PERFORMANCE COMPARISON BETWEEN DRAG REDUCERS FOR DIESEL OIL FLOW TESTS

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Abstract. *Hydrodynamic drag reduction has important applications in petroleum engineering, allowing the production and transportation of oil and derivatives in relatively higher flow rates. The continental dimensions of Brazil imply the necessity for an efficient network distribution for oil products, such as diesel oil. This study aims at the investigation of the performance of two commercial drag reducer agents (DRA's) injected in very small proportions in a diesel fuel pipe flow. This may result in significant decrease in the turbulent shear stress, thus reducing the frictional pressure drop along of the pipeline. DRA performance was first tested in a rheometer provided with a Couette-type cell. In order to define the optimal DRA concentration to be used in diesel fuel, the torque ratio with and without DRA addition measured at a given angular velocity, was analyzed for two different commercial DRAs. It was also observed that the DRA performance does not vary significantly with the temperature. However, tests showed a substantial loss of the drag reduction potential with time. This is attributed to due to mechanical degradation of the polymers present in the DRAs, when the diesel was continuously sheared. The analysis of drag reduction in flow tests involves the ratio of pressure difference over the test section (4 m long) at a given flow rate of diesel with and without DRA addition. Several runs at different flow rates and concentrations were performed until the best operational range could be performed. It was also observed loss of drag reduction capability with time, probably due to mechanical degradation of the DRA agents. Despite the high shear rates reached in rheometer experiments, together with their simplicity, better control of flow variables and lower consumption of materials, the results provided by the tests inside the Couette cell were quite different from flow tests. This is an indication that the degree of turbulence in the flow line was probably much higher than in the Couette cell. Pipe flow tests are, of course, closer to the real demands therefore important for understanding the drag reduction phenomenon.*

Keywords*: fluid mechanics, turbulence, drag reduction, petroleum production and transportation*

1. INTRODUCTION

The transportation of fluids such as oil and fuel can be done in several ways, as in large rooms or in pipelines, and transportation by pipeline has lower cost and more efficient energy consumption. Despite the high efficiency of pipes, a considerable percentage of the total cost of pipelines for transportation comes from energy consumption. Thus, the reduction of energy consumption in the transport of fluids through pipes becomes even more attractive (Cuenca *et al.*, 2008).

The addition of small amounts of drag reducer agents (DRAs) to a liquid flowing in a pipe in the turbulent flow can produce an increase in the flow to a certain pressure gradient, a phenomenon certainly desired. Conversely, for a given flow of transport fluid, the addition of polymer can induce the reduction of the viscous pressure drop. This phenomenon, known as drag reduction (DR) was also discovered by Toms in 1940. Adding as little as 1 ppm (parts per million) of polymers in appropriate flow for transportation of crude oil, for example, can increase throughput by 30%, keeping the pressure gradient (Nakken *et al.*, 2001). In short, the economy of this process can be significant, especially in the transport of liquids of high intrinsic value. One of the main examples of applying the Toms effect is pumping oil from Prudhoe Bay and the Bay of Valdez along the 1287 km Trans-Alaska pipeline. On occasion, there was an increase of approximately 10% in oil flow (Burger et *al.*, 1980). Recently, experiments performed on oil pipe of Compañía Logística de Hidrocarburos (CLH), obtained between 36 and 45% DR using between 12 and 25 ppm of drag reducer agent (Cuenca *et al.*, 2008).

The phenomenon of drag reduction in pipe flow has common characteristics observed in a Couette cell type (Groisman and Steinberg, 1996). This system is a simple arrangement of two coaxial cylinders (external and fixed internal rotation) with the fluid of interest in the annular space between them. In these experiments, the transition to turbulent flow occurs through a sequence of changes in flow pattern (Draizin and Reid, 1981). With increase angular velocity of inner cylinder, to a certain Reynolds number, the flow in the Couette cell is laminar for the formation of Taylor vortices, which consist of two pairs of counter rotating vortices, superimposed with the Couette flow (Taylor, 1936, Groisman and Steinberg, 1996). These vortices dissipate energy, resulting in increased torque (Macosko, 1994). However, the Taylor vortices are macroscopic structures, organized, where the DRAs does not act (Bizotto, 2008). The Taylor vortices are stable until the beginning of turbulence, which occurs with the formation of smaller vortices, described by the Kolmogorov cascade, and interaction with DRAs modifies their development (Pipe and Monkewtiz, 2006) - this is Toms Effect.

