EXPERIMENTAL ANALYSIS OF TEMPERATURE EFFECTS ON DRAG REDUCTION BY POLYMER ADDITIVES

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Abstract. *The addition of a minute amount of polymer within Newtonian fluid in a turbulent flow regime can result in a large reduction of the frictional drag. This phenomenon discovered for almost half a century has received special attention because its practical benefits such as the increase of pipe line capacities. Following the pioneering works, several investigators have analyzed the problem of drag reduction in many aspects. Although, the physical mechanism that causes this phenomenon is still not sufficiently clear. An important aspect scarcely analyzed is the effect of temperature on drag reduction. Therefore, the goal of the present work is to conduct an experimental investigation of drag reduction of aqueous Polyacrylamide solution (Sigma Aldrich - 5.0 X 10^6 g/mol) in turbulent flow for a range of temperature from 20ºC to 50ºC. Besides the effect of temperature on friction losses, polymer degradation is also investigated. A commercial rheometer equipped with a double-gap sample holder is used to study the phenomenon.*

Keywords: *drag reduction, polymer degradation, temperature effects, viscoelastic materials, turbulent flow.*

1. INTRODUCTION

The addition of a few parts per million of high-molecular weight polymer leads to considerable decrease in friction factor in turbulent flows. This phenomenon has been studied for ages since it was related for the first time by Toms (1948) and has generated significant interest in some practical applications such as oil transport in pipelines, cavitation prevention in turbomachines, detritus flow in drainage systems, fast ocean transport etc. Several investigators have analyzed the problem of drag reduction in many aspects (Virk *et al.*, 1967, Hershey and Zakin, 1967, Lumley, 1969, Gyr and Tsinober, 1995), but despite theoretical and experimental efforts the physical and chemical mechanisms that cause this phenomenon are still not well known.

The clear understanding of drag reduction involves a detailed description of both rheology and turbulence of polymer solutions in complex flows. Since both these phenomena remain unsolved, the detailed description of drag reduction is still in debate.

A minute amount of polymer within Newtonian fluid in a turbulent flow regime gives rise to stress tensor contributions that are non-linear function of the fluid flow field shear and elongation rates. Due to viscoelastic nature of polymer normal stress differences will depend on the frequency and history of the flow field changes. These complex contributions to the stress tensor affect the fluid dynamic instabilities and consequently the formation of secondary flows when the average shear rate is increased. It is believed that the presence of polymer affect the time and length scales at which most of kinetic energy is converted to thermal energy. As a final result the changes in the fluid flow field provided by the addition of polymers leads, for many secondary flows, to a drastic reduction in total energy dissipation for a given mass flow.

An important factor associated with the drag reduction by polymer additives is the scissions of the polymeric chains caused by large fluid flow shear fields (Solomon *et al.*, 2005). For low fluid flow shear fields the polymeric chains are initially coiled and the polymer contributions to the stress tensor are irrelevant. As the flow shear field increases the polymeric chains assume a stretched configuration and their contributions to the stress tensor becomes significant. The total energy dissipation decreases as flow becomes more turbulent (White and Mungal, 2008). Although for high Reynolds numbers the polymeric chains are fragmented and the drag-reduction capability decrease. The details of the polymer degradation mechanisms were scarcely investigated. Nevertheless studying polymers can lead to better understanding of the phenomenon in question.

Pipe-flow facilities provide realistic testing of polymer drag reduction and polymer degradation. Several investigators have been using these installations (Escudier, 1999), but the experimental systems are considerable voluminous and the measurements consume great amounts of samples and time. Some other researches have been using non-commercial (Kalashnikov, 1998) and commercial rheometers (Nakken *et al.*, 2001) with axial symmetric geometry.

In the present work, the measurements were carried out using a commercial rheometer model HAAKE MARS II manufactured by Thermo Scientific, Karlsruhe, Germany, capable to be well-applied for analysis of both polymer induced drag reduction and polymer degradation caused by turbulent flows. The rheometer was equipped with an axial symmetric double gap sample holder. We investigated the drag reduction of Polyacrylamide (Sigma-Aldrich - 5.0 X 10^6 g/mol) in two different solvents: deionized water and concessionaire water (provided by the local concessionaire, Companhia Espírito Santense de Saneamento - CESAN). Lastly, the polymeric degradation was also investigated. The tests were carried out for a range of temperature from 20ºC to 50ºC. After review, no work about the effects of temperature on polymer scission was found and this is the principal motivation of the present research.

