of searching for information to get a basic idea on the project, and this is done by reading through journals by researches that are available in SPE or Science Direct web page. Apart from reading, research also includes meeting respective lecturers and postgraduates that have area of expertise in the following field namely PAM, WLM, DRA, and experimental set-up. Among the information that I have to grasp for this stage is:

- What is a DRA?
- How does it work?
- What are PAM and WLM?
- What are their common and special properties?
- How can I measure their drag reducing efficiency?

Procurement stage is where a list of chemicals, materials, and other consumables are prepared and confirmed to be used for the future tests. This requires the author to contact the external laboratory supplier – Sigma Aldrich. Prices and amount of chemicals needed have been quoted and after going through approval by the university’s financial unit, the purchase order will be created and order is official. The chemicals will take about 2 months to deliver.

Testing is the experiment phase, where PAM and WLM will undergo various testing procedures to obtain the optimum results. This stage includes meeting with lecturers and postgraduates to further understand the concept of the experiments and to get their thoughts and ideas about what could be improved from the original experimental procedures and what set of criteria to be focused on. Meeting the lab technicians are also included to book the required equipments, and ask them what parameters the respective machines could address. This is done to avoid wasting time on performing an experiment without knowing the limitations of the equipment.

The following table shows what equipment are needed with their respective parameters:

Table 2 Equipments needed with their parameters

Equipment	Parameters
Turbulent pipe flow	<ul style="list-style-type: none"> • Pressure drop • Drag reducing efficiency
Viscometer	<ul style="list-style-type: none"> • Shear rate • Viscosity • Shear thinning
Aspirator	<ul style="list-style-type: none"> • Flow rate • Drag reducing efficiency

Last but not least, is the analysis stage where results from the testing stage is observed to determine whether the additives could meet the project’s objectives and perform as studied theoretically before. This stage required an in-depth and critical observation and

understanding on the obtained results through several discussions. From here, we could determine whether the objective of the project is being met, or not.

3.2 Key milestones

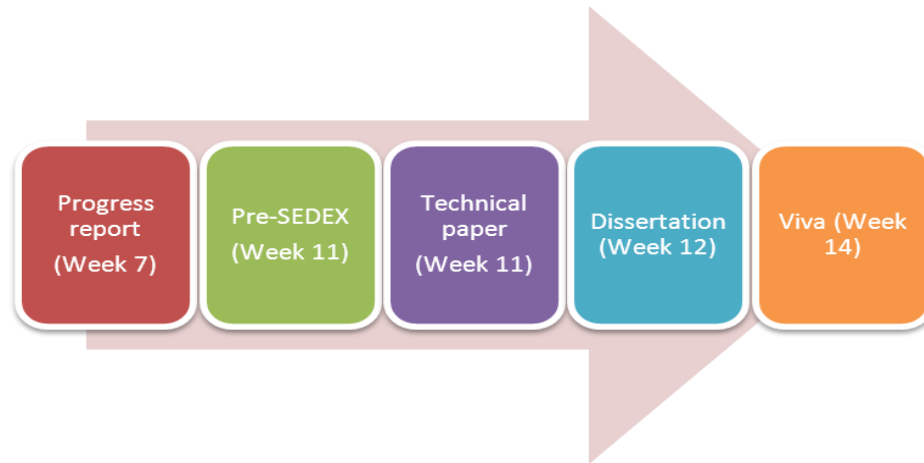


Figure 10 Key milestone

Figure 10 shows the key milestone for the project which is a more detailed form compared to the project activities explained previously. The first milestone would be to come up with the progress report. This report would cover the latest progress made for the project since the beginning of the semester, and also to highlight on any alterations. This stage takes about 2 weeks to develop.



For Pre-SEDEX and final presentation, students need to explain verbally to the audience about the project, with the help of a poster. Basically it is an oral presentation in front of a panel of examiners from the industry, hence requiring the student to fully understand the project and to demonstrate this by the ability to answer questions from the examiners. Pre-SEDEX event is done 2 weeks after mid-semester break and is a one day event while taking about a week to prepare.

For the technical paper and final dissertation, they require a written form of document to explain the technical side of the project, such as its significance, problem statement, objectives, job scope, methodology used, results, conclusions and recommendations. This stage takes about 3 weeks to prepare.

3.3 Study plan

Table 3 Gantt chart for FYP II

ACTIVITIES/WEEK NO.	WEEK															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Experiment work																
Update methodology																
Purchase aspirator																
Check for material availability																
Book equipments i.e. stirrer																
Experiment on PAM																
Experiment on anionic WLMs																
Progress report draft																
Submission of progress report																
Pre-SEDEX																
Submission of Technical report																
Submission of Dissertation																
Oral presentation (Viva)																

 Target dates for report/presentation
 Work period

Submission of progress report: 7th November 2012

Submission of technical report: 30th November 2012

Submission of dissertation: 5th December 2012

Viva: 19th December 2012

3.4 Tools

Apart from that, for this project, there are two major procedures which are going to be carried out in order to obtain the results which are reflective according to the field practices as well as providing validated of results. DRAs dissolved in water are going to be tested with various parameters with a few experimental set up.

The rheological side of the project i.e. viscosity of DRA will be studied using the viscometer and others with the vertical and horizontal flow apparatus. Experimental results will be used in relating the model parameters to the relevant physical properties. The following table will show what the parameters that the tools will measure and their main achievable result.

Table 4 Tools description and measuring parameters

Tools	Objectives to achieve	Parameters	Reason for using
Parallel plate viscometer	To measure viscosity	Shear rate, shear thinning, and viscosity.	Easy to use, repeatable, small sample volume and can observe change in viscosity by varying the shear rate.
Water flow	Aspirator-To measure DRA efficiency for vertical flow. Turbulent pipe-To measure DRA efficiency for horizontal flow.	Pressure drop, flow rate, concentration.	More realistic fluidic flow.

