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Drag Reduction Efficacy of CTABr and Nanosilica Particles Using Rotating Disk Apparatus (RDA)

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ABSTRACT

Over the years, it has been proven an energy consuming and cost effective to transport fluid in pipe, efforts that have been made to investigate this have not yielded a consensus on the mechanism and principles behind such, polymers that have been used degrade and less effective over time, surfactant which are self repair are not as effective as the polymer, recent studies on this concept with other solid particles have majorly been concentrated in pipe, this work investigated the drag reduction efficacy of silica nanoparticle with cationic surfactant, CTABr in a rotating disk apparatus, it was observed that, these material can reduce drag by 50% and are mechanically stable after degradation. Before drag could be reduced with these materials, proper proportions on the materials should be selected.

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INTRODUCTION

The concept of drag reduction is not a new one as far back as the days of Toms (1948). Nevertheless, it is almost exhaustible due to many works that have been carried out on it, many attempts have been made to postulate theories on why drag reduction takes place, and others, on the potential applications, see Manfield *et al* (1999). Reports have shown that polymer could be used to reduce drag even at the smallest quantity usually in ppms, Kulicke *et al* (1989), Virk (1970), Rose and Foster (1989) and Berman (1978). On this note, many efforts have been made to study the working principle of these materials Lumley (1969, 1973, 1997), Virk (1975) and Hlavacek *et al* (1976).

Despite these theories and postulations, yet, there is yet to be any reasonable conclusions on the main reasons while these materials reduce drag, another important point to note here is that, these polymers break down after a period of time, referred to as mechanical or thermal degradation, which occur as a result of the high shear systems associated with turbulence at which they are exposed, Pereira *et al* (2013). When this takes place, the working efficiency of these materials are reduce, Vanapalli (2005)

In like manner, another group of materials which have the ability to reduce drag and have as well been widely investigated are the surfactants, which have advantage over the polymers, which could withstand such degradation, some of the review papers on surfactants as DRAs have been published, Shenoy (1984), Gyr and Bewersdorff (1995), Zakin *et al*. (1998).

These materials are able to realign or reassemble and self repair after mechanical degradation through the formation of micelles, this has been well reported by the review papers of White and Mungal (2008), Graham (2004), Hellsten (2002) and Zakin and Ge (2010).

As a result of this attributes, they have been individually studied Ohlendorf *et al* (1986), Lu *et al* (1998), Myska and Stern (1998), Gasljevic *et al* (2007) and Qi *et al* (2011) and in combined form with polymers, referred to as complexes, Suksamranchit *et al* (2006), Anthony and Zana (1994), Mya *et al* (2000, 2001, 2003). When in complex mixtures with polymers, they could modify the properties of these polymer after mechanical degradation. Other DRAs that have been studied are solid particles, such as wood pulp fibers, Lee and

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Duffy (1976), bubbles,Van Gils *et al* (2013) rigid polymer, Japper-Jaafar *et al* (2009).

These DRAs have been proven less effective in drag reduction as their working principle are as well believed to of different physical working mechanisms, in addition non-polymeric additives susceptibility to degradation are more less than polymers, Liu and Lao (2010). Another interesting mechanism which have proven evidence is the combination of fibers and polymers which could result into more significant drag reduction and less prone to degradation than polymers alone Paschkewitz *et al* (2004). These could as well be used to form nanofluid. But less studies have been focused on nanofluid as a drag reducing mechanism, although in recent study, successful efforts have been made in this regards with nanoparticles, Pouranfard *et al* (2014) and CNT, Adam *et al*, 2014.

Neverthess, these were concentrated in pipeline flow system and none has been studied in a rotating disk apparatus. Nanofluid suspensions have great tribological properties effects on drag reduction and few of these studies have been conducted with different nanoparticles, there are missing popular results to give general correlations on the concept. When nanoparticles are introduced into base fluid, effective anti-wear and friction reduction are inevitable, studies on nanotribology also reports that few of these nanoparticles, such as nano-SiO2 are unique anti-wear, high load capability, friction reduction in tribology and lubrication and tribology as well as reduces pressure drop of fluids in pipe flows, Liu *et al* (2010), Liou and Lin (2012), Sun *et al* (2008), Garbacz *et al* (2007), Radice and Mischler (2006), Ma *et al* (2009), Hu *et al* (2009), Li and Zhu (2003), Liu (2003), Wu *et al* (2007) and Goto and Honda (2004)

In this present work, we investigate, for the first time, drag reduction efficacy and the mechanical degradation of Silica nanoparticle (nano-SiO_2), hexadecyltrimethylammonium bromide (CTABr) Complex mixture with Silica nanoparticle (nano-SiO_2), and compared the result with the drag reduction performances of their Nanofluid in a rotating disk apparatus.

