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Drag Reduction Study of Xathan Gum with Polydiallyldimethylammonium Chloride (PDDAC) Solutions in Turbulent Flow

Abstract- The transportation of liquids through pipelines is attributed with high-energy consumption due to the turbulent nature of their transportation. Low concentrations of polymeric additives were proven effective flow enhancing agent when injected into these pipelines due to its viscoelastic property capable of suppressing the turbulent structures; however, the mechanical degradation of polymers is a disadvantage, which can be controlled efficiently by using complex in a surfactant-polymer interface. In this presented work, turbulent drag reduction (DR) efficacy of anionic Xathan gum and nonionic surfactant (PDDAC) regarding the surfactant-polymer interface was studied using a rotating disk apparatus (RDA) technique and pipeline. The effect of surfactant addition, critical concentration of XG, and the dependence of drag reduction on the turbulent strength from the rotation speed were also studied. The critical behavior of the interface was found at XG (700 ppm) and (1000-ppm) concentrations, respectively. The drag reduction (~70%) was observed at critical concentration behavior, which is largely reliant on the alkyl chain in the surfactant molecule. The result of the a rotating disk apparatus (RDA) gave about 51% drag reduction with the Xanthan gum alone while in the pipe, about 58% drag reduction percent (DR%) was obtained. (PDDAC) alone yielded about 32% and 36% drag reduction in the rotating disk apparatus (RDA) and pipe respectively. However, combining the Xanthan gum polymer and Polydiallyldimethylammonium chloride (PDDAC) surfactant gave 62% drag reduction. Thus, it could be inferred that the combination of these duo has greater impact than the individual materials. It could thus be concluded that the complex formed by these materials is another form of drag reducing agents.

Keywords- Drag reduction, Polymer, Rotating Disk apparatus, Turbulent Flow, Complexes

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1. Introduction

It is known that, the addition of minute quantities of polymeric additives have huge impact in improving the liquids flow in pipelines due to its viscoelastic nature and high molecular weight [1], since the discovery of drag reduction phenomenon first to lower the friction pressure losses up to 80% over solvent of polymer solution in pipe flow). Some of these polymers were used successfully as drag reducers in many commercial applications such as crude oil pipeline flow, firefighting, waterborne shipping, water supply and irrigation systems and cooling and heating circulation systems [2-4]. Other possible applications include the improvement of blood flow for treating circulatory diseases [5-6]. Several types of water-soluble polymers are classified as an effective DRA's in a turbulent water flow media such as (PEO), poly (acrylic acid) (PAA) poly (acryl amide), and poly

(ethylene oxide) [3,4], but their drag reduction effectiveness was reclassified depending on their mechanical degradation resistance [5]. On another words, The use of these polymeric Drag Reducing Agents (DRA's) was accompanied with many drawbacks such as the resistance of these long-chained polymers to high shear forces when it interacts with turbulent structures inside the pipelines (eddies) or when it passes through the main high precession pumps. Such high shear force will cause breaking-up the polymer molecules which will lead to lose its drag reduction capabilities. Several solutions suggested by several authors for the polymer shear degradation resistance problem, most of the efforts focuses on changing, modifying and reconstructing the polymer itself in order to give it more firm and shear-resistive structure that can last longer when injected in the pipelines [6, 7]. Energy saving in form of pumping power as an important concept to be noted in frictional losses