3.4.1 Viscometer

The viscometer is primarily used to measure the viscosity and shear rate. Early investigations of polymer degradation were conducted in pipe flows (J. Culter *et al*, 1975) until most recently, behavior in rotational flows such as the Taylor Couette and rotating geometries has been studied (H. J. Choi *et al*, 2002). Experiments in rotational flows like the viscometer have the advantage of requiring less fluid volume (as for this viscometer, a few drops of pre-mixed solution will do).

Extensive measurements of the DRA effect for a viscometer can be performed at different RPM and DRA concentrations. In this study, the flow conditions necessary to elongate the drag reducing agents, the drag reducing (DR) efficiency of the agents of various apparent molar masses, and their degradation kinetics have been measured with the viscometer shown in Fig. 11.

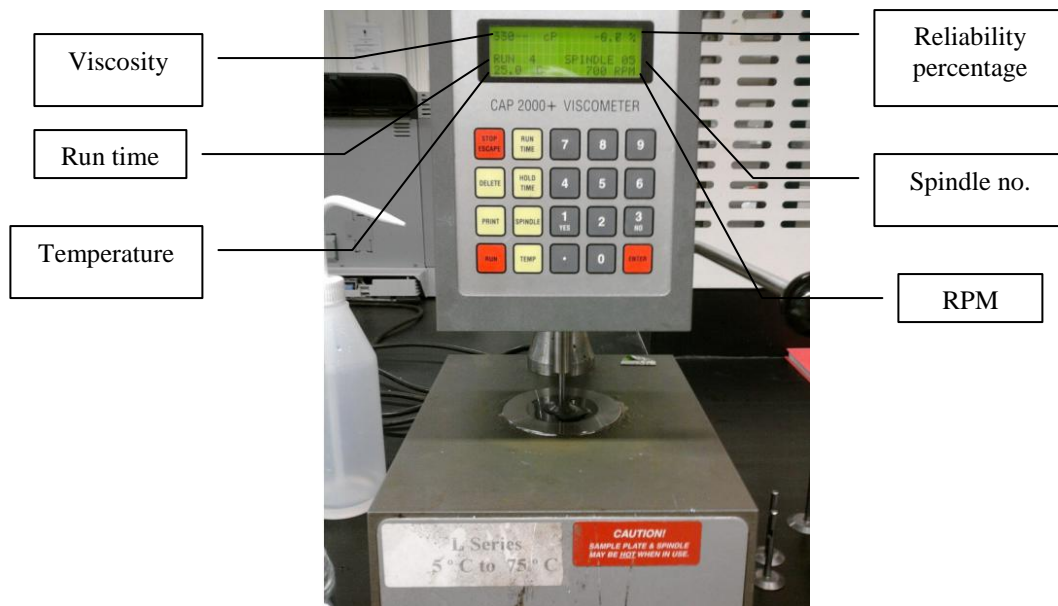


Figure 11 Picture of Viscometer

With the viscometer, the following questions can be answered:

1. What is the viscosity of fluid?
2. Does the viscosity change with rotational speed and shear rate?
3. How does the drag reduction capability change with an increase in DRA concentration?
4. At which concentration does shear thinning occur?

After the experiment using the viscometer, the next one using vertical and horizontal flow can be conducted.

3.4.2 Turbulent Pipe flow

Despite the significant advances in the mentioned rotational flow, to our knowledge no framework exists to quantitatively describe the bounds that polymer chain scission places on the maximum drag reduction that can be attained in the turbulent pipe flow. Although pipeline construction may be rather expensive and the measurements time consuming, the advantage of pipe-flow measurements is in the large amount of general knowledge that could be obtained from turbulent flow in pipes. Moreover, there is a connection between local conditions in pipe flow, turbulent flow in a round channel, and turbulent flow in a developing boundary layer (L.I. Sedov *et al*, 1979).

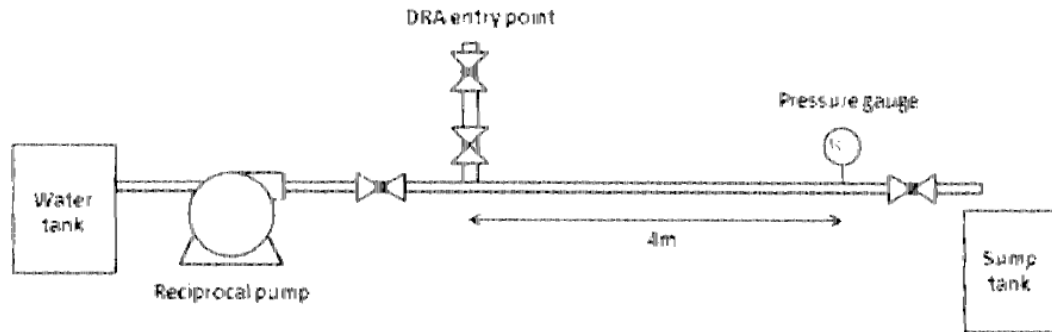


Figure 12 Schematic of pipe flow set up

As shown in Figure 12, the experimental set-up of this study will consist of the following components:

- i) A 50L tank
- ii) A 4-m galvanized pipe at the test section
- iii) A reciprocal pump to feed the fluid to the test section
- iv) Pressure gauge
- v) Pipe diameter 0.0254m

The support structure for the test facility consists of a trussed boom and a four post tower structure to allow sufficient potential energy to feed the reciprocal pump. The length of the galvanized pipe has been confirmed, as a research has been done to prove that a 4-m pipe length will not be sufficient enough to make sure that the flow patterns are fully developed.

In addition, 4-m pipe is too short as once the DRA is injected into the flowing solution, turbulence might cause it to backflow towards the pump. Hence, a longer pipe is needed to ensure that this does not happen. A pipe with length 12.5m was build, so that the flow reading when reaching the pressure gauge does not fluctuate, with the test section remaining as a 4m section. The additional length comes from before the 4m pipe section. Also for the pressure gauge, instead of just one the experiment will need two pressure gauges; one will be situated next to the injection point and another one near the end flow point. The test fluid will flow into the sump tank where a fluid sample will be taken for further analysis.