The determination of drag reduction in Couette-type cells is to reduce the torque on the rheometer, and the torque of the non-liquid additive as reference (Choi *et al.*, 2000, Cowan *et al.*, 2001). The result is less effort (torque) made by the rheometer to keep the angular velocity of the cylinder in relation to the torque applied to the pure solvent. Tests on pipeline transport circuits are usually expensive and time-demanding. The great advantages of comparative tests DR performed on rheometers are the use of small sample size, better control of flow variables and reduced analysis time. The rheometers, however, does not reproduce the real conditions of flow of liquids in pipes with regard to the magnitude of strain rate. Thus, the results of bench tests can not be directly extrapolated to real pipe flow systems.

Under turbulent flow conditions, the drag reduction effect caused by the DRA can be directly calculated by the ratio between the solution (T_p) and the pure solvent (T_s) measured torques, (Eq. 1):

$$\%DR = \left(\frac{T_s - T_p}{T_s}\right) x100 \tag{1}$$

The Reynolds number (*Re*) for the flow produced in a Couette cell type can be determined using Eq. 2 (Goodwin and Hughes, 2000):

$$Re \approx \frac{\dot{\gamma}(R_o - R_i)^2 \rho}{\eta} \tag{2}$$

where $\dot{\gamma}$ is the shear rate, R_o and R_i are respectively the outer and inner radii of the cylinders.

In experiments conducted in tubes (Al-Sarkhi and Hanratty, 2001; Zhang et al., 2005) the %DR is the relative reduction of pressure loss of flow with (ΔP_p) and without the drag reduction agent (ΔP_s), or the friction factor, given the linear dependence for a given Reynolds number:

$$\%DR = \left(\frac{\Delta P_s - \Delta P_p}{\Delta P_s}\right)_{Re} x100 \tag{3}$$

In pipe flow of Newtonian fluids, the drag reduction appears only in turbulent flow, *i.e.* for $Re > 2300$; if the flow is laminar the turbulence mechanisms lack and there is no influence of the drag reducer agents (Manfield *et al.*, 1999).

The Reynolds number is defined by:

$$Re = \frac{\rho U D}{\mu} \tag{4}$$

where D is the pipe diameter (m); ρ is the density (kg m^{-3}); U is the mean fluid velocity (m s^{-1}) and μ is the dynamic viscosity (Pa s).

Using the techniques of determining the reduction of friction in a rheometer and pipes, we intend to establish a relationship between them in order to be able to use the rheometer as a screening method for selecting the most efficient concentration of reducing agent friction.

2. EXPERIMENTAL SETUP

2.1. Drag reducer agents (DRA)

Initially, for the experiments run in rheometer, stock solutions of the two DRAs commercial (A and B) were prepared in commercial diesel oil metropolitan S-500. These solutions were maintained under gently stirred until complete dissolution of the additive and then diluted to the required DRA concentration. All solutions were prepared by gravimetry, and maintained in the water bath to 25 ºC. For the experiments were run at flow pipe, the stock solutions of the DRAs were prepared in diesel directly in the tank injector, by volumetric method. The mixture solution was made by circulating the solution through a by-pass. The chemical constitution of DRA is not available because it is a commercial patented product.

2.2. Experimental apparatus

Rheological measurements were performed with a Haake Instruments RheoStress 1 rheometer at IQ/UNICAMP. Measurements were made using a Couette-type cell (Z34Ti-DIN 53019/ISSO 3219) with the active rotor height, H = 51.0 mm and with inner radius cylinder R_i = 17.00 mm, and outer radius cylinder R_o = 18.44 mm. The Couette cylindrical cell placed in the liquid rotate about the axis of the cylinder while the sample holder is stationary. The volume of liquid sample (40.1 ml) was kept fixed in all the experiments and the temperature of the system was maintained at 25.00 ± 0.01 °C by a constant temperature circulating apparatus (Haake DC30). The torque ratio with and without DRA addition were measured at a given angular velocity (2479 rpm).