reduction, this is as a result of the high volume of fluid to be transported viz a viz cost of transmission, this becomes a crucial issue in the transmission of fluids from one point to another. However, reduction in skin friction in turbulent flows was aided with high molecular polymer additives for more than 60 years before now (Toms) but these polymers degrade over a period of time, especially under shear, this calls for the need for surfactants which are repairable after they have been mechanically degraded. Polymers as well as surfactants micellar structures degrade over critical shear stress, although the surfactant solution are able to self repair after mechanical degradation, moreover, the mechanism surrounding drag reduction is still not well understood, surfactants when added to polymers generates threadlike micelles that are self repairing after they might have degraded, addition of the cationic surfactant leads to greater drag reduction in the presence of organic salts whose ions are capable of binding strongly to the micellar structures formed, thereby yielding an entanglement network even at very low concentration (about 1mM). Other efforts suggested the combination of polymer-surfactants in the form of complexes that can introduce a new integrative structure that have the flexibility and shear resistance in the same time . Generally, complexes are formed through the combination of oppositely charged polymers and surfactants due to the natural tendency of these ingredients to interact [7]. The driving force for the formation of these complexes is provided by the attractive interactions which can be either weak (between nonionic polymers and anionic surfactants) or strong (between oppositely charged polyelectrolytes and surfactants [8,9]. From the drag reduction point of view, the performance of the polymeric DRA's was progressively improved when combined with oppositely charged surfactants. Such success also resulted in some drawbacks due to the limited numbers of the oppositely-charged polymer-surfactant complexes that can be created with an enhanced drag reduction performance. Hydrophobically modified polymers (HMP) played a role in narrowing this gap by activating weak interactive polymer-surfactant complexes [10]. HMP are water soluble polymers with hydrophobic group attached to its back bone Such additional property will increase the spectrum of water soluble polymers that can be used to create an effective polymer-surfactant complex for industrial needs. Drag reduction wise, hydrophobically modified polymeric DRA's (HMP-DRA) were tested by few authors

such as [9]. The complexes are widely used in many industrial applications such as detergency, cosmetics, food, and paints , but its applications in drag reduction is not well explored yet. Most of the research work conducted focuses on the rheological behaviour of the HMP-surfactants complex where several dramatic changes were observed after the formulation of such complexes . Stephen et.al, stated that the viscoelastic surfactants combined with hydrophobically modified polymer are found to be useful for water control operation in oil fields. Polybetaines have found utility as water and brine viscosity enhancer and DRA's. In this research, a new complexes (polymer-surfactant) will be formed using well known polymeric drag reducing agents (Xanthan gum and surfactant Poly diallyl dimethyl ammonium chloride (PDDAC)) .The formed complexes rheological behaviour, drag reduction performance and resistance to high shear forces will be tested. Transmission Electronic Microscopy visualization technique will be used to visualise the possible aggregates that will be formed.

2. Materials and Experimental Procedures

I. Materials

2.0×10^6 g/mol molecular weight Xanthan gum and 400.000 g/mol molecular weight Poly diallyl dimethyl ammonium chloride (PDDAC) were purchased from Sigma Aldrich. It was used without any purification. Its chemical formula is $(C_8H_{16}ClN)_n$. The polymer was used to prepare bulk concentration which was used for the experiment. The sample was left unstirred for another 1 day to equilibrate and relax any form of structure formed due to stirring as well as natural diffusion of the sample. Although there are cases where some required counter ions. Therefore, the counter ions were mixed with such and for those without, they were prepared and mixed the required additives to form a complex mixture.

II. Preparation of Polymer Working Solution

Polymer bulk solutions of 1000ppm was prepared. Required quantity of the dry sample was mixed with tap water by gently sprinkling on the shoulder of a well-developed vortex with the aid of an initially set high speed paddle mixer. On dissolution and a transparent solution, mixing speed was gradually decreased and left for hours for thorough hydration.

III. Transmission Electronic Microscopy (TEM)

The morphology of the formulated complexes are tested using Transmission Electron microscopy

Furthermore, cryo-TEM service was used to test the molecular morphology of certain samples that required further investigation.