3.4.3 Vertical pipe flow



Figure 13 Aspirator

It is an aspirator bottle (as shown in figure 13), which contains a valve at its bottom, where a sudden contraction takes place, applying shear force to the flowing fluid. Basically it has a very simple set up, and calculation.

3.5 Chemicals

These following chemicals will be tested as the DRA, namely:

- Polyacrylamide (PAM)
- N-tetradecyl-N,N-dimethyl-3-ammonio-1-propanesulfonate (TDPS) and Sodium dodecyl sulphate (SDS).
- Brine solution, NaCl.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Experimentation

4.1.1. Preparation of PAM and WLM solution

First of all, solution containing PAM solution at different concentration for flow test is prepared. The concentrations required are a range of 100ppm until 6000ppm. The reason for this large range of concentration is to get a thorough study on the workings of a PAM and determine the exact concentration where PAM is giving its optimize result in terms of DRA efficiency.

To prepare, first weigh the amount of PAM powder needed; for example for a concentration of 100ppm, 0.2g of PAM powder is weighed and mixed with 2L of distilled water. The following table shows the concentration for formation of PAM:

Table 5 Concentration of PAM

Concentration (ppm)	PAM (g)
200	0.40
400	0.80
600	1.20
800	1.60
1000	2.00
2000	2.20
3000	2.40
4000	2.60
5000	2.80

The mixed solution is then placed in a beaker containing magnetic stirrer and is left to stir at a low speed for one hour for optimum mixing as shown in the figure 14 below.



Figure 14 Stirring of a solution using hot plate and magnetic stirrer

After that, the mixed solution is covered with aluminum foil and is left overnight. The reason for this is to ensure that there are no trapped air bubbles (de-aerate) in the solution – this might affect the results later on. After leaving it overnight, the solution is then measured for its viscosity.

The procedure for preparing the WLM solution is similar to PAM as they first are done by weighing the chemicals required. For this project, WLM is a product made by mixing Sodium dodecyl sulphate (SDS), N-tetradecyl-N,N-dimethyl-3-ammonio-1-propanesulfonate (TDPS), and 0.5M NaCl. After diluting the individual chemicals with distilled water to their required concentration, they are left overnight to ensure equilibrium. Both SDS and TDPS are prepared with a ratio of 0.45, which is represented by the expression $R = [\text{SDS}]/[\text{TDPS}]$. This means that with 0.45mM of SDS, there must be 1mM of TDPS, and a constant 0.5M of NaCl. The WLM is prepared within a range of 100 to 6000 ppm. Concentration of WLM formation are as follows:

Table 6 Concentration for WLM

TDPS(mM)	SDS(mM)	R = [SDS]/[TDPS]
1	0.45	0.45
5	2.25	0.45
8	3.60	0.45
10	4.50	0.45
20	9.00	0.45
30	13.50	0.45
40	18.00	0.45
50	22.50	0.45
59	26.55	0.45

The next day, the solutions are mixed together using a volumetric flask up till the required volume of 1L, and then mix with magnetic stirrer for 6-8 hours to ensure equilibrium as shown in figure 15 below.

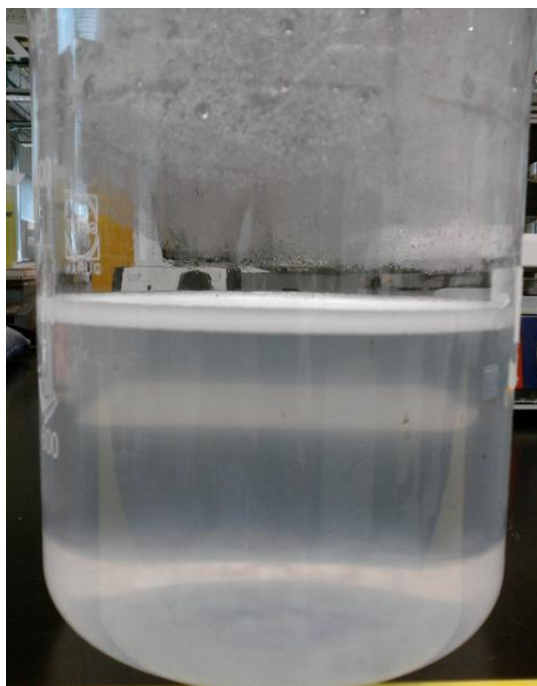


Figure 15 WLM solution that was mixed, and left overnight

Due to the lack of equipments and tools i.e. Cryo-TEM, a few steps have been identified to confirm the point at which WLM starts to form. According to an experiment done by Nash, T.J. in 1956, a simple procedure was carried out that consists of swirling vials containing WLM solutions and observing the movement of the small air bubbles trapped in the solution. If the solution is non-viscoelastic or in other terms, not a WLM, the bubbles stop as soon as the circular movement of the vial is interrupted. However if the

solution is viscoelastic (which is typical of WLM), the bubbles move in opposite trajectory (backwards) when the swirling is interrupted. This simple test allows the determination of the boundary between viscoelastic and non-viscoelastic solutions for a large number of samples with different concentrations.

4.1.2 Vertical flow test



Figure 16 Vertical flow test

After measuring the viscosity, the solution is then transferred into the aspirator tank. Test and measurements were made for at least one day after the solution preparation to ensure that it has reached equilibrium. The solution is poured slowly as to reduce the formation of bubble. Next, the valve is opened and time is taken for the solution to displace 1L of solution as shown in figure 16. Procedure is repeated for each concentration. The following formula is used to calculate the flow rate given time and volume (Jasamai, M., 2012):

$$Q \text{ (rate)} = \frac{V}{t}$$

Where Q = Flow rate (m³/s)

V = Volume displaced (m³)

T = Time (s)

The results are interpreted in the following section.

