Investigating the Drag Reduction Performance of Rigid Polymer–Carbon Nanotubes Complexes

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ABSTRACT

Transporting liquids in commercial Pipeline is very expensive due to cost incurred in the installation of pumping stations. This cost can be reduced by polymeric additives. However, these polymeric additives degrade over time as a result of mechanical stress the fluids are subjected to. Previous efforts to address these problems have not been successful. It is thus inevitable to find alternative means of reducing the frictional drag in fluid flow. In this present work, the experimental study of rigid polymer, Carbon Nanotubes (CNT) Nanofluids and the complex mixtures for drag reduction in a rotating disk apparatus. The finding shows that, about 50% drag reduction was achieved; a comparative study was made on the drag reduction of both complex and nanofluids, where both were able to reduce drag, however at different concentrations. It could thus be concluded that combination of xanthan gum and Carbon nanotubes could reduce drag at a particular concentration

1. INTRODUCTION

Energy cost associated with fluid transportation is one of the greatest problems faced in petroleum industries. As a result of this, pumping stations are positioned at strategic places for a drag free flow of fluids. To reduce such costs, several approaches have been put in place such as the passive, active and interactive methods of drag reduction (Zheng and Yan, 2010). The passive entails modifications of the wall such as, their structures, attack angle adjustments which also consist of some large eddy breakup device (LEBD), Riblets, wavy wall, convex curvature and adverse pressure gradient. The interactive on the other hand involves examining the coherent turbulent structures thereby controlling their turbulent boundary layers with thermal or physical additives in wall surfaces. Examples are wall heating/cooling, wall oscillation and compliant wall. However, these practices are very expensive to achieve and lacked true mimicry in many respects. The last category is the active mechanism which involves the introduction of some materials (additives) into the flow, ranging from solid particle, bubble, surfactant, polymer solutions, nanoparticles or a combination of polymer-surfactants herein referred to as complexes. Previous researches had shown that introducing minute quantity of flexible polymers to turbulent fluid flow, could achieve more than 50% of drag reduction in pipeline (Gry and Bewersdorff, 1995). As a result of this, turbulent drag could be reduced since low pressure drop is achieved at given flow rates (Rozenblit *et al.* 2006) This is achievable by some molecular parameters such as aggression, molecular weight and chain flexibility possessed by these polymers (Rouse, 1953). In spite of series of studies on the use of polymeric additives, the major disadvantage is that, they degrade under the influence of shear of turbulent forces as well as, susceptibility to mechanical and thermal degradation at high shear stress and temperature (Zhang *et al.* 2005) As a result of this, their effectiveness and efficiency is greatly affected. It is therefore inevitable to find materials that could withstand the high shear stresses or temperature. Studies have revealed that many industrial polysaccharides are capable of shear-stability when undergoing such stresses (Kim *et al.* 1985; Deshmukh and Singh, 1986; Chakrabarti *et al.* 1991). These materials have advantages of great mechanical stability against degradation with

respect to other flexible polymer, although susceptible to biological degradation. Their structures are very stable and rigid against any form of mechanical degradation, but altered by salinity and temperature. Increase in temperature, alters their ionic forces which in turns translates the helical configuration to coiled one thereby decreases the Xanthan gum's ability to reduce drag. From this observation, it is expedient to note that, temperature plays an important role in XG structural configuration. To solve the problem of mechanical degradation of polymers, introductions of surfactants have been suggested (Kim *et al*. 2000; Suksamranchit *et al*. 2006; Gasljevic *et al*. 2007; Suksamranchit and Sirivat, 2007). Since their molecules could realign and self-repair after degradation (Zhou *et al*. 2006). Polymer–surfactant complex could improve the duo molecules bonding forces especially ionic binding between ionic polymer and surfactant or hydrophobic bonding between nonionic polymer and surfactant. These complexes have been well investigated, for instance the complex mixtures of ionic poly (acrylic acid) and sodium dodecyl sulfate (SDS) polymer–surfactant interaction was investigated by Kim *et al*. (2011) in a rotating disk apparatus, their turbulent drag reduction (DR) efficiency result reported that, the torque was gradually reduced with tiny quantity of additives at fixed rotational speed, drag reduction efficiency was increased via a conformational structural change. This was observed to increase polymer chain dimensions when the surfactant was introduced. It was concluded that, increase in rotational speed increased the drag reduction irrespective of polymer and surfactant concentration. From this report, both the polymer and surfactant molecular interactions played important role in the study.