3. Experimental Procedures

I. Rotating Disk Apparatus

The concentration of the soluble additives was determined in (ppm) by adopting the weight per weight basis. The stock solution was prepared by dissolving the desired weight of the soluble additives into distilled water and by stirring using a magnetic stirrer for 6 h. In the present study, use will be made of the rotating disk geometry to assess the drag reducing capability of water soluble polymers and surfactants. The rotating disk apparatus used in the current work is the same used and analyzed by Edward, 2014. The schematic representation is denoted by Figure 1. a solution was prepared 1200 mL which is the maximum capacity of the container connected to a holding structure. A rotation shaft connected to servo motor of DS2-20P7-AS model, servo motor rpm range between 50 and a maximum value of 3000 rpm. Also, rotating disk having a radius of about 14cm is constructed the centre of the container which is completely inserted in the liquid. Torque readings from servo motor is used to depict drag reduction and flow resistance performances which is read from a visual system. This readings represent liquid resistance to shear force exerted by the motor. RDA Reynolds number is computed with the formula presented in equation (1).

$$Re = \frac{\rho \times R^2 \times \omega}{\mu} \quad (1)$$

From the equation 1,

Re= Reynolds number (dimensionless)

ρ = density of the fluid, 1000 (kg/m³),

R = radius of the disk, (14 cm)

ω = rotational speed of the disk, (rpm),

μ = viscosity of the fluid = 0.001 n.sec / m² (c.p)

Different concentrations of the polymer XG and the surfactant (PDDAC) 50,100, 200,500,700 and 1000 ppm were prepared from the bulk solution and taken for further test in the RDA where tests to verify their mechanical degradation at various rotational speed of about 50-3000 rpm was carried out. Since these materials were able to withstand the mechanical degradation of the RDA, they were taken for further tests in the pipeline loop to mimick the practice in the petroleum industries .

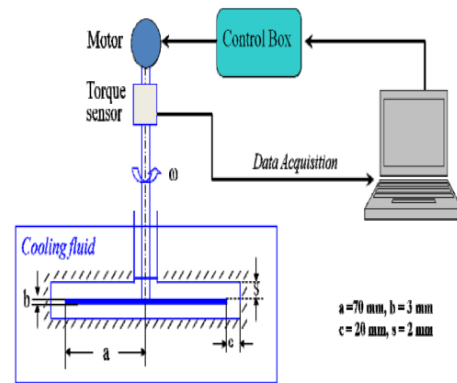


Figure 1: Schematic diagram of the rotating disk apparatus for drag reduction measurement

II. Schematic Pipeline loop

Further investigations were conducted on these additives as individual and as complexes in the pipeline. In which case, both the surfactants and the polymers alone were first investigated and the complex mixtures of the polymers and the surfactant. The schematic of the pipeline loop adopted in the current study is represented with Figure 2. It is made up of reservoir tank, flow meters, pumps, pressure drop sensors/gauges, pipes which were all constructed for maximum flexibility. Readings were taken at four different points measuring at 1m each and transferred to a computer system for further analysis. To prevent materials degradation, the system is short down whenever there is temperature increase. The precision Pump is used to circulate solutions to fro the tanks and the testing testions where readings are taken. With this arrangement, solutions circulated to fro the tank are circulated while the variables such as flow rates, pressure drops are measured and analyzed. Data were taken from different flow rates (6, 5.3, 4.8, 4 and 3.5 m³/ hr) for material concentrations of (50,100,200,500,700 and 1000 ppm), at pipe length 6 m. After the dissolution, materials were poured in the tank and left undisturbed for sometime and then circulated round the tank for a minute before taking data. Such was to allow viscous substances which might have been formed during solution preparation to be fully elongated. The solution circulation round the loop enable data (pressure drops) to be taken at fixed flow rates and it was continued until all flow rates, materials types and concentrations have been investigated. The differential pressure transmitter (DPT-301) of measurement scale up to 6 bar as shown in Figure 2 is used to read the pressure drop across each of the testing parts. In addition to this, Burket 8035 minisonic flow

meter type (FT-301) is also positioned after a meter away from the T-joint which prevents any form of disturbance to the expected fully turbulent flow delivered to the pressure testing sections. All the readings (Either flow rates or the pressure drops) are conveyed online with the help of the custom made interface to the SCADA system specially fabricated for the close loop under current investigation. Such SCADA system helps the user to take the pressure drop and the flow rate readings with time and save it.