MATERIALS AND METHODS

Experimental Procedure:

All investigations reported in this present work were performed with silica nanoparticle of 20–30 nm at density of 2.4 g/ cm^3 but the specific surface area (SSA) was 180–600 m2/g, hexadecyltrimethylammonium bromide (CTABr), Sodium salicylate (NaSal) purchased from Sigma Aldrich, Malaysia. In this study, the maximum surfactant concentration used was 700ppm, since only few ppms was needed for drag reduction and thus suggests diluted solutions working liquids. All samples supplied in solid form and the needed concentrations were prepared on their gentle dissolution in deionized water as solvent.

Surfactant-Counterion Preparation:

Surfactant used in the course of this experimental work was hexadecyl trimethyl ammonium bromide (CTABr, molecular weight 364 kg $kmol^{-1}$) and sodium salicylate (NaSal; molecular weight 160 kg $kmol^{-1}$), the surfactant–counterion solutions were prepared when accurate measured quantities of both were well dissolved in deionzed water of about 5.07 kg) coupled with 15 min mechanically stirred process for thorough dissolution and homogenization of the samples. On testing, different surfactant–counterion solution concentrations of samples which are highlighted by the Table 1.

Table 1: Surfactant–counterion solution concentrations

Samples	A	B	C	D	E
Materials					
HTABr(g)	0.256	0.512	1.008	2.007	4.004
(ppm)	50	100	200	400	700
(mmolL^{-}1)	0.139	0.277	0.546	1.09	2.08
NaSal (g)	0.257	0.514	1.008	2.004	4.002
(ppm)	100	100	200	400	700
(mmolL^{-}1)	0.317	0.634	1.24	2.47	4.74

From the available data, concentrations of aqueous solutions of surfactant and salt were found to be 0.14Mm (50ppm), 0.27mM (100 ppm), 0.54mM (200 ppm), 1.09mM (400 ppm) and 2.08mM (700 ppm) of HTABr respectively while 0.31Mm (50 ppm), and 0.62mM (100 ppm) or 1.24mM (200 ppm), 2.47 (400) and 4.74 (700) of NaSal respectively. The viscosities of 50ppm, 100ppm, 200ppm, 400ppm and 700ppm solutions of HTABr and NaSal were initially taken followed by the rheological measurements of HTABr–NaSal mixtures, this was carried out thrice for every samples by leaving the samples for a period of 1:30 minutes and re measured after each viscosity measurement.

Complex Mixture of Surfactant-Nanoparticle Preparation:

The conventional method for dispersing nanoparticles in water coupled with its oscillation in water was undertaken to prepare the complex mixture, each of the silica nanoparticles that has been previously tested alone was mixed with the best surfactant concentration that exhibited the maximum drag reduction and 100, 200, 500, 700, 1000ppm of complex mixtures were prepared from it respectively, it was followed with dispersing the nanosilica into deionized water, oscillating the suspension in an ultrasonic bath for 24 h. Although, the complex was able to reduce drag for a week, after which sedimentation was observed. To be effective for a longer period of time, A coupling agent, Silane to surface-functionalize the nanoparticle was prepared at mass ratio of silane to nano particle of 0.110. After the preparation, same was maintained at room temperature for 24h, and this was able to disperse well for months without any noticeable sedimentation.

Nanofluid Preparation:

Nanofluid used in this present study was prepared from distilled water (DW) and nanosilica particles, particle size of the nanoparticle used was 20–30 nm at density of 2.4 g/ cm^3 but the specific surface area (SSA) was 180–600 m^2/g. Since surfactant is to be used for the dispersion, the surfactant was first dissolved into the base liquid at the rate of 0.5 wt% with the aid of magnetic stirrer, then mixed with the solid nanoparticles to make well-dispersed homogenous suspensions by continuous stirring with magnetic stirrer and further sonicated with 9 W of 30 kHz ultrasonic processor for a period of 24h. Producing nanofluid at ranges of 0.2-1.0 wt % nanoparticle concentrations.

