Polymer Drag Reducer Mechanism in Light of Rheological and Molecular Behaviour in Fluid Streams

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ABSTRACT

Drag reduction is a well known phenomenon, however not fully understood. Possible mechanism deduced from heat transfer has been suggested earlier for non isothermal Newtonian fluid treated with visco-elastic drag reducer (DRA) polymer.

First and second onset wall shear velocity are determined for isothermal system at stated temperatures between 30, and $57^{o}C$ and non_isothermal system. The first onset is related to deviation from Newtonian and the second onset is related to the apparent degradation.

Temperature largely affects both the drag reducer performance and shear degradation where both are enhanced by temperature.

The apparent degradation is shown to follow a first order trend which is dependent only on the concentration after exceeding maximum drag reduction where the dissolution/degradation equilibrium process is shifted toward degradation process. The magnitude of the both processes is temperature dependent.

An exponent K of the degradation process is shown to have a linear relationship between drag reduction and wall shear velocity for the tested oil soluble drag reducer polymers (DRA1 and DRA2).

A proposed explanation on the effect of the temperature on the degradation and DRA performance is given based on molecular behaviour of the polymer in fluid flow.

INTRODUCTION

Usui [1] (1990) suggested that the main interaction between the polymer thread and turbulence takes place in the centre part of the flow and is due to the suppression of the small-scale eddies. Smith and Tiederman[2] (1991) concluded that drag reduction occurred mainly due to diffused polymer from the polymer thread. Hoyt and Sellin[3] (1991) did visual studies of the movement of the polymer, they concluded that the drag reduction is due to dissolved molecules removed from the thread at high Reynolds numbers, whereas at low Reynolds numbers they found considerable support for the idea of a "thread" mechanism which can interact with the large-scale eddies in the flow. Bewersdorff, Gyr, Hoyer and Tsinober (1993)[4] concluded from their study that drag reduction is in part caused by small amount of dissolved polymer in the near-wall region as well as by an interaction of the polymer thread with the turbulence.

Virk[5] (1971) suggested that an elastic sub-layer evolves between these two zones when polymer is injected into a turbulent flow regime. It originates at onset and grows with increasing drag reduction. The polymer molecules interfere with the transverse instabilities and reduce the frictional pressure drop.

The suppression of eddies is perhaps due to a local increase of the extensional viscosity. This is based on experiments at low flow rates, where an increase rather than decease of the pressure drop in presence of

the DRA polymer that can not be explained based on the shear viscosity measurements at these low polymer concentration.

Literature shows the effect of the drag reducer polymer on the heat transfer efficiency. This was used to explain the alteration of the velocity profile[6]. Drag reduction asymptote is related to the extension of the laminar sublayer/transition layer thickness. The extent of the thickness defines the drag reducer efficiency.

EXPREMINTAL

The loop is described in detail else where, Hamouda et.al[7] (1999). The main heat exchanger consists of 8 concentric pipes having a length of 25 m. The oil flows in the inner tube with an id of 0.008624 m.

The heat exchanger is made of aluminium with a thermal conductivity of 200 W/m^2. The differential pressure and temperature transmitters are installed at the inlet and at the outlet of every section. The heat exchanger loop, is connected to an isothermal loop (no cooling) consists of 35.4 m length and 0.0143 m id. The operating pressure is 100 bar. A 2.5% wt of DRA polymer (of the supplied material dissolved in green diesel oil) is injected into the isothermal loop (upstream the heat exchanger system). This allows to study the effect of dissolved polymer on the heat transfer and depict possible mechanism. The data are continuously monitored and displayed by a lab-view system on a monitor.

DISCUSSION

Drag reduction is best presented by a drag reduction envelope. This envelope is bounded between two universal asymptotes, the Prandtl-Karman law for Newtonian turbulent flow and the maximum drag reduction asymptote.