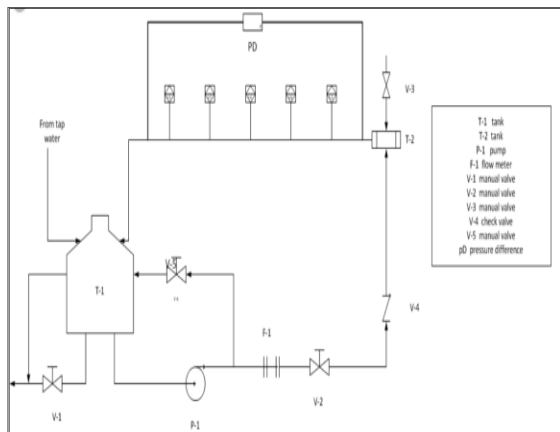


Figure 2:Schematic representation of the pipeline loop

4 . Results and Discussions

I. Transmission Electron Microscopy TEM

The morphology of the formulated polymer–surfactant complexes is tested using Transmission Electron Microscopy TEM and cryo-TEM. In the research work, the polymer–surfactant complexes form whether the main ingredients are oppositely or similarly charged from the results ,it can be observed that similarly charged polymer and surfactant molecules have the ability to form certain aggregates with the aid of the free counter ions in water. Figure 3(a) shows how the XG–(PDDAC) aggregates are connected together at 50–1000 ppm concentrations, where a complete XG molecule network forms, connecting the PDDAC micelles. the picture shows clearly that the (PDDAC) core micelles shrink, becoming barely distinguishable. Figures 3(b) and 3(c) show the images for the (XG–PDDAC) complex. Figure 4 shows image from the 200–1000 ppm(XG–PDDAC) solution. Figure 3 (c) shows image from the 500–1000 ppm (XG– PDDAC) solution. There are observed (XG-PDDAC) aggregates which are formed from such complexes The XG molecules are observed to be connected with those of the (PDDAC) micelles and such

arrangement could be observed in the figures 3(b) and 3(c) show the images for the (XG–PDDAC) complex. Figure 3(b) shows image from the 200–1000 ppm (XG–PDDAC) solution. Figure 3(c) shows image from the 500–1000 ppm (XG– PDDAC) solution. There are observed (XG- PDDAC) aggregates which are formed from such complexes The XG molecules are observed to be connected with those of the (PDDAC) micelles and such arrangement could be observed in the Figures. Figures 3(d) and 3(e) show the TEM pictures of (XG700ppm-1000 PDDAC) ppm and(XG1000ppm-1000PDDAC) complexes. From the pictures, it could be seen that the semi-circular shape surrounding the polymer molecules also connects to other similar molecules and the chain continues until micelles are fully formed in the flow media.

II. Rotational Disk Apparatus Effect of Shear Rate (Rotational Speed)

From this study, the rotating disk apparatus was used RDA to simulate external flows of the samples and to test the extent to which these additives could withstand mechanical stability. In all,one polymer, namely Xanthan Gum of the rigid classification of the polymer was investigated in this present work as well Apart from this,one surfactant:(PDDAC)was as well as investigated. Figure 4 shows the impact of rotational speed on the Torque for the various concentrations of the Xanthan gum. This was conducted to verify the ability of the polymer to withstand shear stress in the RDA.From the Figure, it could be observed that the polymer, irrespective of the concentration, is able to reduce drag. From the Figure, an important observation is that as their rotational speed increased, it also has a direct correlation on the Torque reading. From this, it could be deduced that the material has the ability to reduce drag as well as withstanding mechanical degradation. Apart from such observation, there is also the role of concentration on the polymer, in which case, the drag reduction increases as the concentration of the polymer increases. From these observation, it is a further testimony of the previous studies which have been carried out on Xathan Gum [11-13]. From their studies, the authors attributed the behaviour to the rigid nature of the polymer, thus, this characteristic assist them to withstand degradation,similar observation is what is also reported in this work. From this findings, it indicates the importance of turbulence on DRAs performance in RDA.