Rheological Tests:

Verification of sample viscosity and rheological tests were all carried out at various rotational speeds using Brookfield DV–III Ultra Programmable Rheometer made up of 12.1 cm height testing container and inner diameter of 8.25cm. The equipment was equipped with a temperature controllable water bath with a constant operating condition of 25^{o}C ±0.05^{o}C in temperature. The spindle rotational speed is altered from 20-200 rpm respectively. From the nature of the materials tested, they were Newtonian mixtures, thereby easy to measure directly. All measured values were compared with values taken from the capillary viscometer and quite good conforms to calculated values. Low concentrations were not shear-thinning, but at higher concentrations, such was observed. The samples, originally prepared at various concentrations, the apparent viscometer of the mixtures were investigated, data were taken. The coaxial cylinder rotational viscometer which could be operated at varied shear stress with cylindrical spindle and a housing tube for the spindle, materials were put annular space between the spindle and the tube, different rpms were entered and corresponding shear rates and shear stresses were taken respectively.

Rotating Disk Apparatus (RDA):

External flow simulation and all other investigations were carried out in a Rotating Disk Apparatus (RDA). A schematic diagram of the RDA is shown in Fig. 1, comprises of a stainless steel solution container in dimensions (88 mm high /165 mm diameter), covered with 60 mm removable lid thickness. The disk thickness and diameters are 3mm and 148mm respectively. The cylinder has a maximum solution capacity of about 1200mL. It is coupled with a digital computer maximum operated rotational disk speed of 3000 rpm, a computer display system for recording the Torque value exerted by the fluid of inbuilt servo motor model from Xin Jie Electronic Co. Ltd. with the servo driver DS2-20P7-AS, where the motor capacity is 0.75 kW.

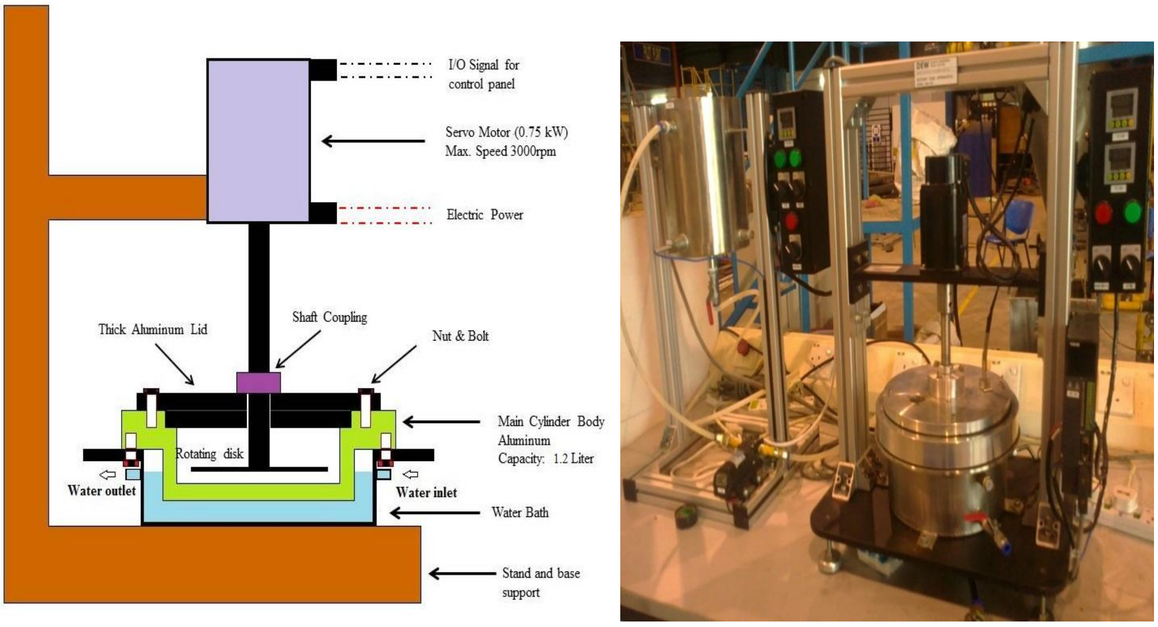
Data were taken from the rotating disk apparatus to measure torque at stipulated angular velocity, taking nominal shear stress and mean shear rate determined as a function of the torque applied and rotor speed and within a period of time respectively. Final angular velocity of rotor speed was attained, thus, calculating the fanning factor. Samples were measured at different rotational speed ranges from 50 to 3000 rpm of each sample as well as the complex mixture at temperature of 25^{0}C ±0.05^{0}C. Calculating the percentage drag reduction by:

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

T_s and T_p are required torques before and after additive addition, respectively. Flow characteristics are represent by the rotational Reynolds number N_{Re} and is calculated by the formula as follows:

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

Where ρ, μ, R, ω denote fluid density, fluid viscosity, radius of the disk and rotational speed of the disk respectively. All of the experiments in this study were performed at a different rotational speed from 50 rpm to 3000 rpm.



a **b**

Fig. 1: The test rotating apparatus sketch (a), The test rotating apparatus real system (b)

RESULTS AND DISCUSSIONS

Drag Reduction Studies:

Drag reduction studies of surfactants alone could be used to investigate the stability (Thermal or mechanical degradation) of this material when in solutions in a turbulent flow. Nevertheless, when this material was mixed with nano-sio$_2$, it enhances the mechanical stability of the material. These materials were prepared at different concentrations in water solution, with Torque % as a function of rotational speed (Figures 2, 3, 4 and 5 depict the drag reduction of the nanoparticle, surfactant, surfactant-nano-sio$_2$ and their nanofluid), respectively. A decrease in Torque % DR was observed, which is in direct correlation with increasing concentration and the rotational speed. There was no observed drag reduction with the particles alone, but the surfactant exhibit better drag reduction efficacy, when the surfactant was mixed with the particle and tested at various concentrations, the best concentration was 200ppm, before and after which drag reduction was less.

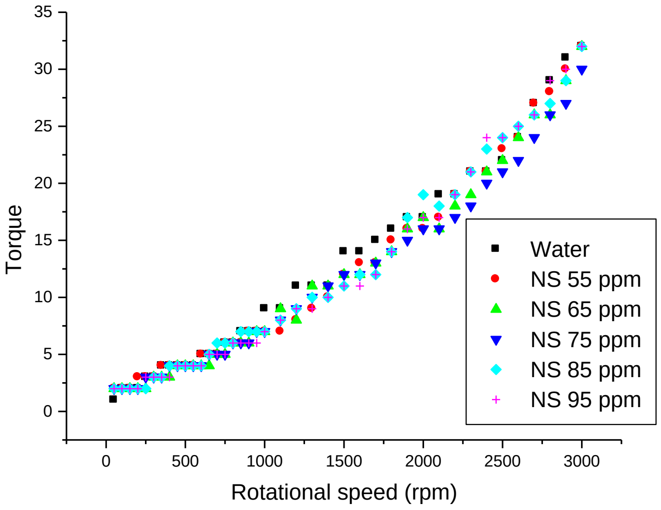


Fig. 2: Different concentrations of Nanosilica particles at various rotational speed