Suksamranchit and Sirivat, (2007) also reported that the complex mixtures of water-soluble polymers such as polyethylene oxide (PEO) with cationic surfactants, attaches surfactant micelles to the polymers, resulted into characteristic change in solution viscosity. This was achieved by the increased hydrodynamic volume of the complex. The complex formation thereby enhanced the DR efficacy in different forms such as decreasing a critical polymer molecular weight or the optimum polymer concentration for the DR respectively.

There are synergistic interactions which changed the solution characteristics in this regards expected to have taken place as a result of many factors such as the type of head or polar group of the surfactant embedded in the polymer backbone, polymer hydrophobicity, flexibility (Parathakkatt *et al*. 2009)

According to Shang *et al*. (2008), in such type of complex formations, the surfactants micelles behave as emulsifiers which enhance surface tension control. However, the polymer additives changes solution rheological behavior and aided micelle stability. Stabilizing the micelles already bonded to these polymers is aided by the reduction of interfacial tension between hydrophobic core and water. Also, special interactions in polymer-surfactant head groups as well as reduced

electrostatic repulsion between charged headgroups could be another factor for such (Hormnirun *et al*. 2000)

Apart from surfactants, fibers have also been combined with polymers for similar study since they are not prone to degradation (Paschkewitz *et al*. 2004) Carbon nanotubes (CNT) nanofluids, which have similar characteristics with other additives has been reported used to enhance drag reduction. This is due to the fact that they are less susceptible to degradation as a result of their noticeable physical and chemical features (Salvetat-Delmotte and Rubio, 2002). Furthermore, attempt to use same CNTs for drag reductions in turbulent flows has not been yielded positive results. Liu and Liao, 2010, Ko *et al*. 2007). Such hurdle was conquered with a breakthrough in a recently published article (Adam *et al*. 2014). Drag reduction effect of carbon nanotube (CNT) additives dispersed into water–glycerin pipe flow was investigated with proven enhanced drag reduction reported (Adam *et al*. 2014).

Nevertheless, such an investigation has not been carried out in a rotating disk apparatus. Moreover, drag reduction in flow has not been investigated with rigid polymers. The main objective of present work is to investigate the effects of rigid polymer nanofluid, complex mixtures of CNT-rigid polymers-surfactant and compare their performances on drag reduction in a rotating disk apparatus.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The experimentation in this work were performed using multi-walled CNTs with 20–40 nm diameters and 10-30μm lengths, supplied by Chengdu Organic Chemicals Co. Ltd. China, while Xanthan Gum (XG) with molecular weight, $M_v = 2.0 \times 10^6$ g/mol was purchased from Sigma Aldrich, Malaysia. In spite of the reported molecular weights, the molecular weight was calculated for verification purpose. Data obtained from measured intrinsic viscosity was fitted into Huggins equation as reported by Flory (1971). The obtained values were close to the reported molecular weight by Sigma Aldrich. Solute's contribution to the viscosity (intrinsic, ŋ) has been used to accurately determine the overlap concentrations of flexible polymer using the relationship $c*[\, ŋ\,] = 1$ (Anselmo *et al*. 2013). This could not be used for Xanthan gum, due to the high shear-thinning nature and as such, the method by (Wyatt *et al*. 2011) was adopted. In this study, the maximum polymer concentration used was 105ppm. Since only few ppms were needed for drag reduction in the diluted solutions working liquids. All samples used were in solid form and the required concentrations were made by their gentle dissolution in deionized water as solvent, this was left undisturbed for about 24hours so the polymer molecules could fully exhibit natural diffusion to prevent any form of polymer degradation before the commencement of the experiment