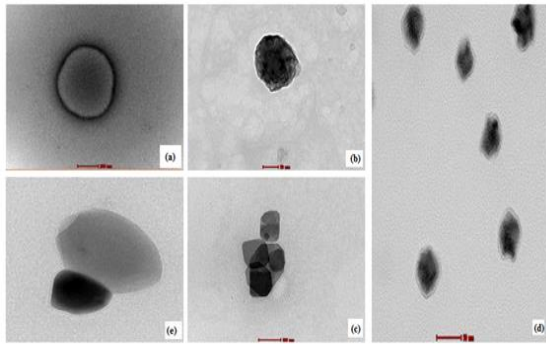


Figure 3: TEM image of the (XG-PDDAC) complex at : (a) (50-1000 ppm),(b)200-1000 ppm , (c) 500-1000 ppm ,(d) 700-1000 ppm , (e) 1000-1000 ppm concentration

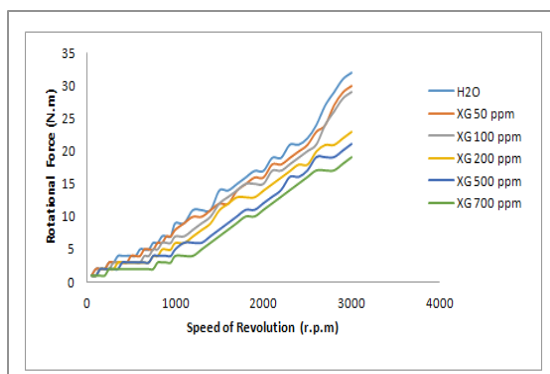


Figure 4: Torque effect at various rotational speed of Xanthan gum at various concentrations

Figure 5 shows the impact of rotational speed on the Torque for the various concentrations of the Xanthan gum. This was conducted to verify the ability of the polymer to withstand shear stress in the RDA. From the Figure, it could be observed that the polymer, irrespective of the concentration, is able to reduce drag. From the Figure, an important observation is that as their rotational speed increased, it also has a direct correlation on the Torque reading. From this, it could be deduced that the material has the ability to reduce drag as well as withstanding mechanical degradation. Apart from such observation, there is also the role of concentration on the polymer, in which case, the drag reduction increases as the concentration of the polymer increases. In contrast to flexible polymers, polymer side chain elongation cannot occur with rigid polymers. Furthermore, rigid polymers are generally noted to be relatively more sturdy and shear-resistant than flexible polymers. From these observation, it is a further testimony of the previous studies which have been carried out on xathan gum [11-13]. From their studies, the authors attributed the behaviour to the rigid nature of the polymer, thus, this characteristic assist them to withstand degradation, similar observation is

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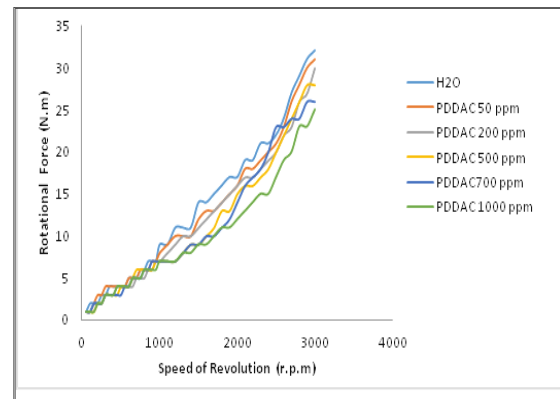


Figure 5: Torque effect at various rotational speed of PDDAC at various concentrations