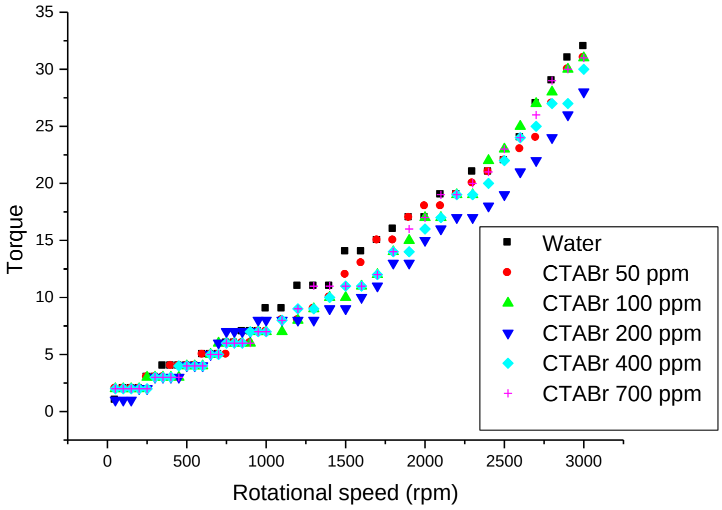


Fig. 3: Different concentrations of CTABr at various rotational speed

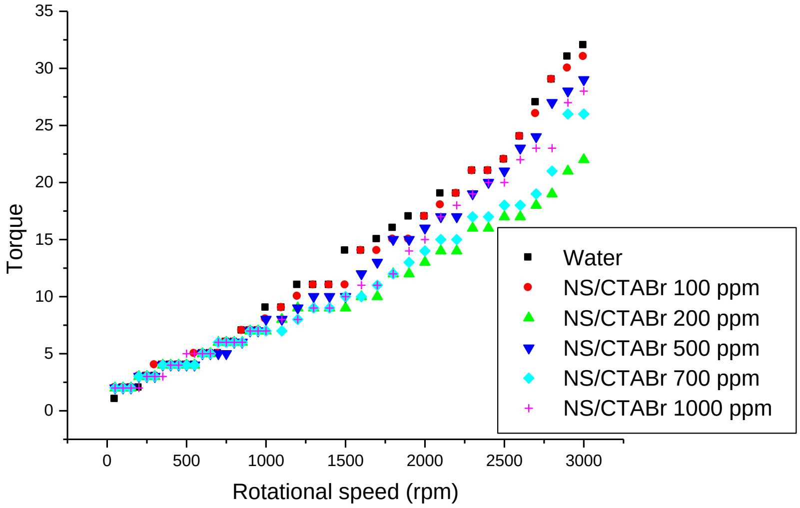


Fig. 4: Complex mixtures of NS/CTABr at various concentrations

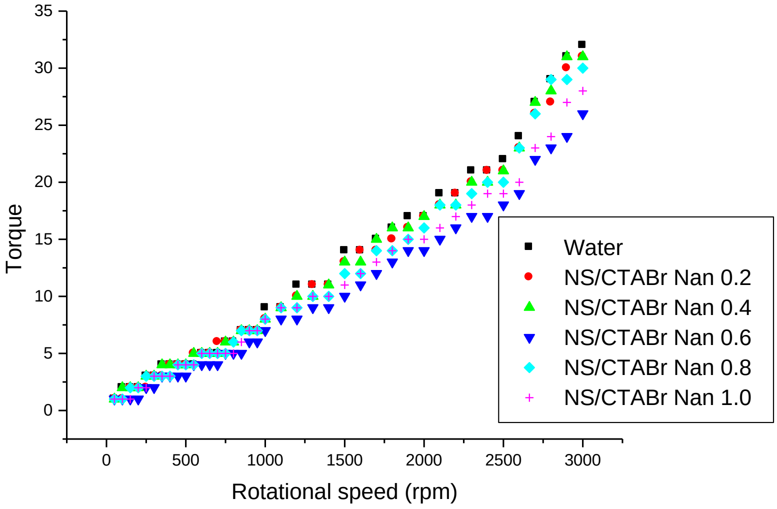


Fig. 5: Nanofluid of NS/CTABr at various Concentrations

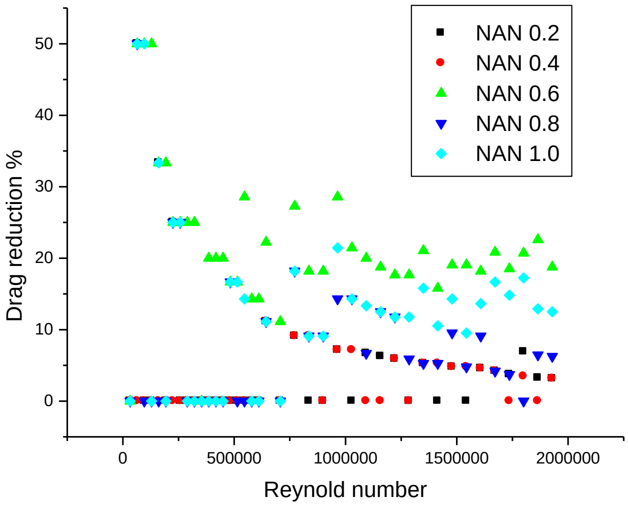


Fig. 6: Drag reduction of various Nanofluids with respect to Reynolds number

Drag Reduction of Solid Particles:

Although, wood fiber has been used to study drag reduction, Lee and Duffy (2007) as well fibers in combination with polymers, Paschkewitz *et al* (2004)**.** Nevertheless, the nano-SiO2 used alone to test the drag reduction in turbulent flow, in this study were unable to reduce drag, according to the study, they exhibit similar character with the water and this could be seen from the figure 2, This was verified by preparing different concentrations of these materials and testing their drag reduction capability, where all results yielded no drag reduction of the system. In contrast, when these materials were used in combine form with the surfactant, they were able to reduce the drag, yielding a maximum drag reduction of about 50%, this could have resulted from the impact of the surfactant in this complex mixture. From this observation, it could be deduced that, these particles could augment the drag reducing ability of the surfactant. Another interesting fact is that, they enhanced the mechanical degradation on the surfactant; although, surfactants in their original nature are self repair after degradation, nevertheless, when investigation was carried out on the surfactant alone and in combine for with these particles, it takes longer time before degradation. This could have been as a result of the special attribute exhibited by these particles on the surfactant as reported by Liu *et al* (2010), Liou and Lin (2012), Sun *et al* (2008), Garbacz *et al* (2007), Radice and Mischler (2006), Ma *et al* (2009), Hu *et al* (2009), Li and Zhu (2003), Liu (2003), Wu *et al* (2007) and Goto and Honda (2004).

Drag Reduction of Surfactant With Time:

It was realized that, there is decrease in the drag reduction efficacy of the surfactant which could have resulted from the mechanical degradation of the surfactant which reaches a point whereby it became stable, at this point, they are re aligning with the formation of micelles, thereby self repairing. On the concept of drag reduction with time, Drag reduction is not exclusively related to molecular degradation, it could be said that, DR is a complicated function with respect to time.

Drag Reduction of Nanofluid:

A very important discovery on the nanofluid of these materials is that, at low concentration of nano-SiO_2. The drag reduction was very low and exhibit similar characteristic as the water alone, this could be seen from figure 5 below. This could be as a result of the inability of these particles completely smoothen the disk wall, nevertheless, as the concentration increased, drag reduction was effective and this could as a result of the availability of reasonable quantity of these particles to smoothen the disk surface, similar study was reported by Pouranfard (2014), although the study was carried out in pipe, but this is the first reported discovery in a RDA. It could thus be said that, the one of the main function of these particles in nanofluid is surface modification as a result of their rigid nature, thereby reducing the drag, friction factor and mechanical degradation of their host materials**.** Another factor that could have resulted into this is that, there might not be enough dispersion of the solid particles in the surfactant. Nevertheless, the particles rigidity could have prevented their ability to reduce drag when used alone, but could interact with the surfactant to yield structures that withstand the mechanical degradation of these surfactants over a period of time as well as maintaining some flexibility, although, similar attributes have been observed with CNT and PEO in pipes, Adam *et al* (2014) but not with surfactants or RDA.

Comparing the Complex with Nanofluids:

Comparing the drag reduction efficacy of complex mixtures of nano-SiO_2 with the surfactant and their nanofluid, it was observed that, these materials in these dual natures could reduce drag, but the concentrations and efficacy of their drag reduction differ, as the drag reduction efficacy of these materials in nanofluid is augmented when nanofluid concentration increased. A critical concentration was attained, where these materials no longer reduce drag. Figures 4 and 5 clearly show their ability to reduce drag, it is also an interesting here, that, similar concentrations of these materials gives the best drag reduction.

Degradation effects of Complex and Nanofluid:

Investigating the capability of the surfactant, complex mixture with nano-SiO_2 and their nanofluid, it was observed that, the surfactant alone has the ability to realign after mechanical degradation, this is as a result of the micelles formed as well as re-micellization, although similar result was observed for both complex and the interactive the nanofluid mixture, but the time taken to self repair as well as for mechanical degradation is longer when compared with the surfactant alone, this could be as a result of the presence of the nano-SiO_2. One of the most important attributes of the complex and the nanofluid is the micelles formed by these mixtures, as the increase in volume in larger assemblies of wormlike micelles was observed, this could be traced to the counterion used with this surfactant, which aided its packing parameter, thereby reducing distance between the molecules of the surfactant head groups and the effective surface area of the headgroup at micellar interface, this has as well been reported by Qi and Zakin (2002), Clausen *et al* (1992) and Myska and Mik (2004).

Molecular Degradation:

It is a difficult task to analyse the concept of drag reduction whereby an acceptable theory would be derived on the molecular degradation of DRAs, this is as a result of many interdisciplinary relationships between chemistry and fluid mechanics, although many works have been carried out to address such, in terms of effects of 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).

Effect of Nanofluid Concentration on Reynold Number:

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

Study on the relationship between Reynolds number and the Drag reduction is depicted by figure 6.

Conclusion:

1. Drag reduction mechanism by SiO2 nanoparticles was the surface modification by nanoparticles owing to their contact with pipe surfaces.
2. The proportion of drag reduction in 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, Silica Nanoparticle could play a key role.

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