The experimentations of the drag reduction in diesel oil pipe flows were conducted in a specially built horizontal flow loop at LabPetro/UNICAMP, in conditions close to the actual transport of fluids in pipes. These experiments were planned with the previous results of the rheometer, in terms of optimal concentration of DR. The flow loop is shown schematically in Fig. 1. The stainless steel pipe had an inner diameter 2 inch and 75 m of total length, including the inlet, development, test and exit sections.

One carefully calibrated differential pressure transducer (Smar LD301) measured the pressure drop over the test section (4 m long) at a given flow rate of diesel with and without DRA addition. Their signals were acquired and stored by a National Instruments board connected to a desktop computer. The signals were acquired during 10 seconds at a 400 Hz sample rate and processed by the Signal Express software. The complete flow set-up comprises a diesel reservoir, centrifugal and helical pumps, two frequency inverters to drive the pumps, and additional instrumentation, as Coriolis mass meters and temperature and pressure sensors.

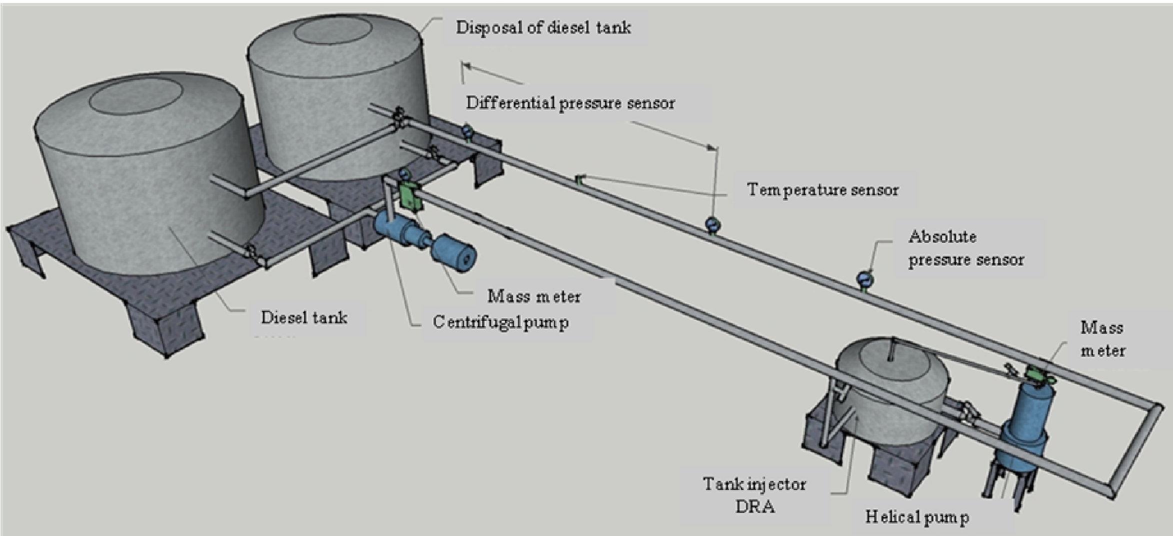

Figure 1. Schematic representation of the pipe flow setup for the study of drag reduction.

The injection of the stock solution DRA on the main line is made by a helical pump just after the horizontal inlet section to avoid the strong degradation process caused by the intense shearing inside the centrifugal pump - the DRA can not be sheared because the shear pump may degrade the compound, influencing DR. The DRA solution was measured by a small size Coriolis mass meter before being injected in the main flow through a hole at the bottom of the pipe. In each run the drag reduction solution was added steadily in the flow, driven by the helical pump and controlled by a frequency inverter.

The stock solution was added to the main flow after a previous estimation made with a software spread-sheet, taking into consideration the concentration of stock solution, the real-time flow rate in the test section and the desired DRA concentration in the main section.

The Fig. 2 shows the graph obtained from a DRA injection test in the main flow. The DR is calculated from the average diesel oil pure points and average diesel with DRA points by using the Eq. 3. The intermediate points between these two situations are referred to disturbances that valves turn operation produce in the flow.