4.1.3 Horizontal flow test

The experimental procedure is as the following:

1. Make sure the reservoir tank is filled with water.
2. Fill the DRA into the inlet.
3. Start pump.
4. Open the DRA valve so it flows into the turbulent flow.
5. Take pressure reading from both ends of the pipe.
6. Take time taken for the tank to be filled with 36L of water.
7. Repeat steps 1 to 6 with different chemicals or concentration.

4.1.4 Viscosity measurement

The viscometer uses six spindles with different diameter, and since different solutions require a certain spindle for it to have the best viscosity measurement, a trial and error method is applied. A few drops of solution are placed onto the test surface and spindle is lowered down just enough to leave a gap between fluid and spindle. The RPM and spindle number is set and the spindle rotates for about 20s. Results showing the shear rate, error percentage, and viscosity are recorded. This procedure is repeated using different spindle size, and best viscosity measurements which has less error percentage is taken as the result. This experiment was repeated 2 times and the result was calculated from average.

4.2. Data Gathering and Analysis

Shear thinning happens because when the solution is subjected to high shear rates, the DRA molecules will be stretched, forcing the solution to be more laminar making it easier for the solution to flow, hence a reduction in the viscosity. Shear thinning is significant to the working of the DRA because it helps to dampen the small eddies formed in a turbulent fluid resulting in less frictional drag. This would lower the rate of pressure drop in the pipeline and maintain the throughput volume. The shear thinning phenomenon is observed by performing a test on the viscometer, with concentration ranging from 100ppm to 6000ppm, each subjected to increasing shear rates as shown in figure 17 below. From the experiment on PAM, the result of viscosity as a function of shear rate and concentration can be studied:

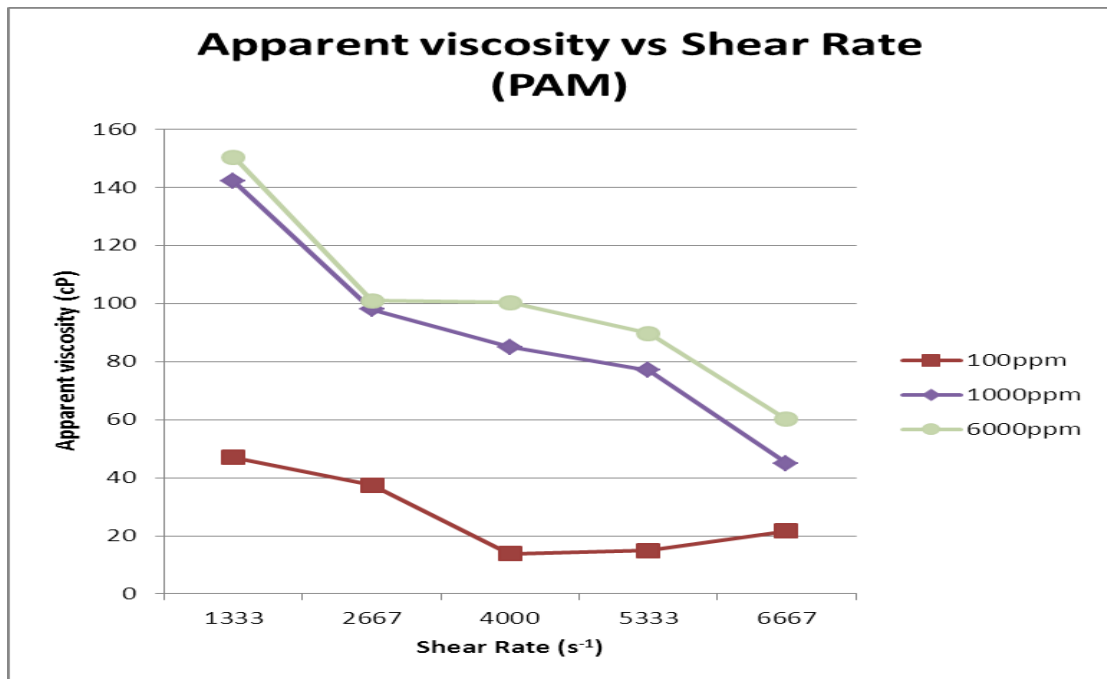


Figure 17 Graph of PAM Apparent Viscosity vs Shear rate

Figure 17 shows the relationship between the viscosity and shear rate of PAM solution when subjected to a shear force using the Brookfield viscometer. The PAM concentration used is a range of 100ppm to 6000ppm. As can be seen from the graph, an increase in the shear rate leads to a gradual decline in the viscosity – this is termed the

shear thinning phenomenon. The following are results for concentration and its corresponding viscosity:

Table 7 Concentration and Viscosity reduction for PAM

Concentration (ppm)	Viscosity reduction (cP)
100	25.3
1000	97.0
6000	90.1

As observed from the table 7 above, the increase in concentration of PAM will result in a higher viscosity reduction when the solution is subjected to a known shear rate from $1333s^{-1}$ to $6667s^{-1}$. Viscosity reduction is a product of the initial apparent viscosity minus the final apparent viscosity. With increasing concentration, there are more PAM molecules available in that 1L of solution. Hence, when it is subjected to a shear rate, there are more molecules that will stretch and elongate to suppress the energy burst by small eddies in the turbulent flow – resulting in a reduce drag at the surface. This could explain why 100ppm of PAM has a lesser viscosity reduction which was only 25.3cP compared to 1000ppm which was 97.0cP. Theoretically, the 6000ppm should give more viscosity reduction compared to 1000ppm but the result showed otherwise. This could be either the fact that there is a critical concentration whereby the viscosity reduction is at its optimum value. So instead of expecting that higher concentration gives more viscosity reduction, one should perform an experimental study to observe the truth behind its phenomenon. For this case, not all increasing concentration could give higher viscosity reduction.

The following figure 18 shows the viscosity as a function of shear rate and concentration for WLM.