2. EXPERIMENTAL METHODOLOGY

2.1 Rheometer parameters

The measurements were carried out using a commercial rheometer model HAAKE MARS II manufactured by Thermo Scientific, Germany. As shown in Fig. 1 the sample is located between two rigidly interconnected and stationary surfaces (cup) whit cylinder symmetry. A coaxial thin-walled tube (rotor) is located between these two fixed cylindrical surfaces. The rotor can rotate over the sample holder axis of rotation symmetry with a given angular velocity or harmonic angular displacements.
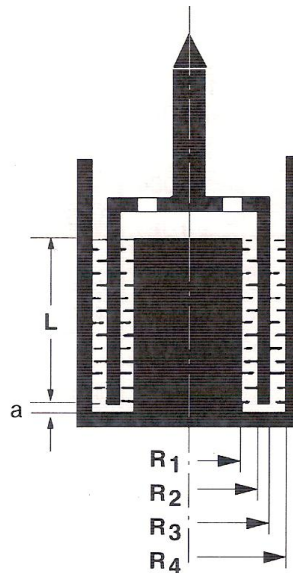

Figure 1. Schematic illustration of the axial symmetric double gap sample holder utilized in the present work.

The double-gap geometry values are presented in Tab. 1. The maximum rheometer speed of rotation employed in the present work was $n = 3000$ rpm (revolutions per minute). The sample volume equals 6.3 ml.

Table 1. Axial symmetric double gap sample holder parameters.

Rotor height L [mm]	Radius R_1 [mm]	Radius R_2 [mm]	Radius R_3 [mm]	Radius R_4 [mm]
55.00 ± 0.06	17.75 ± 0.004	18.00 ± 0.004	21.40 ± 0.004	21.70 ± 0.004

At 25ºC, the mass density of deionized water is $\rho_1 = 997.11$ kg/m³ and the shear viscosity is $\eta_1 = 0.000891$ Pa s. For the concessionaire water at the same condition the mass density is $\rho_2 = 997.11$ kg/m³. The concessionaire water shear viscosity, η_2, was not provided by the local concessionaire (CESAN).

The relation between flow field shear rate ($\dot{\gamma}$), rotor speed of rotation (n) and angular velocity (ω) is given as

$$\dot{\gamma} = K \cdot \omega = K \frac{2\pi}{60} n, \tag{1}$$

where K is the rheometer shear rate factor

$$K = \frac{2 R_a^2}{R_a^2 - R_i^2}, \tag{2}$$

with

$$R_a = R_4, R_2 \tag{3}$$

and

$$R_i = R_3, R_1.$$ (4)

For the used standard double gap sample holder $K = 72.62$.

2.2. Dimensionless Parameters

In the reported work, two dimensionless parameters were analyzed: the Reynolds number and the Fanning friction factor. These parameters were calculated as

$$\text{Re} = \frac{\rho D u}{\eta} = \frac{\rho (2\bar{R})(\varpi \bar{R})}{\eta}$$ (5)

and

$$f = \frac{2 \cdot \tau}{\rho u^2} = \frac{2 \cdot \tau}{\rho (\omega \bar{R})^2},$$ (6)

where D is the characteristic length and the average radius $\bar{R}$ is given by

$$\bar{R} = \frac{R_2 + R_3}{2}.$$ (7)

The term u represents the linear velocity of the rotor and τ is the nominal shear stress. The flow field becomes turbulent when the Reynolds number

$$\text{Re} = \frac{\rho D u}{\eta} \geq 50,000 \cdot$$ (8)

Considering $R_2 \cong R_3 = \bar{R}$ and $\delta = R_4/R_3 = R_2/R_1$, the torque on rotor

$$T = \frac{4\tau \pi L (\delta^2 R_3^2 + R_2^2)}{1 + \delta^2} = 4\tau \pi L \bar{R}^2.$$ (9)