2.1 Polymer Dissolution

Basically, there are two methods which could be adopted to carry out drag reduction experiments using xanthan gum which are the homogenous and pseudo homogenous (Wyatt *et al*. 2011). However, investigations have shown that, the pseudo-homogenous method is more effective, thus, it has been implemented in this work. An appropriate weighted quantity of prehydrated polymer powder, was dissolved in deionized water to obtain concentrated stock polymer solutions. This was further gently magnetically stirred for several days until complete dissolution. The solution was left unstirred for at least 24h thereby relaxed any structure formed during stirring and to allow it to equilibrate. The solutions used in this experiment contained polymer samples in the concentrations of 65, 75, 85, 95 and 105ppms. Measurements were performed at 25- 40 ◦C.

2.2 Nano-Particles Solution Preparation

CNT nanofluids for this present work was prepared using method described by Adam *et al*. (2014) with slight modification. The baseline solution was prepared using 55% wt. glycerin and 45% wt. of water to 60% wt. glycerin and 40% wt. of water in achieving our own desired viscosity of approximately 8.10×10^{-3}. In this work, Xanthan Gum (XG) of $M_v = 2.0 \times 10^6$ g/mol, molecular weight was mixed with the prepared water–glycerin solution and 80 ppm concentration of multi-walled CNTs 20-40nm in diameter, 10-30μm in length, 90% purity and used as supplied by Chengdu Organic Chemicals Co. Ltd. China. Zhang and Lockwood, (2004) established that CNT is hydrophobic, thus they agglomerate or precipitate especially in the absence of dispersant or surfactant. Although many trials and errors on several materials been previously experimented to stabilize CNT. These materials include benzene sulfonate (SDBS), sodium laurate (SL), sodium dodecyl and gum Arabic (GA) (Yulong Ding *et al*. 2006), polyethylene glycol (PEG) dimethacrylate (Heister *et al*. 2012). However, SDBS failed at elevated temperatures (Wen and Ding, 2004). Sodium dodecyl sulfate (SDS) was adopted in this present work, as the dispersant. Other methods that can be used for preparations of nanofluids besides SDS include (a) sonication of CNT sample with known weight in an ultrasonic bath for hours, e.g 24 hours, (b) dispersing the sample in distilled water containing the dispersant material at suspension adjusted to known pH level and (c) treatment with high shear homogenizer for a stipulated period of time: nanofluids in this manner are found very stable for months without visually observable sedimentation (Yulong Ding *et al*. 2006). We have decided to disperse CNT with surfactant. In this present work, thus, sodium dodecyl sulfate (SDS) was adopted as the dispersant and a relatively stable CNT solution was achievable without necessarily undergoing sonication. It was observed that the CNT nanofluid was in suspension for over 18 h without any recurrent mixing.

2.3 Rotating Disk Apparatus (RDA)

The RDA employed in this present work to simulate the external flow consists of a stainless steel solution container of 88 mm high x 165 mm diameter dimensions, covered with 60 mm thick removable lid. The rotating disk is of 148 mm diameter and 3mm thickness. Maximum solution capacity of the cylinder is almost 1200mL. The RDA has a computer operated maximum rotational disk speed up to 3000 rpm and a computer display system which could be used to take Torque value exerted by the fluid, an inbuilt servo motor model from Xin Jie Electronic Co. Ltd. with the servo driver DS2-20P7-AS and motor capacity of 0.75 kW.

Data were taken from the rotating disk apparatus to measure torque at stipulated angular velocity, taking nominal shear stress and mean shear rate as a function of the torque applied and rotor speed within a period of time respectively. Final angular velocity of rotor speed was attained. Samples were measured at different rotational speed ranges from 50 to 3000 rpm at temperature of $25^0C \pm 0.05^0C$. Calculating the percentage drag reduction by:

$$\%DR = \frac{T_s - T_p}{T_s} \times 100 \tag{1}$$

T_s and T_p are required torques before and after additives, respectively. Flow characteristics are represented by the rotational Reynolds number N_{Re} and iscalculated by the formula as follows:

$$N_{Re} = \frac{\rho R^2 \omega}{\mu} \tag{2}$$

Where ρ, μ, R, ω denote fluid density, fluid viscosity, radius of the disk and rotational speed of the disk respectively. Figure 1 represents the schematic representation of the rotating disk apparatus used for the experiment.
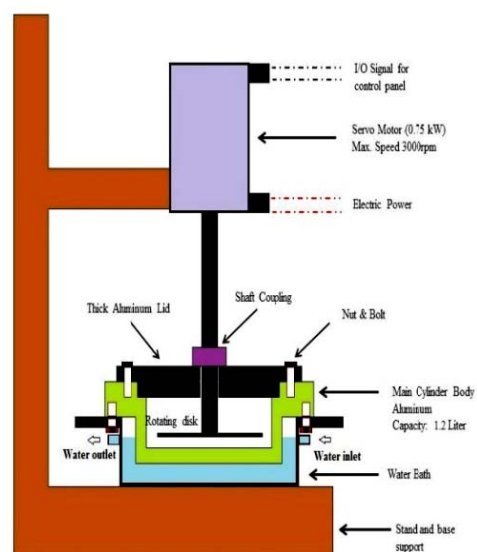

Fig. 1. The test rotating apparatus sketch.

2.4 Sample Interaction Determination

This was obtained by plotting the zero-shear rate viscosity η_o, against the solution concentration, c, this is done to obtain the critical overlap concentration c* of each sample, this is referred to as a point which individual polymer molecules begin to interact with each other (Lapasin and Pricl, 1995). Studies on Xanthan gum critical Concentrations, viscosity scaling and concentration regimes in salt free and salt solutions have been well reported by (Wyatt and Liberatore, 2009, 2010). But the method used in the work to obtained the critical overlap concentration c* of XG as a result of its shear thinning nature was the one by (Wyatt *et al*. 2011)
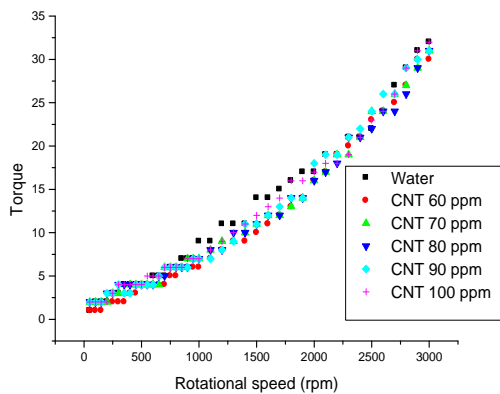

Fig. 2. Influence of Concentration on torque with respect to various rotational speed of CNT.

3. RESULTS AND DISCUSSIONS

Figures 3 and 5 depict the different concentrations of polymers alone and the respective nanofluids from CNT and Xanthan gum, it could be observed that drag reduction efficiency was as a result of their respective concentrations, It could be observed in both polymer and the nanofluids that, increase in the concentrations of the materials in any of these materials have direct correlation on their drag reduction ability, which were observed to increase. From this trend, one could say that, concentration of these materials played an important role in their ability to reduce drag irrespective of the quantity introduced. From Figure 3, at the point very close to the c* of XG, noticeable DR was observed, this is the point where the polymers effect started to be felt, this is similar to the observation of (Wyatt *et al*. 2011). Who reported significant increase in drag reduction effectiveness near this point, in a similar study, it has as well been observed by (Wyatt and Liberatore, 2009) showing similar trend at zero shear rate viscosity near this point increasing by a factor approximately five at concentration range around 15 ppm**.** From this observation, the influence of concentration on drag reduction cannot be over emphasized as believed to be a function of the concentration. Increase in concentration determines the percentage of drag reduction achievable
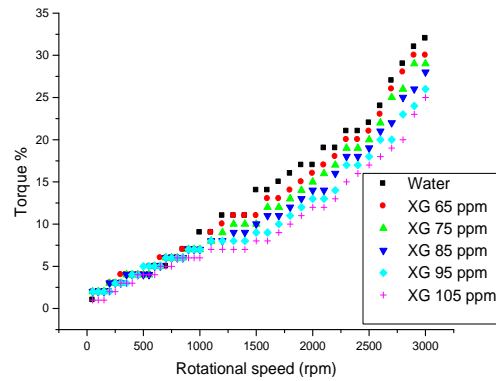

Fig. 3. Influence of Concentration on Torque with respect to various rotational speed of XG.