Drag reduction (DRA) envelop is presented by Prandtl-Karman and Virks maximum drag reduction equations. (DRA) envelop defines the zero and maximum drag reduction, where between these two limits is

a polymeric regime, in which the friction factor relations are characterized. DRA envelop is extended to include the laminar region of the flow to give an overview of the total picture of the flow regime.
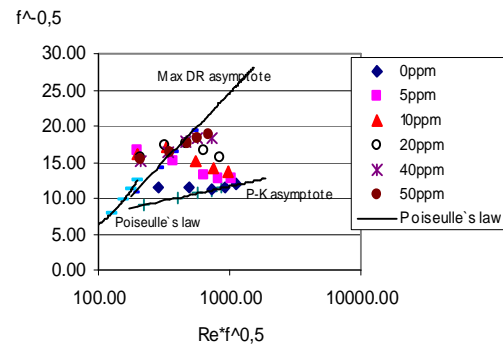

Fig.1 Prandtl-Karman plot, pipe 3, DRA1, T=57 C.

Prandtl-Karman equation for Newtonian fluid is presented as follow:

$$f^{-0.5} = 4.0 \, \log(\mathrm{Re} \cdot f^{0.5}) - 0.4$$
(1)

The maximum drag reduction is a modification of Prandtle-Karman equation to address the friction reduction caused by the polymer drag reducer.

$$f^{-0.5} = 19.0 \, \log(\mathrm{Re} \cdot f^{0.5}) - 32.4 \qquad (2)$$

In the laminar flow region of the envelop is presented by Poiseulle's law

$$f^{-0..5} = \frac{\mathrm{Re} \cdot f^{0.5}}{16} \qquad (3)$$

As shown in Fig.1, a maximum drag reduction is attained when the oil is treated with the polymer drag reducer (DRA1). It can also be seen that deviations at different points of Re.f$^{0.5}$ occurred where a friction increases reaching the Newtonian fluid behaviour predicted by Prandtle- Karman

theory. These deviations are due to shear degradation of the drag reducer polymer.

Degradation of polymer solutions occurs when the fluid stresses that is developed, during deformation and /or flow, becomes large enough to break the molecular chains[8] The shear degradation depends on the structure of the molecule, molecular weight, solution concentration, preparation technique, storage conditions and the flow system.

Mirinov et al [9] detected the critical point at a Reynolds no of 30,000 for polyacrylamide solution in water. They showed that the rate of shear degradation is greatest for high molecular weight polymers at low concentration.

Critical wall shear velocity/mean fluid velocity relation is used, in this work, to address the second onset point/critical point and its dependence factors. The first onset point determines the deviation from the Netonian fluid behaviour, hence the starting point of the drag reduction. In the text, the wall shear velocity is also expressed for simplicity, in the text, as shear velocity

ONSET DRAG REDUCTION

The wall shear velocity is calculated from the wall shear stress by

$$u_{t,cr} = \sqrt{\frac{t_{w,cr}}{r}} \quad \text{m/s} \qquad (4)$$

where, $u_{t,cr}$ is the critical wall shear velocity and $t_{w,cr}$ is the wall shear stress at critical shear velocity and ρ is fluid density. The dependence of the onset drag reduction on temperature is demonstrated in fig.2 (a-c). The deviation from the mean fluid velocity $\bar{U}$ starts at 3.7, 2.9 and 2 m/s at temperatures of 30, 40 and $52 \pm 1^{\circ}C$, respectively for polymer concentration of 5 ppmv. As the polymer concentration increases, the corresponding wall shear velocity/mean fluid velocity deviation also increases. For example for a polymer concentration of 10 ppmv, the deviation

starts at $\bar{U}$ of about 3.7 m/s for system with $40^{\circ}C$, while no deviation is observed for that concentration at $30^{\circ}C$.

Durst et al[10] have shown that it is possible to determine the critical shear stress where a sudden increase of the friction factor occurs. They also reported the dependence of the critical point on the polymer concentration where, it increases as the polymer concentration increases.

The dependence of the shear degradation of the polymer on the concentration may be explained based on the wide molecular weight distributions of the polymer drag reducer, so at higher concentrations the remained un-degraded molecules may still sufficient to provide drag reduction. This is true since the shear degradation is determined by its relative friction reduction. The degradation process is, therefore, termed, in this paper, as "apparent degradation".

In summary, figure 2 shows the dependence of the onsets on the temperature. The first onset is due to the start of the drag reduction. The second onset is due to polymer degradation. The first onset is shown to be dependent on temperature. At higher temperature, first onset occurs at lower wall shear velocity. The second onset is shown to be affected by temperature and concentration.