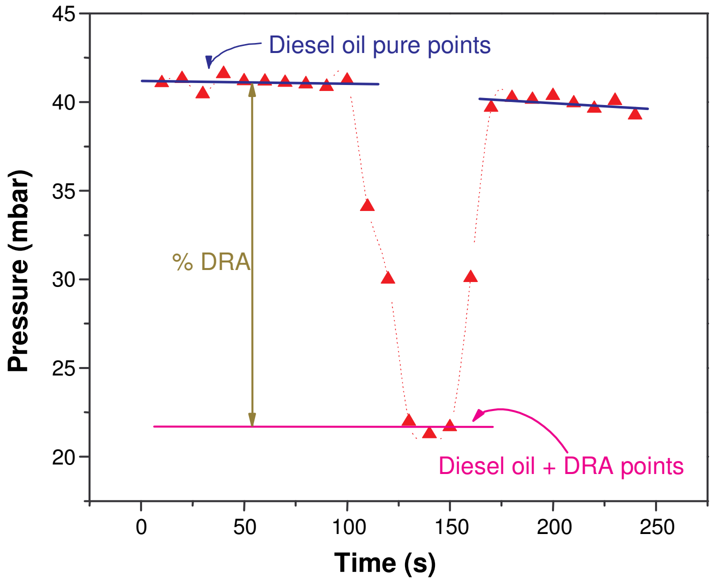

Figure 2. Example of DR determination from a pressure as a function of time.

One of the main difficulties noticed during flow tests is related to the probable formation of foam within the diesel tank and flow line, causing flow rate limitations and affecting DRA injection and differential pressure values.

3. RESULTS AND DISCUSSION

Initially, to determine an optimum concentration of DRA based on the % DR, flow curves were obtained in the rheometer for both commercial DRAs. The results of torque as a function of Re can be observed in Fig. 3.

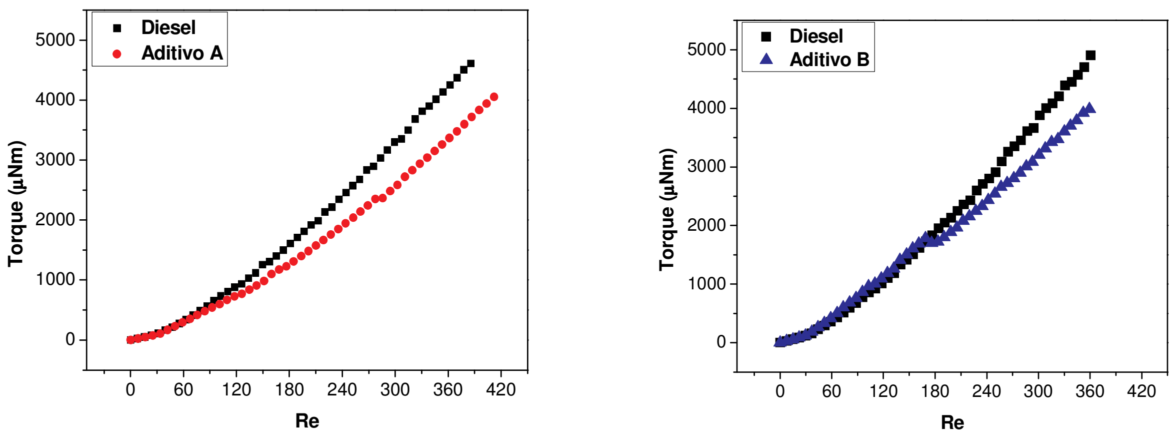

Figure 3. Flow Curve - Torque as a function of Reynolds number for diesel oil with and without 7 ppm of additive A (left) and additive B (right) at temperature 25ºC.

It is observed that laminar occurs up to Re ≈ 37 followed by the Taylor vortices region until Re ≈ 83. After this point, the turbulence develops and drag reduction is observed, as can be clearly observed for the additive A curve. Also in Figure 3 we can observe that the presence of DRAs modifies the pure diesel oil flow pattern, reducing the effort (torque) done by rotor at a given angular velocity.

For the range of Reynolds numbers studied, the magnitude of %DR is taken as the median, and this is due to the fact that the Reynolds number that can be achieved in the rheometer still represent situations of moderate turbulence. The critical *Re* to develop turbulence in the Couette system is 83 for additive A and 180 for additive B.

Figure 4 shows the effect of DRA concentration for both additives for the condition of maximum turbulence achieved in the rheometer (Re_{max} ≈ 400). A plateau is reached for both additives at nearly 7 ppm, additive B being more effective than additive A (about 18% DR and 13% respectively). Higher concentrations cause an increase in viscosity and do not get better results in the drag reduction.