3.1 Drag Reduction of Materials Studied

Drag reduction in RDA is related to total drag reduction in that, it is drag in its wholly form i.e friction plus any other form of drag, unlike in pipes which measures only internal flow and as such, related only to frictional drag. Due to this fact, a maximum of 80% of the drag reduction could be obtainable in pipe flow, but only approximately 50% in a RDA at maximum

3.1.1 Drag Reduction of Carbon Nanotubes (CNT) Alone

It is however an interesting observation in this present work, to realize that, despite the impact of CNT on the Xanthan gum and nanofluids which enhanced their drag reduction ability as well as mechanical degradation, these CNTs in their pure forms do not reduce drag, different concentrations were prepared and run through the rotating disk apparatus, nevertheless, none of these were able to reduce drag and it is efficiently shown in Figure 2. From this figures, one could notice that, when the water is tested in the RDA, it has same effect like these CNT concentration and this is to say, the CNT on their own cannot reduce drag, but only in combined form with other materials. Ordinarily, the best concentration to reduce drag should have been selected to be combined with the Xanthan gum or to prepare the nanofluids as the case may be, but, after much trial and errors on the best concentration to be used, 80 ppm concentration yielded the best result in the complex, thus, we have only reported such in this work as could be observed in Figure 4.

3.1.2 Drag reduction of XG Alone

Figure 3 clearly shows the different concentration of Xanthan gum prepared and tested for drag reduction, relating their performance to water, since these polymers were dissolved in water, the drag reduction ability of xanthan gum was confirmed, irrespective of the concentration prepared, they were found to reduce drag even at their smallest quantity. It could clearly been observed that increase in the toque has a direct correlation to the rotational speed but their drag reduction when compared with water, it was observed that, they are able to reduce drag compared to the effect on water,

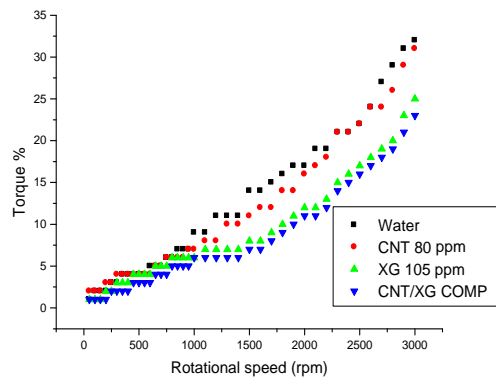water was used here as the standard because these polymers were dissolved in it.

Fig. 4. Influence of concentration on torque with respect to various rotational speed of CNT, XG and XG-CNT complex system.

Although it is not a new thing to prove the drag reducing ability of polymers, they have been well studied in different forms and it has been proven beyond reasonable doubt that, they are able to reduce drag, they have been tested with respect to concentration with proven fact that drag reduction is enhanced with increased concentration, same is with time, molecular weight etc. When the drag reduction efficiency of Rigid polymers, especially xanthan gum was investigated, it has been observed that, they are as well able to reduce drag with reported maximum drag reduction of about 33% (Sohn *et al.* 2001; Kim *et al.* 1998; Den Toonder *et al.* 1997; Bewersdorff and Berman, 1988; Escudier *et al.* 1999; Brostow *et al.*1990; Ching *et al.* 2006). The most important postulations on these studies are, drag reduction increases when Xanthan gum concentration increased. Also, studies in their dilute and entangled form has as well been reported by (Wyatt *et al.* 2011), on the effects of salt addition which affects their conformation by (Wyatt and Liberatore, 2009). Drag reduction increased with Xanthan concentration and It has as well been reported that, the required concentration for maximum drag reduction decreases as molecular weight increased (Sohn *et al.* 2001), thus, molecular structure is an important criteria considered here (Kim *et al.* 1998) as well as Drag reduction is influenced by chain flexibility (Bewersdorff and Berman, 1988). From all these, it is evident that XG has ability to reduce drag, nevertheless to confirm this, result of the drag reduction test carried out on XG and represented by Figure 3 which shows and supports the above studies, nevertheless, this is not the main purpose of this study, thus, further investigations are needed to be carried out when these materials are combined with other materials to fulfill the purpose of carrying out these investigations.