In other words, the performance and degradation are enhanced by the temperature. In the first glance, this looks to be a controversial statement. In order to explain this, polymer performance processes that take place after injection of the polymer into a flow should be addressed. When the polymer is injected into a flowing fluid dissolution and degradation processes take place simultaneously. If high portion of the high molecular weight remains after degradation, drag reduction process continue to be apparent. When equilibrium between the dissolution and degradation of the high molecular weight is reached, degradation process starts to dominate and polymer

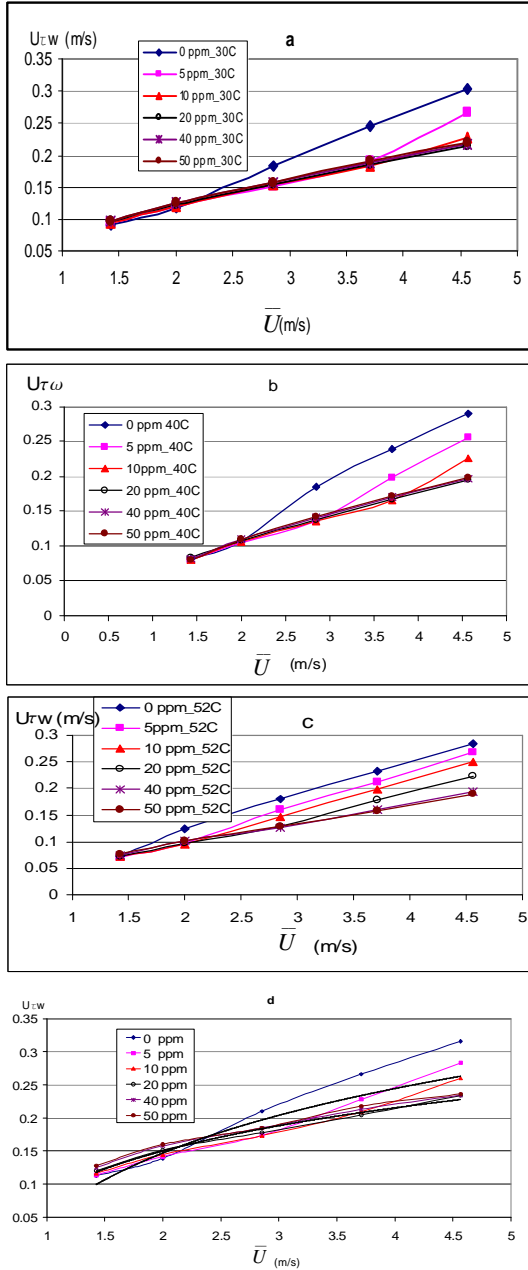degradation will, then be detected by the reduction of the polymer performance.

Fig.2 Wall shear velocity ($U_{t\,w}$) as a function of fluid mean velocity for isothermal (a-c) and non-isothermal system (d), a) 30°C, b) 40°C, c) 52°C and d) 40/35°C.

In the non-isothermal system (40/35 ± 1°C) the deviation occurs at $\overline{U}$ of about 2.9 m/s for both polymer concentration of 5 and 10 ppmv as shown in Fig.2 d. This may indicate that temperature gradient from the wall, caused by the cold wall temperature, has an effect on the apparent shear degradation of the polymer however, it follows similar trend of the temperature effect as that for the isothermal system presented in Fig.2 (a-c).

The discussion so far did not address the reason for the enhanced performance of the drag reducer polymer by the temperature. Reduction of viscosity with temperature is an obvious reason. However, Lescarboura et al [11] (1970) stated that DRA performs better in viscous oils than that with low viscosity at low Re (2100-10,000) and performs equally well in all viscosity levels at Re above 10000. Lester [12] (1985), on the other hand reported that the effectiveness of DRA depends on the viscosity of the solvent and decreases with the viscosity. Hamouda et al [6] (2005), reported that DRA performance in a non-isothermal system can be 20% lower than that for the isothermal system at the same conditions of flow and polymer concentration. However, it is difficult to relate DRA performance to one process solubility /degradation/viscosity, since the two former processes acting simultaneously on the polymer. It has been suggested in literature that long chain visco-elastic polymer molecules are stretched in the flowing fluid.