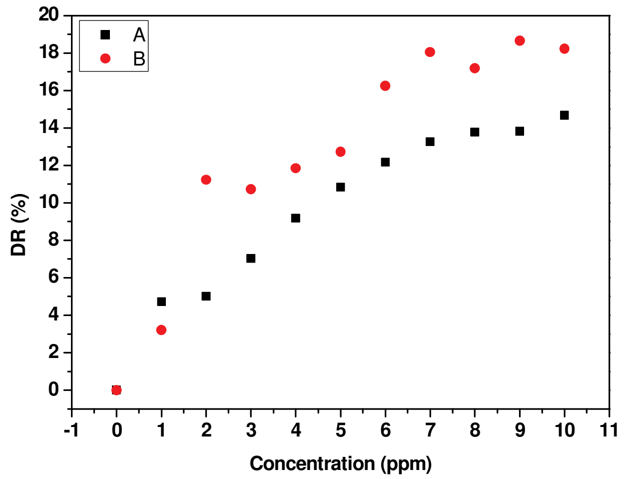

Figure 4. Percentage of drag reduction (%DR) as a function of concentration for both additives for the experiments conducted in the rheometer.

The pumping of diesel in a pipe involves greater turbulence and thus higher Reynolds numbers compared to those obtained in a rheometer. Higher Reynolds number flows can provide greater gains in terms of drag reduction. For this reason, it is important to conduct pipe flow experiments. Figure 5 illustrates the results for the flow of diesel oil containing both additives.

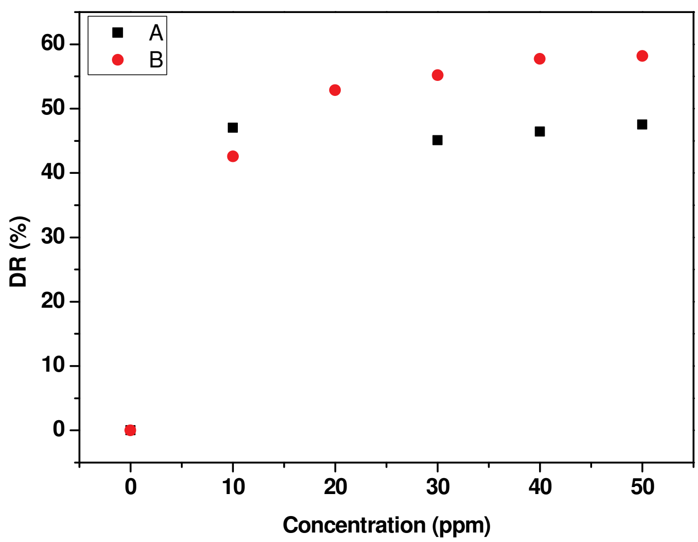

Figure 5. Percentage of drag reduction (%DR) as a function of concentration for both additives for the experiments conducted in the pipeline ($Re_{max} \approx 43000$).

The maximum DR reached by additive A is 48%, while for additive B is 58%, both at the same concentration of 50 ppm. However a plateau is reached for additive A at 10 ppm with 47% DR and for additive B the plateau is attained at 20 ppm with 53% DR. The maximum *Re* reached in the pipe was 43000. One of the main difficulties noticed during flow tests is related to the probable formation of foam within the diesel tank and flow line, causing flow rate limitations and affecting DRA injection and differential pressure values.

The results shown in Fig. 5 are in qualitative agreement with those in Fig. 4, i.e. the %DR for additive B is somewhat higher than additive, although this is not the only variable to be focused. It can be realized that the concentrations of DRAs required to get the maximum DR in pipe flow are somewhat higher for both additives. However, the %DR levels obtained in the pipe are much higher, about 35%, because of the higher turbulence level achieved in comparison with the rheometer.

As the DRAs are commercial products supplied by companies without burdens, we have no commercial values thereof. To choose the best DRA in practice, it should be considered the combination of cost, DRA amount and % DR. Another point to consider for this choice is the resistance to mechanical degradation of the DRA, selecting the DRA that presents the highest resistance to mechanical degradation, since it will require the lowest number of DRA injections in the runoff to maintain the %DR. In experiments carried in the rheometer, submitting DRA solutions to high shear for long periods of time, it was observed that both DRAs degrade with very close rates, i.e. the decrease in the %DR with time was similar. Figure 6 illustrates the results of experiments carried in the rheometer on mechanical degradation for the diesel oil containing both additives. Samples were subjected to constant shear (fixed speed 2000 rpm) for a period of time of 30 min.