Similarly, Figure 6 which depicts the result obtained for the (PDDAC) also showed similar trends where there is increase in the torque reading as the concentration of this material increases. Apart from this, there is the possibility to record the energy dissipation with respect to friction by the surfactants as the disk rotates. In the present work, PDDAC surfactant is tested in more tense flow media (rotating disk RDA), where the shear forces are extremely high. Researchers believe that the high shear rate exposed by the RDA disk breaks the polar surfactant aggregates (micelles) that form in the static systems and even in less turbulent flow systems, which contribute to drag reduction. These micelles have the ability to reform after deformation, that is, after the surfactant solution is subjected to very high shear forces. The molecule aggregates are broken, but the aggregates reform and re-gain their drag reduction ability. By contrast, when polymers pass through a high shear force zone (a pump), the polymeric molecules are permanently broken (degraded) . From the results, it could as well be observed that such increase is in favour of corresponding increase in the concentration of the material used. From this observation, it attests to similar observation reported by [11]., that concentration plays an important role in the ability of DRAs to reduce drag. In addition, irrespective of the concentration used here, drag reduction was observed which is a further confirmation by other authors that irrespective of the concentration of surfactants, they are able to reduce drag, however, their performances vary [14]. Figure 6 reports the results obtained for various additives which include both polymer,

surfactants and complex formed from them. This was done to investigate the performance of each against a complex type. From the Figure, there was observed an increasing in the torque as the rotational speed of these materials increase which showed that they are all able to reduce drag.

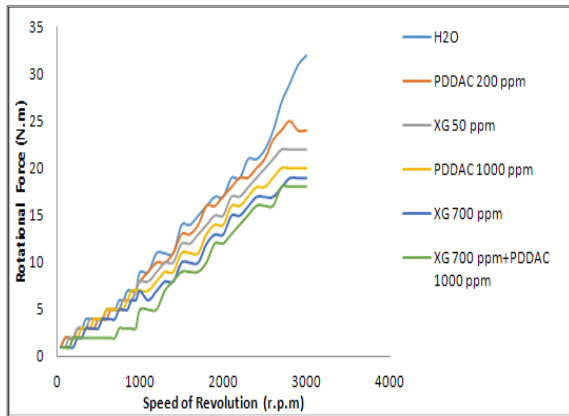


Figure 6: Torque effect at various speed of revolution of the various complex mixtures and individual additives

However, going by what has happened in the Figure, it is clear that the complex performed best compared to every other additives. Interestingly, looking at all the DRAs which were prepared at different concentrations, it was observed that the PDDAC of about 200ppm showed least performance while XG of 50ppm was able to perform better than the PDDAC, this is a confirmation of the report presented by Edward that the Rigid polymers are very effective and only a little concentration has great impact on drag reduction [15]. In addition the XG of about 700ppm was able to reduce drag more than the PDDAC of 1000ppm which further confirms the report by [14]. The mechanical resistance of these polymeric additives is low due to its very high molecular weight and long chain and as such degrades over critical shear stress, surfactants ability of self repairing after degradation resulted into combining these, surfactants when added to polymers generates threadlike micelles that are self repairing after they might have degraded, addition of the surfactant leads to greater drag reduction. However, comparing the XG at 700 ppm to the complex, it could be seen that the complex showed greater performance and this could be as a result of the synergy offered by these individual additives [15,16]. One of the reasons behind the development of complexes is to enhance polymer drag reduction abilities and resistance to mechanical stability.