The torque on rotor of the double gap is twice that of a compact cylinder with radius $\bar{R}$. Consequently the Fanning friction factor can be wrote as

$$f = \frac{2 \cdot \tau}{\rho u^2} = \frac{2 \cdot \tau}{\rho (\omega \bar{R})^2} = \frac{T}{2\pi L \rho \omega^2 \bar{R}^4} = \frac{2D}{u} \left(\frac{\tau}{\eta}\right)\left(\frac{1}{\text{Re}}\right).$$ (10)

2.3. Polymeric samples preparation

At 25ºC, the Sigma-Aldrich Polyacrylamide has mass density $\rho_p = 0.75$ g/cm³ and molecular weight $M_p = 5.0 \times 10^6$ g/mol.

The polymer powder was gently deposited on the solvent surfaces. After 24 hours, time for the completely natural diffusion, the tests were carried out. This procedure was adopted to guarantee that any scission occurs before the experiments.

3. RESULTS AND DISCUSSION

3.1. The solvents

At first, tests with the solvents at 25ºC were carried out to evaluate the behavior of the rheometer when double-gap sample holder geometry is used and turbulent flow occurs. Figure 2 shows the nominal shear viscosity of the solvents as function of the rotor speed of rotation. As seen, the equipment presents satisfactory accuracy and reproducibility for the conducted experiments.
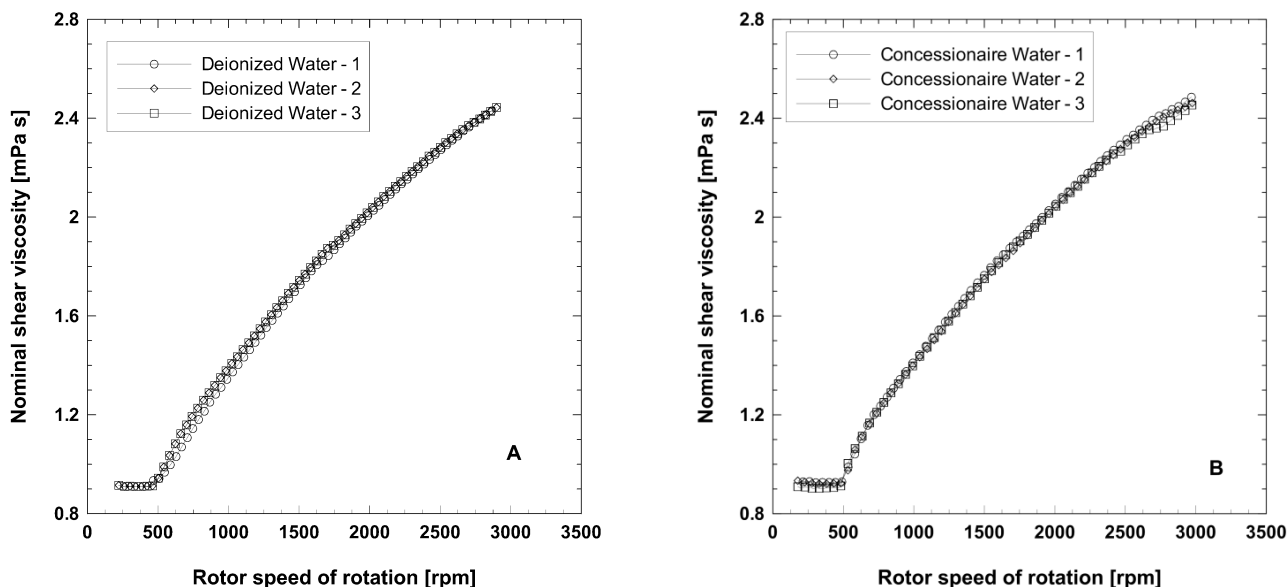
Figure 2. (A) Nominal shear viscosity of deionized water at 25ºC as function of rotor speed of rotation, *n* (given as revolutions per minute - rpm). The rotation was gradually increased from 0 to 3000 rpm. The test was carried out for three different samples of deionized water. (B) Nominal shear viscosity of concessionaire water at 25ºC as function of rotor speed of rotation. The test was carried out for three different samples of concessionaire water during three months.