3.1.3   Drag   Reduction   of   XG-CNT Complex.

The complex mixture system of Xanthan gum (XG) and Carbon nanotubes (CNT) was represented by Figure 4, from this, it was observed that the drag

reduction of both polymer alone and the complex mixture was verified and the complex system has better drag reduction efficacy, from the figure, at the lower rotational speed, there was no much drag reduction effects, until the 1000rpm, at this point, there is constant drag reduction effects after which it abruptly ascended at about 1500rpm, this could be the point whereby the XG-CNT inhomogeneous extensional synergistic viscosity takes place. Over the years, Complex mixtures (combination of polymer with surfactants) have been used to reduce drag, where their drag reductions have been confirmed (Kim *et al.* 2000; Suksamranchit *et al.* 2006; Gasljevic *et al.* 2007; Suksamranchit and Sirivat, 2007). Nevertheless, there are no available literatures to investigate these rigid polymers with carbon nanotubes, although studies have been conducted with other fiber materials, and this has necessitated this study, in this present work, the drag reduction ability of complex mixtures of XG and CNT was investigated, one of the concentrations prepared for CNT was combined with the highest concentration of the XG, as this combination gave the best drag reduction enhancement, this complex mixture was able to reduce drag with a decrease in the percentage torque which is in direct correlation an observed increase in concentration and the rotational speed. This is clearly depicted in the figure 4 below, from this observation, it could be opined that, combination of these materials are able to reduce drag.

It is however amazing in this complex mixture, that a synergetic behavior was observed in the drag reduction between the xanthan gum and the carbon nanotubes (CNT), whereby they were able to reduce drag effectively, one of the most important characteristic which had resulted into this could be the viscous nature as well as the random coil size of the xanthan gum molecules which has great effect and had enhanced the rigidity of the complex system. Thus, combination of these individual materials yielded better linearly additive effect in drag reduction unlike the polymer molecules alone.

3.1.4   Drag reduction of Nanofluid

Figure 5 shows the nanofluid prepared at various concentration of the CNT and polymers, different fractions were studied for different concentrations in the RDA, with Torque % as a function of rotational speed (rpm), decrease in Torque % DR was observed, which is in direct correlation with increasing concentration and the rotational speed, from this observation, it was observed that, these material have ability to reduce drag when compared to the water alone.

It was observed that, the presence of low concentration of the CNT in the nanofluid exhibits same characteristic as the water alone, one major factor that could have resulted into this is the ability of these particles not to smoothen the disk wall, it was however observed that, with the increase of CNT concentration in similar nanofluid prepared at different concentration, drag reduction was effective likely attributed to reasonable percentage

of such materials, available to smoothen the disk surface, this similar observation was reported by (Pouranfard *et al.* 2014), although it was conducted in pipe with silica nanoparticle, notwithstanding, this is the first time such is reported with RDA. From this observation, it could be believed that the main function performed of these materials are surface modification because of their nature, by so doing, the drag, frictional factor, mechanical degradation of the host material is thereby reduced. In like manner, incomplete dispersion of CNT in the polymer could have been another reason for this, since the particles are rigid and tend to aggregate. This behaviour might have resulted in their inability to reduce drag alone as reported above, but they interact with the polymer to yield structures that withstand their mechanical or biological degradation over a stipulated time interval but in so doing, slight flexibility is enhanced, this same attribute is reported with the work of Adam Steele *et al.* (2014) in pipe with flexible polymer, but the first reported on rigid polymer and RDA.
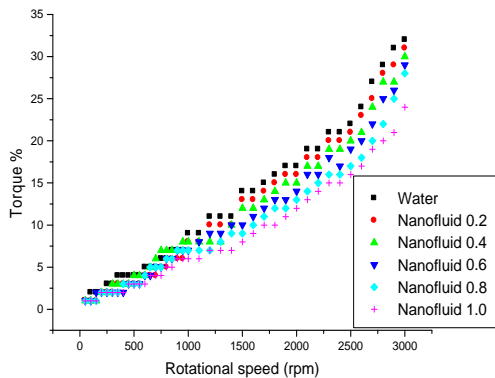

Fig. 5. Influence of concentration on torque with respect to various rotational speed for various nanofluids investigated.