MOLECULAR STRETCHING

The influence of the polymer on the turbulent flow is connected to the extension of the polymers by the flow deformation, which would result in high extensional viscosity that could possibly affect the turbulent structures by damping small eddies, causing a thickening of the viscous laminar sub-layer and consequently drag reduction, stated by Lumley [13] (1973) and Hinch [14] (1977).

Ptasinski et al [15] (2003) showed from their computational results high extension of the polymers compared to their length in

equilibrium, especially in the neighbourhood of the wall. In other words they concluded that the ability of polymers to stretch is an essential ingredient for high polymer drag reduction.

In this section of the paper, it is attempted to explain the effect of the viscosity based on the degree of polymer stretching. Roy and Larson [16] (2005) developed a model based on onset asymptotic Tourton ratio (Tr) of maximum extensional viscosity to zero-shear viscosity. Weissenberg number (WS) is calculated her from WS=$\lambda \bar{U}$/D where, $\bar{U}$ is the mean fluid velocity, D is the inner diameter. The fluid time scale (λ) is estimated from Powell-Eyring model[17] (1944)

$\eta_a = \eta_\infty + (\eta_0 - \eta_\infty)*[\sinh^{-1}\lambda*\gamma / (\lambda*\gamma)]$ (5)

where, η_a is the apparent viscosity at the wall temperature, η_∞ infinite shear rate apparent viscosity, η_0 is apparent viscosity at zero shear rate. Tr is given by Tr=2(1-β)b, where β= (η_∞/η_0) and b$\equiv 3L'^3/\langle R^3 \rangle_0$, L' fully stretched length of the polymer chain and $\langle R^3 \rangle_0$ is the equilibrium mean square end - to – end distance. Tr = 180 calculated from b=900 and β=0.9[16]. The degree of polymer stretching, predicted by tanh(WS/$\sigma\Theta^+$), is plotted as a function of dimensionless distance from the wall, Although the model has a limitation in predicting friction reduction at MDR (maximum drag reduction) asymptote, it is used here to demonstrate the effect of WS on the degree of polymer stretching based on the time scale with largest eddies (Θ^+)

$$q^+ = k'y^+\left[1 + \frac{a(q^+)^{1/4}}{k'y^+}\left\{Tr\tanh\left(\frac{WS}{sq^+}\right) + 3b\right\}^{3/4}\right]$$ (6)

where, k'=0.4 is the Von-Karman constant, α=0.26[16] and the model parameter σ=4.5 .

Fig.3 shows the degree of polymer stretching as a function of the distance from the wall for 40 and 30°C and two flow rates 5 l/min and 16 l/min. Two observations may be deduced from this figure. First it demonstrates the effect of WS on the degree of polymer stretching. Since WS is a function of λ , which relates to the fluid shear viscosity, at specific velocity and same diameter. The degree of polymer stretching increases with temperature hence enhances the DRA polymer performance. Increasing temperature reduces the viscosity of the fluid. It may then be deduced from this figure that at low viscosity, polymer drag reducer is more efficient. It is also shows that increasing mean fluid velocity also increases polymer stretching.

The second observation is that the molecular stretching is highest near the wall and decreases with increasing the distance from the wall. This qualitatively agrees with the reported conclusions of the importance of polymer molecular stretching by Ptasinski et.al[15], Housiadas and Beris[18] (2003) and Roy et al[16] (2005). In this paper their conclusion is extended to address the effect of the temperature as well as the mean fluid velocity on the molecular stretching of DRA polymer as shown in Fig.3.