The plots in Fig. 3 show the Fanning friction factor as function of Reynolds number for both solvents. For all Newtonian fluids are expected a superimposition of results, as seen. The fluid flow becomes turbulent for Reynolds number greater than 50,000, as predicted by Eq. 8. In turbulent flow, the relation between the Fanning friction factor and Reynolds is given as

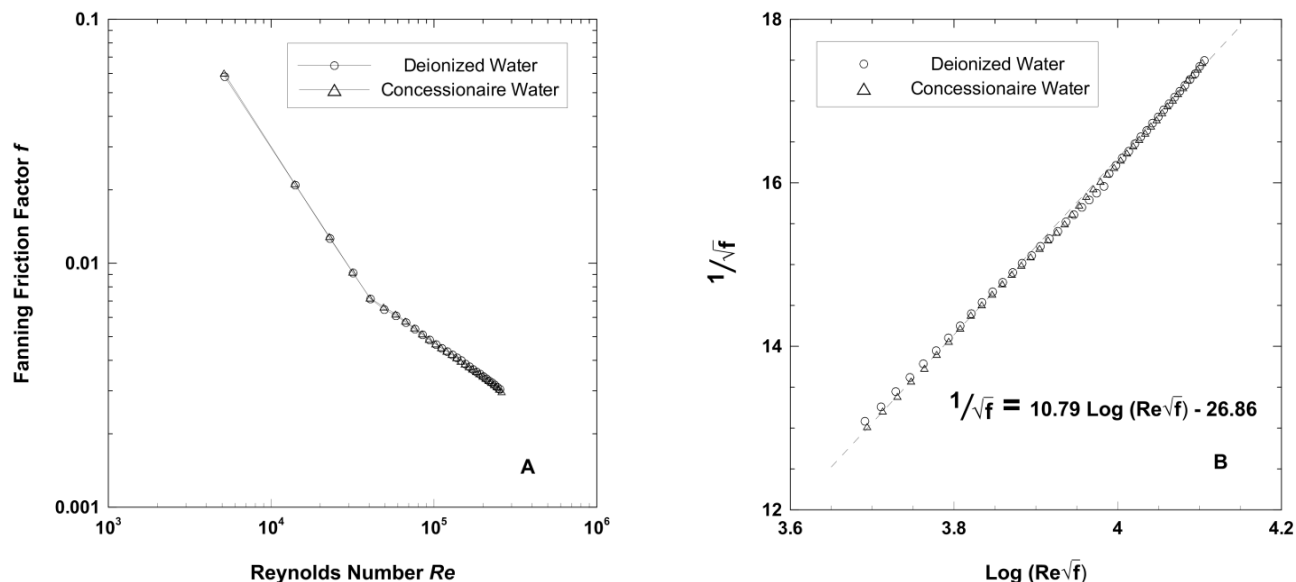$$\frac{1}{\sqrt{f}} = 10.79 \log\left(\text{Re}\sqrt{f}\right) - 26.86 \tag{11}$$

Figure 3. (A) Fanning friction factor as function of Reynolds number for both solvents at 25ºC. The fluid flow becomes turbulent for Reynolds number greater than 50,000. (B) The relation between the Fanning friction factor and Reynolds number in turbulent flow (Eq. 11) is obtained by plotting the results in Prandtl-von Karman coordinates.