III. Pipeline Results

Figure 7 depicts the result obtained for the drag reduction of PDDAC in the pipe. In all the trends, it was observed that concentration played important role on drag reduction increase. This is due to the fact that the concentration increase which invariable increased their drag reduction capability. Apart from this,, their mechanical degradation were as well enhanced as the concentration increased. Thus the role of concentration in drag reduction cannot be over emphasized. Apart from this fact, there is any increase in the concentrations of these materials, a direct drastic increase is felt on the solution viscosity, thus decreasing the turbulent strength (reduction of Reynolds number, N_{re}) of these materials. This invariably decreases the frictional drag experienced in the flow system. Apart from this, there is the possibility to record the energy dissipation with respect to friction by the surfactants as the disk rotates. From the readings, it could be observed that these materials are stable against mechanical degradation. Figure 8 on the other hand depicts the drag reduction percent value against Reynolds number for xanthan gum. From the observation in the Figure, it could be seen that the xanthan gum was able to reduce drag. There was an observed drag reduction percent increase with increasing Reynolds number. From such observation it could be further confirmed that the xanthan gum is a good DRA. This behavior in the pipe is an vital indication of turbulence influence on the drag reduction performance of the Xanthan gum. The viscoelastic characteristic of the xanthan gum interact with the eddies (turbulence structures) formed in the main pipe flow system, thereby reducing the drag and invariably reduce the cost and time taken for the fluid to reach its expected destination. Similar observation have as well been reported by various researchers [3-5]. In term of concentration of the additives, it could also been observed that the concentration played important role in the drag reduction by this additive. From the Figure, it could be seen that the higher the concentration of the prepared sample, the better its drag reduction efficacy. Many authors have as well reported similar observation [8,10]. This could be attributed to the available molecules of the additives to reduce the drag.

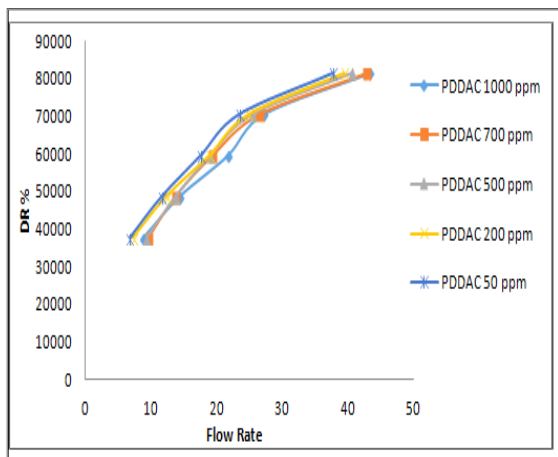


Figure 7: The effects of %Dr against Reynolds number for the different concentrations of PDDAC

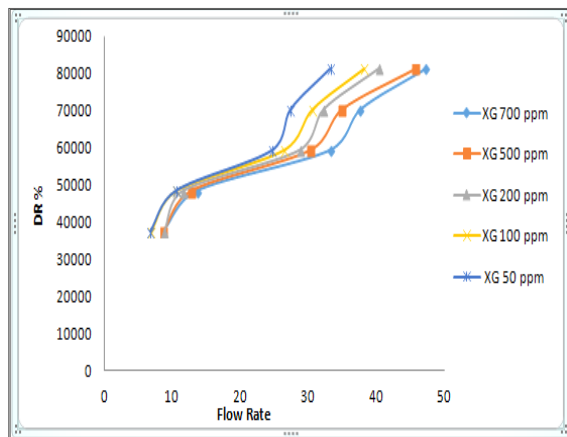


Figure 8: Drag reduction percent against Reynolds number for different concentrations of the polymer alone at section one

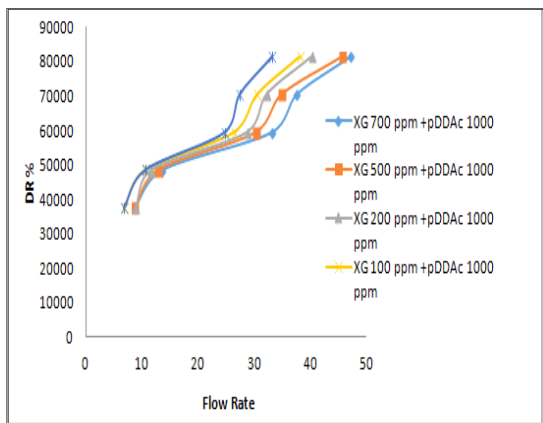


Figure 9: Drag reduction percent against Reynolds number for the complex mixtures of Xanthan gum and PDDAC