The high molecular stretching may affect the polymer molecules to be more susceptible to mechanical shear degradation than that at lower temperature. It may also suggest that at higher temperature, equilibrium between solubility and degradation is attained faster than that at lower temperatures; hence the apparent degradation becomes a dominant process at lower wall shear velocities.
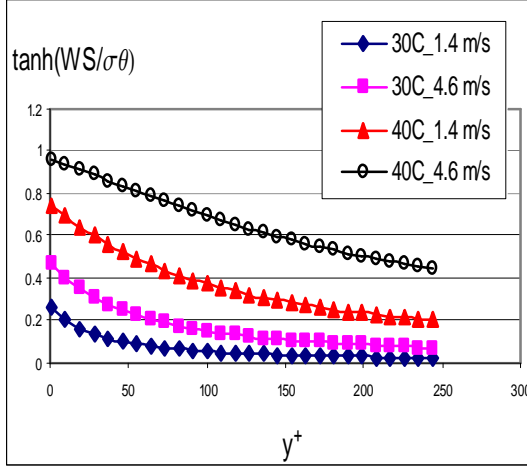
Fig.3 Polymer degree of stretching [tanh(WS/$\sigma\theta^{+}$)] as a function of dimensionless distance from the pipe wall.

SHEAR DEGRADATION

Fig.4a illustrates the effect of the temperature on the degradation onset point. In this figure drag reduction ratio (DRR) is plotted against the wall shear velocity for polymer (DRA1) concentration of 20 ppmv at temperatures of 30, 40 and 57°C. It is interesting to see that there are two distinct lines. These two lines mostly represent a balance between two processes, as explained above. The first line presents the increase of DRR as a function of the wall shear velocity, in which molecular stretching affects the dissolution process. The second line represents a decline in the DRR when certain wall shear velocity is reached. This shear velocity is termed here as the critical shear velocity (CSV). The critical shear velocity (CSV) is defined as the shear velocity at which the balance between the interacting polymer molecules with the flowing fluid, causing the drag reduction, and degradation process of the polymer is reached. Further increase in the wall shear velocity above the CSV, a disproportionation of the balance occurs and the degradation process becomes a dominant process causing a decline in the DRR.

It is interesting to observe that the degradation follows a same line slope representing a linear degradation of the polymer, no matter at what temperature the degradation starts. However, the temperature effect shows a higher polymer performance with the temperature, as explained earlier by molecular stretching. The degradation may be expressed as follow:

$$\frac{-d(DRR)_{C,T}}{d(U_t)} = K(DRR)_{C,T} \qquad (7)$$

By rearrangement of Eq.7

$$-\int_{DRR_0}^{DRR_{U_t}} \frac{d(DRR)_{C,T}}{(DRR)_{C,T}} = K\int_{U_{t\,cT,}}^{U_t} dU_t \qquad (8)$$

The integration result is shown in Eq.9

$$(DRR_{Ut})_C = \left[(DRR_{Utc})_{C,T}\right]e^{-k(U_t - U_{t\,CT})}$$

$$(9)$$

where,
$(DRR_{U\tau,})_C$ = drag reduction ratio at a specific concentration and wall shear velocity,
$(DRR_{U\tau c})_{C,T}$ = drag reduction ratio at the critical shear velocity of a polymer concentration and at specific temperature (maximum obtained drag reduction),
U_τ = shear velocity (m/s), and
K = proportionality constant has the unit of reciprocal velocity (s/m)

The proportionality constant (K) is shown to be almost independent on the temperature but decreases as the concentration increases. K has values of about 0.81 and 0.42 sec/m for DRA1 at concentrations of 20 ppm and 40 ppm, respectively. As can be seen from Fig.4 (a-d), that almost same slope for DDR VS the wall shear velocity is obtained at the same concentration for the two DRA polymers.

DRA1 has almost 5 times higher average molecular weight than that for DRA2.