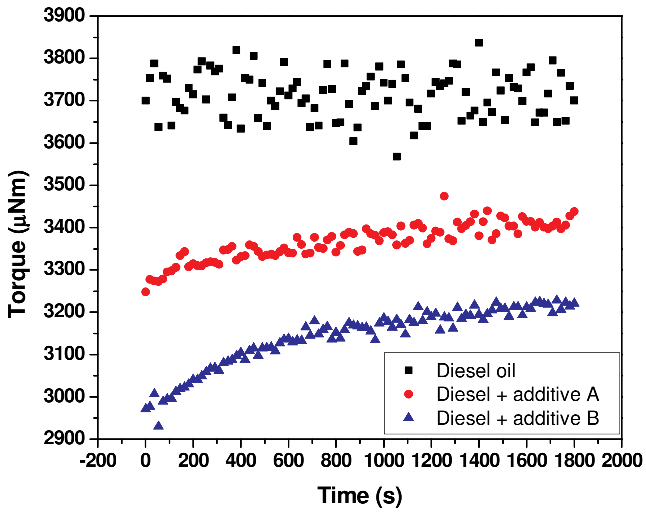

Figure 6. Torque as a function of shear time for diesel with and without additives at fixed speed 2000 rpm.

Is observed in Fig. 6 there are a larger dispersion of points for diesel oil than diesel with both DRA. It shows that DRA acts as an attenuator of turbulence and for this reason DRA can improve the flow in a pipe, decreasing the power applied for this operation.

In these studies is noticed that the DRA's does not regenerate after repose. The both DRA solutions, after 30 minutes of constant shear, were left in repose for one week and the same test was repeated (fixed speed 2000 rpm for 30 minutes). The initial torque observed in both solutions after one week repose is almost the same as final torque for these solutions at the first test (Fig. 7). This indicates the no-renegeration of DRA's solutions.

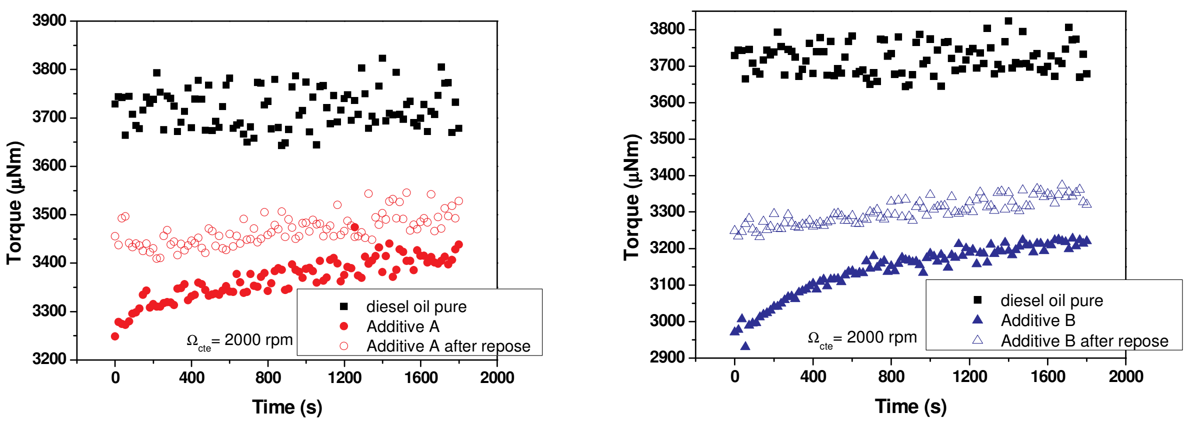

Figure 7. Torque as a function of time for diesel oil pure and 7 ppm DRA solutions during 30 minutes of constant shear in 2000 rpm.

The mechanical degradation effect is observed also in flow loop. Contaminated diesel oil with Additive B (i.e. diesel oil with less than 10% of Additive B) was in a continuous flow for 4 hours and 35 minutes and a sample of this diesel oil was confronted with a pure diesel sample in a rheometer test (Fig. 8). The flow curves show that the contaminated diesel oil curve is overlapped with the diesel pure curve. This means that the same diesel oil batch can be used in multiple tests. The shear imposed by the flow and the pump in this circuit is sufficient for the DRA lose their drag reduction effect.