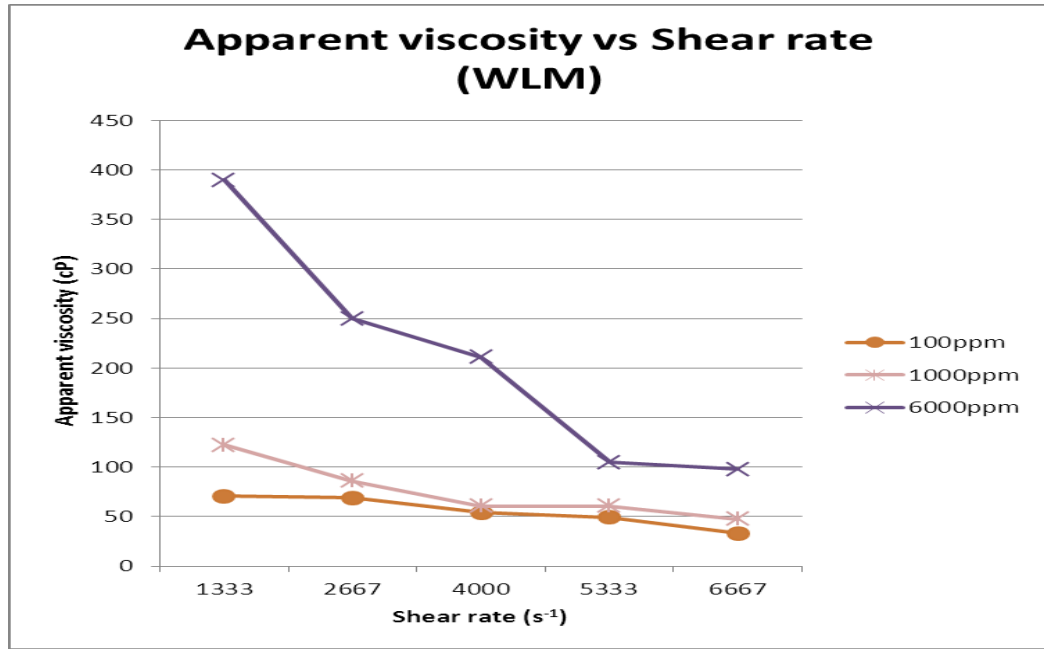


Figure 18 Graph of WLM Apparent Viscosity vs Shear rate

Table 8 Concentration and Viscosity reduction for WLM

Concentration (ppm)	Viscosity reduction (cP)
100	37.5
1000	74.7
6000	292.0

From the figure 18 and table 8 above, it can be seen that WLM gives more viscosity reduction, which is up to 292.0cP. This means that WLM molecules are more active in terms of its shear thinning behavior as compared to PAM. This is a vital criteria for DRA, because in the actual field, the turbulence in the pipe could be high due to rapid production and its capacity. Therefore, if the viscosity reduction is small, the drag reducing effect would be of small magnitude and the energy burst in flowing oil could still be very high leading to pipe leakage, or increased pressure drop leading to pipe damages. Hence, for the first part of the experiment on investigating the shear thinning effect, WLM gives the best result because of its ability to reduce viscosity at a large magnitude than PAM by 69.14%.

A good DRA should possess the ability to provide a high flow rate at a lower pressure drop. This means that with a high flow rate, the fluid in the pipeline could be delivered without the need to increase the pumping pressure. This is because when the pumping pressure increases, it could shorten the life of the pipe due to damages i.e. pipe leakage. The following experiment using the vertical flow system shows the flow rate capability when using PAM and WLM.

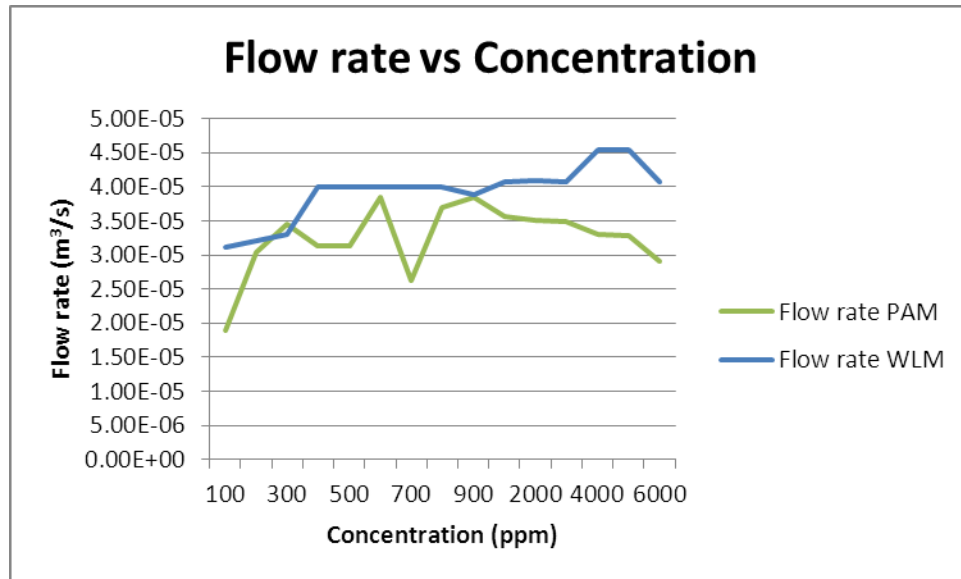


Figure 19 Graph of Flow rate vs Concentration

The above graph demonstrates the relationship between flow rate and concentration of both PAM and WLM when tested with the vertical flow. As concentration increases, the rate at which the solution flows is quicker. From the graph, the highest value of flow rate is $4.54 \times 10^{-5} \text{ m}^3/\text{s}$ for WLM, and $3.85 \times 10^{-5} \text{ m}^3/\text{s}$ for PAM.

For PAM, there is a sudden drop in flow rate at 700ppm, meaning it takes a longer time to displace 1L of solution. The reason for this decline might be from handling or equipment error since the trend of the graph should be increasing gradually. From 1000ppm onwards, the flow rate declines gradually. So from this graph, the most optimum concentration in generating the highest flow rate would be 600ppm.