K of 0.8 s/m is used for concentration of 20 ppm, which is extrapolated to determine K for other concentrations, and then it is used to predict ($f^{-0.5}$) for the various concentrations as shown in Fig.5.
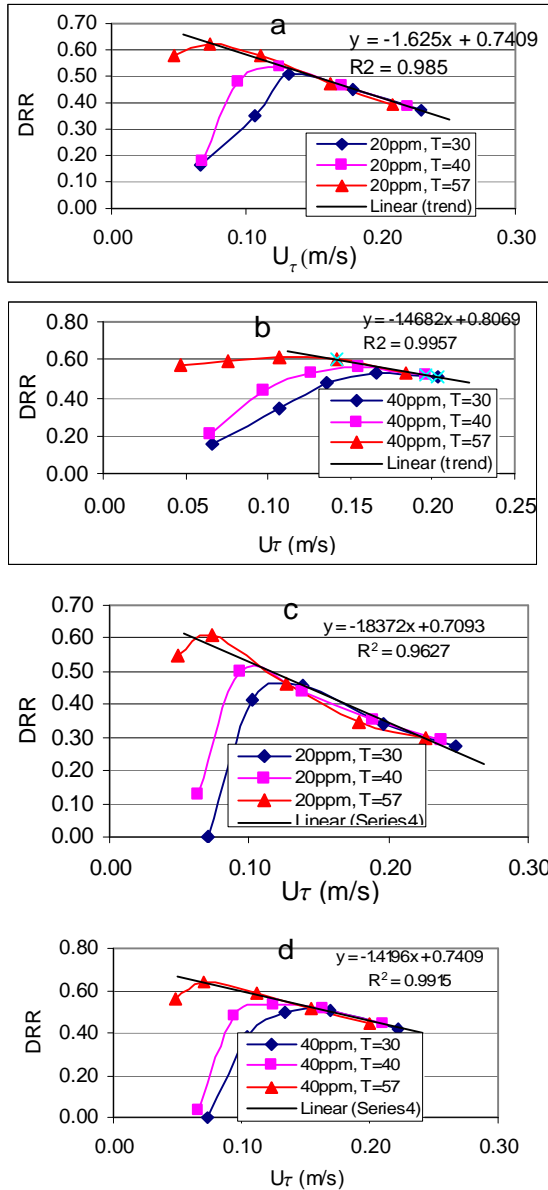

Fig.4 (a-d) Drag reduction ratio as a function of wall shear velocity (-m/s) for DRA1, at 20 and 40 ppmv (a&b) and for DRA2 at 20 and 40 ppmv (c&d). The tested temperatures are 30, 40 and 57C.

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Fig.5 shows the predicted and experimental values of $f^{-0.5}$. The experimental and predicted values of $f^{-0.5}$ for both DRA1 and DRA2 is shown to be within an average of < 10%. The predicted $f^{-0.5}$ is estimated from the reduced DRR at 30°C using the critical wall shear velocity and maximum drag reduction at 57°C for each concentration to illustrate the linear degradation curve (Fig.5) and give a realistic drag reducer performance in transportation systems where a non-isothermal system exists. In other words, at each concentration DRR is estimated by interpolation using DRR/ Ut relationship starting at 57°C
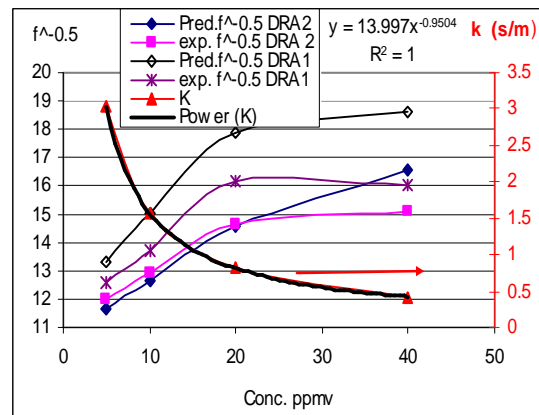

Fig.5 Predicted ($f^{-0.5}$) and relationship between K factor and polymer concentration

The relationship between K and concentration, obtained from the best fit (fig.5) can be presented as follow

$$K=13.997*C^{-0.9504}$$
(10)

where, C is DRA concentration (ppmv).

SUMMARY AND CONCLUSION

Apparent degradation mechanism is shown to be a result of two processes, dissolution and shear degradation. When equilibrium between these two processes is attained the degradation effect appears as a reduction of DRA polymer performance.

Temperature effect on DRA performance and polymer molecular degradation are enhanced by temperature. This may be explained based on the degree of molecular polymer stretching, which is predicted to increase by temperature and mean fluid velocity. In addition the highest degree of the polymer molecular stretching is shown to be close to the wall and decreases with the distance from the wall.

The apparent polymer degradation trend is shown to be dependent on concentration and is enhanced by fluid temperature, where degradation occurs at a lower U_τ . The exponent K / concentration relationship is estimated by (Eq.10).

By knowing U_τ and maximum DDR for a specific concentration, the drag reducer performance including degradation can be predicted by applying Eq.9.

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