3.2. Polymer induced drag reduction

In the present work the polymer concentration ranged from 1 to 50 ppm. The data presented in Fig. 4 show the drag reduction obtained for these different concentrations of Polyacrylamide in deionized water and concessionaire water at 25ºC. The rotor speed of rotation is gradually increased and flow becomes turbulent when the Reynolds number is sufficiently high (Re = 50,000 and n = 500 rpm). For a fixed polymer concentration the total energy dissipation decreases as flow becomes more turbulent. Although, for a fixed Reynolds number, the increase of polymer concentration leads to an increase of the drag reduction capability. A maximum reduction of friction losses of 26% is observed in polymer concentrations greater than 30 ppm and rotation equal to 3000 rpm. For higher concentrations the maximum drag reduction remains constant and equal to 26%.
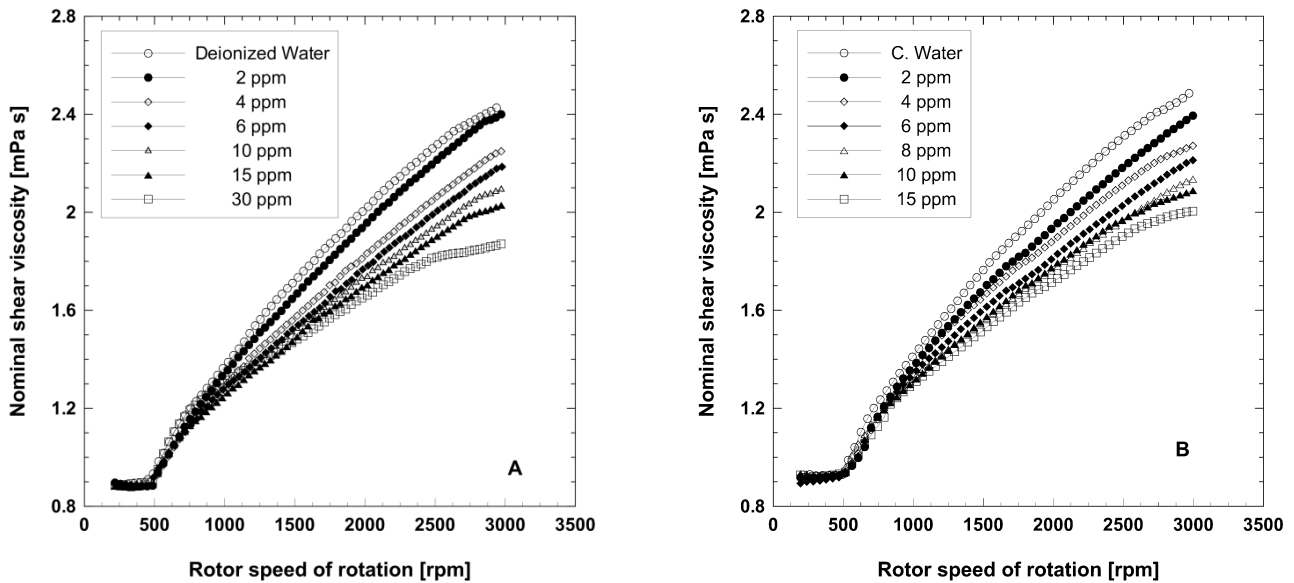

Figure 4. (A) Nominal shear viscosity of several polymer solutions in deionized water as function of rotor speed of rotation. The rotation was gradually increased from 0 to 3000 rpm and the tests were carried out at 25ºC. (B) Nominal shear viscosity of several polymer solutions in concessionaire water as function of rotor speed of rotation.

The drag reduction results obtained for polyacrylamide in both deionized water and concessionaire water are considerably close. Figure 5 presents the maximum drag reduction obtained for both solvent at 25ºC.
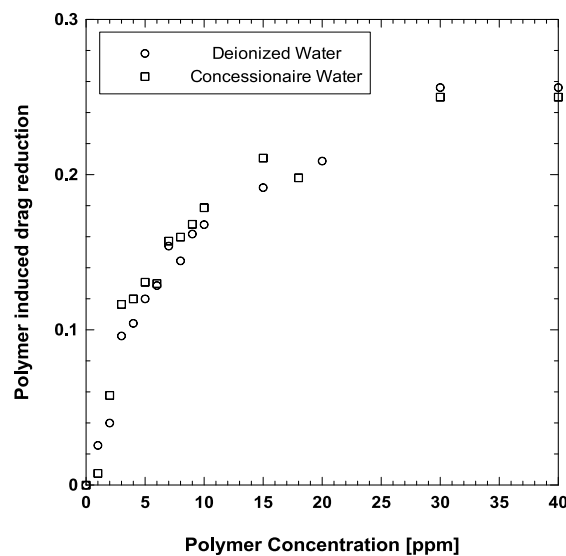

Figure 5. Maximum drag reduction obtained for both solvent at 25ºC as function of polymer concentration.