WLM has a stable trend whereby with increasing concentration, its flow rate increases till it reaches 4000ppm where the flow remains plateau and at 5000ppm the flow rate declines. WLM has a more stable trend because it takes up to 5000ppm till its flow rate declines as compared with PAM. This might be due to the fact that WLMs are more viscoelastic, meaning the molecules can break and reform when undergo turbulence. Unlike PAM, the molecules break permanently, hence unable to suppress the energy burst as effective as WLM. This resulted in the reduced flow rate of PAM at only 1000ppm.

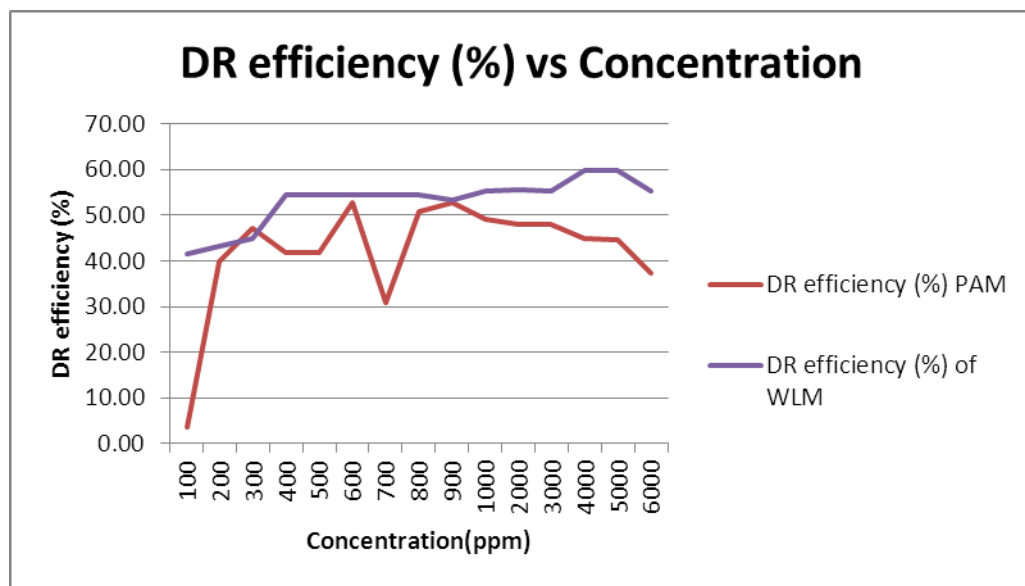


Figure 20 DR efficiency vs Concentration

Figure 20 shows the relationship between the DR efficiency and concentration of PAM and WLM. As the concentration increases, there is an increase in the DR efficiency as well, measured in percentages. A higher concentration of the DRA leads to an increase in the number of molecules present in the solution, leading to a more efficient drag reducing capability in dampening the small eddies formed under the shear rate. DR efficiency is calculated by using flow rate as shown in the following formula (Jasamai, M., 2012):

$$DR\% = \frac{Q_{\text{with DRA}} - Q_{\text{without DRA}}}{Q_{\text{with DRA}}} \times 100\%$$

whereby Q: Flow rate (m³/s)

DR%: Drag reducing efficiency percentage

For example, for the 100ppm solution;

$$DR\% = \frac{1.89 \times 10^{-5} - 1.82 \times 10^{-5}}{1.89 \times 10^{-5}} \times 100\% = 3.70\%$$

This shows that the DR efficiency is highly affected by the concentration as demonstrated in the table below:

Table 9 Concentration and drag reducing efficiency (%) by PAM and WLM

DR% of PAM	Throughput increase (%)	Concentration (ppm)	DR% WLM	Throughput increase (%)
3.70	2.10	100	41.48	34.27
49.01	44.84	1000	55.28	55.68
37.20	29.16	6000	55.39	55.89

The table shows that the higher the concentration, the higher is the drag reducing percentage (%) until it reaches a point where the efficiency reduces. The highest drag reducing efficiency is by WLM at 6000ppm, which is 55.39%. Taking the concentration of both DRA at 6000ppm, the WLM is more effective than PAM by 32.84%. This can be calculated by:

$$\text{Effectiveness} = \frac{DR\% \text{ of WLM} - DR\% \text{ of PAM}}{DR\% \text{ of WLM}} \times 100\%$$

Increase in throughput can be calculated by:

$$\%TI = \left[\left(\frac{1}{1 - \frac{\%DR}{100}} \right)^{0.55} - 1 \right] \times 100,$$

For the horizontal flow, the following graphs could be attained:

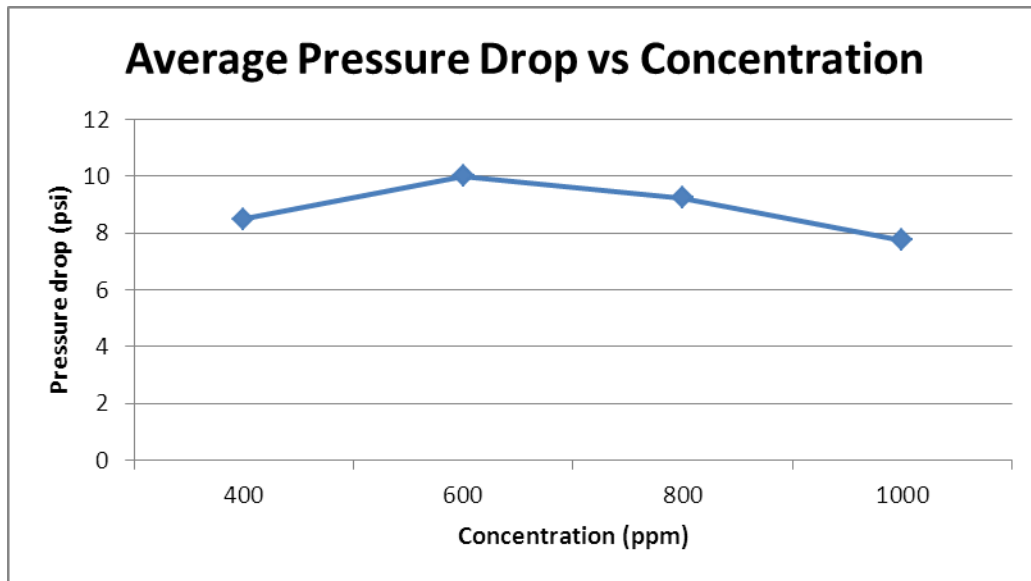


Figure 21 Average pressure drop vs Concentration

The graph above shows the relationship between average pressure drop vs concentration of PAM. As the concentration increases, the pressure drop increases until 600ppm, and then declines linearly until 1000ppm. The significance of this experiment is that it highlights the main function of a DRA, which is to reduce the pressure drop in a pipeline. As proven from this graph, the pressure drop reduces from an initial value of 13.5psi to as low as 7.75psi. At low PAM concentration, the solution did not have enough DRA molecules to collide and stretch. Hence DRA injected were not sufficient to suppress the energy burst in the turbulent flow that is causing eddy currents. That is why the pressure drop did not decline, as the frictional drag still exists in the flowing pipeline.

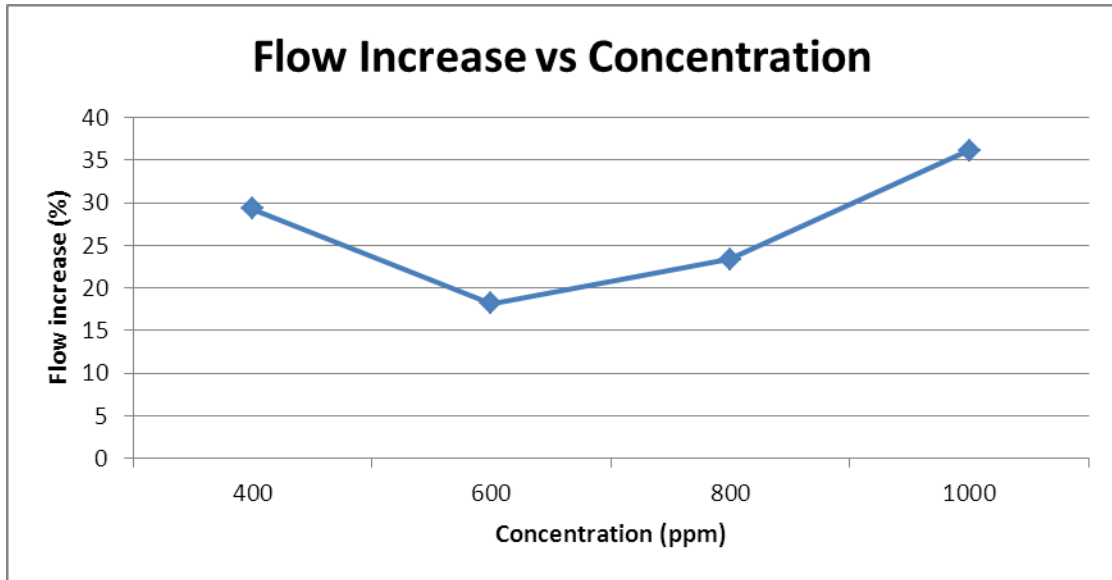


Figure 22 Flow increase vs Concentration

As shown in the graph, the flow increases as the concentration increases. This can be related to the fact that the DRA's significance is to increase the throughput volume since there is a reduction in pressure drop. More fluid volume can be carried to the final point within a shorter time because of the drag reducing ability of the DRA. When submitted to a turbulent flow, the PAM molecules become activated as the molecules tend to stretch and form long polymeric chains. Hence, dampening the eddy currents that are causing the turbulence in the pipe.

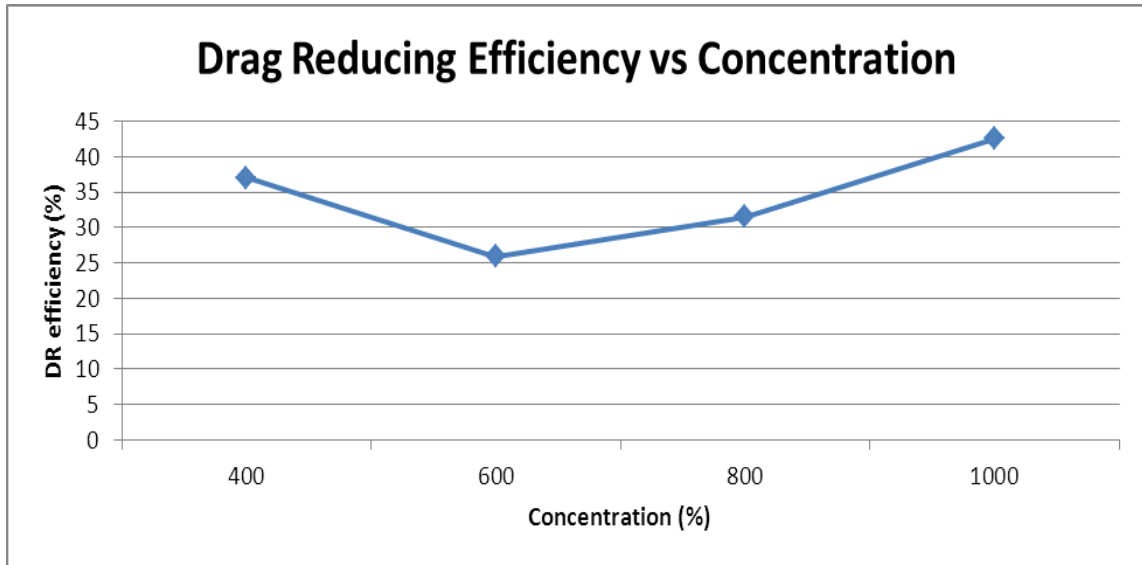


Figure 23 Drag reducing efficiency vs Concentration

The graph above shows the relationship between the drag reducing efficiency and the concentration of PAM using the horizontal flow test. Drag reducing efficiency is calculated using the formula (Jasamai, M., 2012):