3.1.5 Comparing the Complex with Nanofluids.

Comparing complex mixtures of polymer-CNT and their nanofluid drag reduction efficacy, it was observed that, the dual nature of these materials were able to reduce drag, nevertheless, there is noticeable difference in the concentrations at each individual reduce drag, although very close, nanofluid drag reduction enhancement is augmented with increased concentration of XG.

It was realized that both were able to reduce drag, infact, the concentrations at which both materials were mixed and reduce drag were very close, from this finding, it is evident that, there is a concentration through which these materials could reduce drag. It is evident from figure 5 that drag reduction increases with increased concentration of nanofluids, irrespective of the nanofluids tested, they were able to reduce drag, nevertheless, there was a critical point through which their effects were less and it has no further influence on the DR as all yielded no observable impact.

While Considering the dependence of the complex

on time and the effects of CNT on the polymer used, it was realized that DR does not relate exclusively to molecular degradation, in that, time taken for the polymer alone and that of the complex mixture before breaking down was different, upon deformation, their rearrangement as well exhibit similar trend, although (Dimitropoulos *et al.* 2005) suggested that, it takes a period of time for turbulent structures rearrangement after such deformation, as such DR ultimate level is not achieved by DR immediately, therefore making DR a complicated function with respect to time.

Another noticeable action by the CNT on the polymer is that, it makes their network stiffer since individual chains expands between entanglements, knowing fully that DR is at best effective with long chain, flexible polymers (Kim *et al.* 1998), CNT present could have modified their structure which also has positive impact on their drag reduction ability.

Synergistic interactions between the polymer and the carbon nanotube was observed, this is observed in the figure 4 whereby the degree of the CNT composition in the mixture exhibited different drag reduction behavior, this is also determined by the rotational speed of the RDA. When the concentration impact of the CNT is less as a result of rotational speed, the complex and nanofluid behave as single phase systems.

3.1.6 Molecular Degradation

Figures 6 and 7 clearly depict the molecular degradation of the polymer and nanofluids whereby increased Reynolds number at higher turbulent flow led to such degradation, but with the addition of CNT, the time taken for such degradation was increased, this testifies to the effect of CNT in this mixtures, it could thus be opined that, CNT has ability to enhance the mechanical degradation of rigid polymers.

It is a known fact that XG is one of the most important industrial biodegradable polyelectrolytes whose conformation greatly depends on both temperature and ionic strength, when the ionic strength and temperature are high, its solution behaves as disordered coil often re ordered on cooling or when salt is added. This ordered structure has been reportedly involving two chains [Sato *et al.* 1984].

Analyzing the concept of drag reduction with a universally acceptable theory on molecular degradation of DRAs would be a difficult one, many interdisciplinary relationships between chemistry and fluid mechanics are parts of the major factor contributing to such, different works have been reported in this respect with respect to molecular weight, concentration, temperature and Reynolds number on drag reduction effectiveness, some of these are (Nakano and Minoura, 1975; Rho *et al.* 1996; Pereira and Soares, 2012).