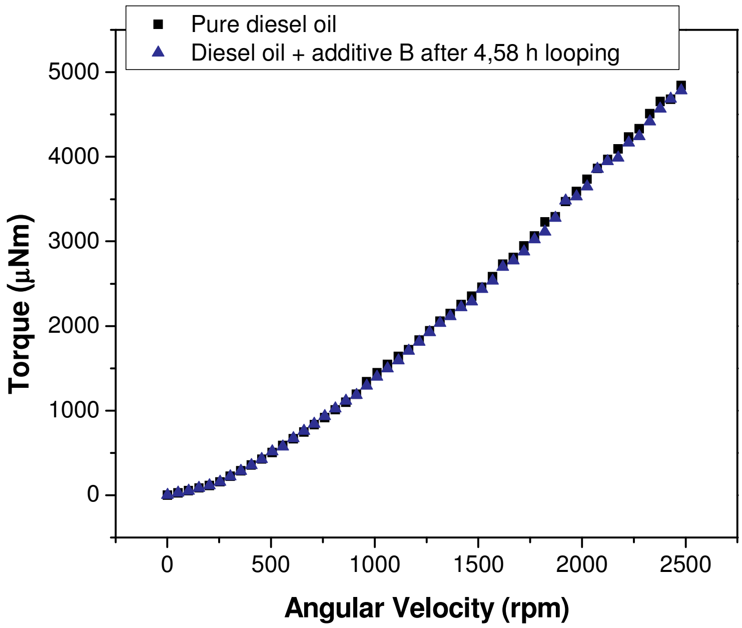

Figure 8. Torque as a function of angular velocity for pure diesel oil and contaminated diesel oil after 4 hours and 35 minutes continuous flow.

The next stage of the research will be the analysis of how the dissipated energy in the rheometer and pipe can be correlated, in view of the results presented above, as well as the size of vortex systems.

As the pipe flow experiments does not have temperature control, experiments to evaluate the effect of temperature were made in the rheometer for diesel with and without DRA in a wide temperature range (Destefani *et al.*, 2010). No significant change in %DR was observed by varying the temperature, indicating that the efficiency of DRAs is not affected by temperature (Fig. 9).

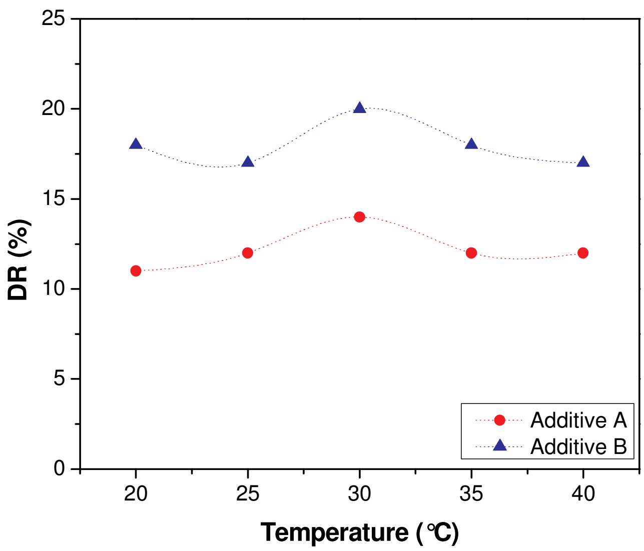

Figure 9. DR as a function of temperature for both DRA at 7 ppm.

4. CONCLUSIONS

This work investigates the evaluation of the performance of DRAs by means of rheometer and pipe flow tests. The use of the rheometer with Couette cell proved to be a quick, cheap and accurate technique to quantify the drag reduction in comparison with flow tests in pipes, indicating no significant influence of temperature. In addition, is observed mechanical degradation both in tube and rheometer, demanding extra injections of DRA in long pipe lines. However, it is known that the nature of the flow and turbulence intensity in Couette cell are quite different in comparison with the transport of liquids through pipes. Thus, the gains from DRA rheometer tests do not necessarily apply equally to the flow pipes, since the Reynolds numbers do not match, requiring more complex evaluations. The results obtained from the rheometer are shown as a good screening method for the type of additive with better DR.

5. ACKNOWLEDGEMENTS

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