$$DR\% = \frac{\Delta P_b - \Delta P_a}{\Delta P_b} \times 100\%$$

The result is rather similar to the result using vertical flow test – increasing the PAM concentration would increase the DR efficiency. The graph shows a decline in DR efficiency from 400ppm to 600ppm, then rising steadily to 1000ppm. The decline in DR efficiency maybe due to the fact that the DRA has not reached its optimized concentration to perform at the best efficiency level. Lesser PAM concentration means lesser amount of DRA molecules present in the turbulent flow, hence a poor dampening effect in the pipe. This links to the previous graph of average pressure drop vs concentration in figure 21, whereby from 400ppm to 600ppm there is an increase in the pressure drop in the flowing pipe. Hence, it can be deduced that the concentration from 600ppm possesses the optimized value for achieving high DR efficiency, which is about 43%.

The horizontal and the vertical flow both have the same objective; that is to determine the drag reducing efficiency of a DRA. However both tests differ in terms of the flow

condition, external power source, flow direction, and flow conduit hence leading to slightly different results. For vertical flow test, the highest DR efficiency for PAM was 52.73% whereas for the horizontal flow was 43.0%.

Unfortunately, the horizontal test using WLM cannot be done because the pump was having technical problems that needed the additional time to repair. Although the horizontal flow gives a more realistic result, the vertical flow system could also provide a near to idealistic approach because the percentage difference does not differ much.

4.2.1 Formation of WLM with SDS and Calcium Chloride (CaCl₂)

WLMs can be formed by many systems, namely cationic, anionic, zwitterionic, and non-ionic. For this project, the author has experiment with two types using anionic and zwitterionic surfactants. The above chemicals were used to form an anionic system WLM. The concentrations used are as follows:

Table 10 Formation of WLM with SDS and Calcium Chloride (CaCl₂)

SDS (10%) mL	CaCl₂ (10%) mL	Distilled water (mL)
1.1535	0.5	3.3465
	1.0	2.8465
	1.5	2.3465
	2.0	1.8465
	2.5	1.3465

This work intended to see whether WLM can be formed using the chemicals. Unfortunately, it did not work out because instead of forming viscous-like and see-through solution, a white solution with dense precipitates were formed. This concluded that the above surfactant and salt system are not compatible to form a WLM solution as depicted in figure 24 below.



Figure 24 Incompatible combination of anionic surfactant system

Another reason is due to the non-availability of SDES chemical in the lab, hence the author has decided to work with SDS in the meantime while waiting for the other chemicals to arrive. This is because it was stated in the scientific journal of *The Formation of WLM in an Anionic System* (Jian H., et al, 2001) that SDES was to be used as a surfactant with calcium chloride, not SDS.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion and expected results

A study has been done on the drag reducing efficiency between WLM and polyacrylamide (PAM). The drag reduction percentage was investigated using a number of variables such as concentration, shear thinning, flow rate, and drag reducing efficiency.

A few experimental apparatus has been highlighted – viscometer, vertical and horizontal pipe flow to determine the drag reduction percentage of each polymer and surfactants systems. Based on the experimental studies, the conclusions are the following:

- WLM gives a better result on drag reduction percentage than PAM by 32.84%.

- Drag reduction percentage (DR %) increases with increasing polymer and surfactant concentration until it reaches a certain limit at which the drag reducing efficiency reduces.

- This is due to the turbulence that is formed in the media at which degradation of the DRA occurs causing the molecular scission of particles.

- The drag reducing efficiency increases when the polymer and surfactant concentration increases because subsequently there will be an increase in number of molecules to help dampen the small eddies in the turbulent flow.

- With an increase in shear rate, the molecules in the fluid tested with the WLMs will undergo shear thinning, which is a decrease in viscosity and this is a vital criteria for DRA. This viscoelastic property has the ability to enhance the shear

degradation effect when the WLM molecules has to undergo turbulence i.e. pumps.

- Unlike commercial polymers like PAM, after undergoing shear degradation the WLM molecules could still revert back to its original molecular structure due to its viscoelastic properties. This means that WLM is less degradable as compared to PAM.
- PAM could have a reduction in its drag reduction efficiency due to the mechanical degradation of flow, where the physical properties of polymers are deteriorated.

5.2 Recommendations

To further understand and obtain a better result from the experiments, a few recommendations have been made:

- Instead of conducting the experiment using a water flow system, try adding a particular amount of refined oil to demonstrate a multiphase flow. This is crucial as it is more reflective of the industrial use of DRA.
- Towards ensuring the solubility of WLMs, an amount of alcohol and co-surfactant needs to be added into the flow system.
- Perform formation of WLM using other types of surfactants, such as cationic, and non-ionic system.
- Vary the temperature of the fluid flow, to study and demonstrate how the increase in temperature could, at a certain point reduce the DR efficiency of a polymer and WLM due to thermal degradation.
- Take into account the field values such as standard viscosity in a flowing pipe, pipe diameter, flow rate.
- Include also a better graphical representation to show the drag reducing phenomenon using Computational Fluid Dynamics (CFD).

- If possible, show the growth of WLM at the dilute and semidilute region (with clear distinction for the critical micellar concentration) using Dynamic Light Scattering (DLS) or Small-angle neutron scattering (SANS).

5.3 Relevancy to objective

With regards to the listed and explained project activities and key milestones, the author thinks that they are relevant to the objectives. This is because early from the beginning of the research until now, the author has done an intensive study to make sure that the project is fully understood and objectives are being met, and this is done through a lot of discussion with lecturers and postgraduates.

With the main objective being to experimentally study the drag reduction ability of WLM as a DRA, this is currently still in progress, but a couple of actions have been taken to make sure the experiment procedures are accurate and reliable, and that is done through early experiment planning, discussions with Msc students who are experts in rheological properties of WLMs (in EOR), and using PAM as a base result so as not to waste other chemicals.

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