3.1.7 Effect of Nanofluid Concentration, Reynold number on Drag reduction

Reynolds number (N_{Re}), mostly attributed to the

ratio of inertial forces to friction (viscous) forces in a pipeline flow. The increase in the RDA rotational speed (Figure 6) influenced the flow characteristic hence increase in the Reynold Number is observed. The maximum drag reduction of ~ 50% was observed at Nanofluid of about 0.6 concentrations. The critical Reynold Number was found to be 4.92 x 10^6, which is analogous to a rotation speed of 2200 rpm in our RDA system.
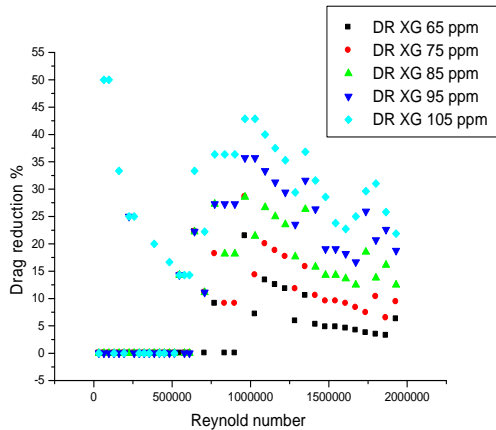

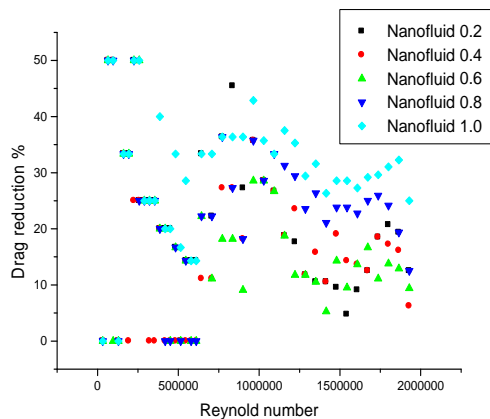**Fig. 6. Drag Reduction percent of Xanthan Gum at various concentrations.**

Fig. 7. Drag Reduction percent of nanofluid at various concentrations.

It is believed that, the controlling drag reduction mechanism in the present work is highly related to the interaction between the soluble additives and the coherent structures forming the turbulence inside the pipe. The soluble additives will be part of the eddies forming the turbulence and that will change the apparent physical properties of the eddy itself by introducing additional properties like the high viscoelasticity. This will result in suppressing the turbulent structures formed and reducing the amount of power needed to complete the shape of the eddies itself. The presence of CNT will enhance the soluble additives (polymers) resistance to high shear forces performed by the turbulent structures which will result in reducing the polymer degradation possibility and enhancing the drag reduction performance of the proposed polymer.

4. CONCLUSION

It is evident from our study that the complex mixture formed from Carbon nanotubes and xanthan gum was able to reduce drag. The process of their drag reduction could however be attributed to the axial movement of fluid around the fibre particles when being subjected to the polymer molecules which mitigate extensional deformations. This phenomenon often leads to stretching and shearing in the process which influenced the extensional viscosity making the system stable; hence drag reduction effect is felt.

The presence of the CNTs which enhanced the polymer tendency to resist elongational deformation could have initiated the complex mixtures to performed better. However, this is not often the case when the polymer is alone which makes it less resistant to mechanical degradation. As a result of that, it leads to reduced radial momentum transport which triggered the nonlinear synergistic behavior.

Consequently, it could be assumed that, pronounced synergism initiated by the cumulative effect of molecular and mechanistic processes of the CNT-XG complex systems in water contributed to enhanced drag reduction. From such complex system, increase in the concentration of the CNT, resulted into two phases behavior until shearing takes place. However, this behavior is not same at low concentration.

Although it has been widely reported that the complex formation of polymers-surfactant is by micellar formation, but it is rather not the same with the rigid polymer and the CNT. From this study, this complex formation could be regarded as XG-CNT inhomogeneous extensional synergistic viscosity, where:

1. Drag reduction mechanism by CNT was the surface modification by fiber nanotubes owing to their contact with disk surfaces.

2. The proportion of drag reduction with complex is almost same with the nanofluids, from this, it could be said that, there is a required quantity and concentrations through which these materials could reduce drag in a combined form.

3. For Drag reduction to be effective, proper concentrations of materials should be mixed with a specific concentration of surfactant, before or after which the drag reduction is not at the maximum level.

4. To withstand the mechanical degradation posed by the turbulent form in which the Rotating disk apparatus is operated, CNT could play a key role.

5. ACKNOWLEDGEMENTS

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