Figure 9 illustrates the effects of Reynolds number against drag reduction for various concentration of the polymer with . From the Figure, it could be observed that the materials and all complex concentration showed drag reduction capability with drag reduction increase as the Reynolds number increase. However, the importance of concentration is further observed in

these complexes. From the Figure, the higher the concentration, the better the drag reduction observed for these complexes. Another important observation is that the PDDAC added significant effect to the drag reduction of the additive. In which case, the physical behavior as well as the performance of the complexes were altered with the PDDAC. They also influence the drag reduction effect of the polymer based on the quantity or the concentration present in the fluid media. However, there is observed synergy which exists between these additives whereby there is increase in drag reduction based on concentration of the accompany additive. Such increment may be attributable to the complete change in the apparent physical properties of the formed complex, which introduces a complete shear thickening This shear thickening behavior is expected because the flow is turbulent. This behavior indicate that the complexes formed showed non-linear behavior and flow mode (non-Newtonian) that enable drag reduction performance [17-20]. Figure 10 depicts the drag reduction against Reynolds number for various additives. Over all, the materials illustrated by the Figure all showed drag reduction efficacy. Basically, drag reduction percent for all the Figures increase as the Reynolds number increase. They all show good efficacy for drag reduction. Besides, the degree of turbulence in the Figures is believed to have completely controlled the efficacy of the drag reduction performance through the behavior of these additives. The %Dr ideally starts to increase when the flow is fully turbulent, and the value of Re is more than 4000. This is clearly depicted with the additives in the Figure, however, such behavior is a factor of the type of the additive. Looking at the samples, their drag reduction percent continues to increase as the solution Re increases, until the degree of turbulence (Re) is reached, where the maximum %Dr is achieved at the optimum Reynolds number. A further increase in Re further increases the degree of turbulence, which in most cases lead to a decrease in the values of drag reduction percent. Such behavior could be seen with all the additives except the complex at length one. This observation could be as a result of the strength of the additives until they begin to lose their values as depicted with the other additives. There are many operation parameters which could control the relationship between the degree of turbulence and drag reduction effectiveness of these additives, some of these are pipe length, pipe diameter, solution Re as well as the surface roughness. Because these additives are soluble in water, there is a combined process whereby the

degree of turbulence is increased by the Re increase, this leads to favorable environment where these additives could interact and interfere with the created turbulent structures. Such actions prevents the eddies formed in the system to complete their shape (suppression) and such is opined to have led to the concept of drag reduction [20-23].

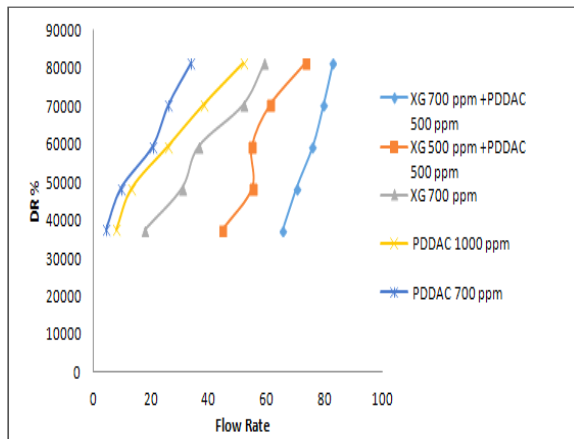


Figure 10: Comparison on the drag reduction percent against Reynolds number for different complex mixtures

5. Conclusion

A new complex for reducing drag reduction has been investigated and confirmed in the present work. It was observed that the complex from each of the additives is able to reduce drag more than their individual. An important variable which played huge role in their performance is concentration. The performance in any complex is only feasible if there is a synergy between the individual additives.

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