Plots presented in Fig. 6 show the considerable reduction of Fanning friction factor provided by addition of 30 ppm of Polyacrylamide in deionized water at 25ºC.
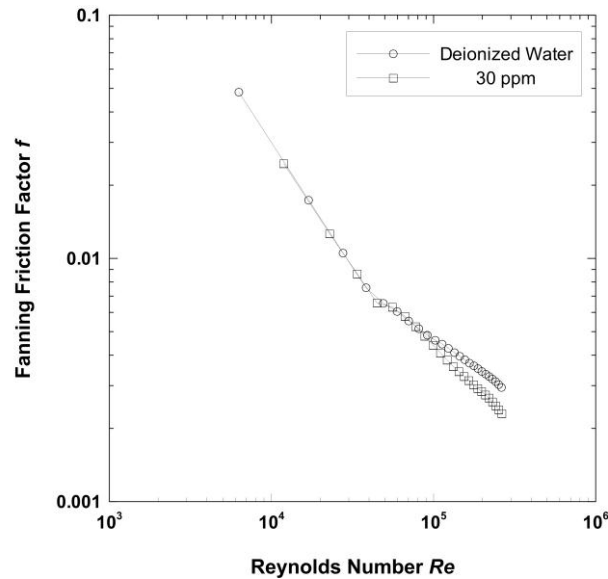
Figure 6. Fanning friction factor as function of Reynolds number for both deionized water and polymer solution of 30 ppm at 25ºC.

Figure 7 shows that the Reynolds number at which drag reduction is first observed depends on polymer concentration. It is believed that the Onset of drag reduction, point from which drag reduction occurs, is a result of time criterion. The time criterion requires that for reduction of friction losses to occur, the polymer relaxation time (average time it takes for a stretched polymer to return to a coiled configuration) must be longer than a representative time scale of the near-wall turbulence. When the ratio of the polymer time scale to the flow time scale of near-wall turbulence, defined as the wall-shear Weissenberg number, is of order unity the drag reduction is observed. The wall-shear Weissenberg number is given as

$$We_\tau = t_z \cdot \left(\frac{\rho u_\tau^2}{\eta_s} \right) \tag{12}$$

where t_z is the polymer relaxation time, u_τ is the wall friction velocity and η_s is the viscosity of the solution. Following Flory (1971), an increase of temperature reduces the relaxation time. Therefore, the wall-shear Weissenberg number decrease and flow must become more turbulent for drag reduction to occur. The effects of temperature on Onset were investigated by Kalashnikov (1998) and the presented results are in agreement with theoretical arguments.
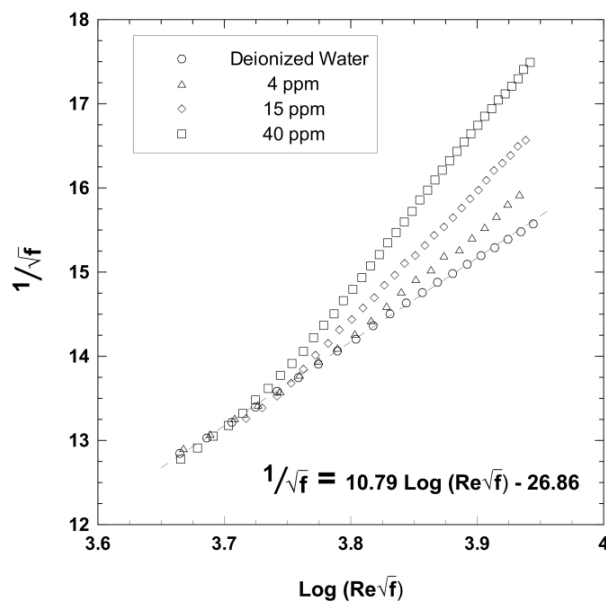

Figure 7. Onset of drag reduction.

The data presented in Fig. 8 show the Fanning friction factor as function of Reynolds number. The tests were carried out for a polymer concentration of 30 ppm in deionized water and a range of temperature from 20°C to 50°C. In the referred experiment the rotor speed of rotation was gradually increased from 0 to 3000 rpm during 300 seconds. As shown, in these short time tests no difference between the friction factor values is observed.
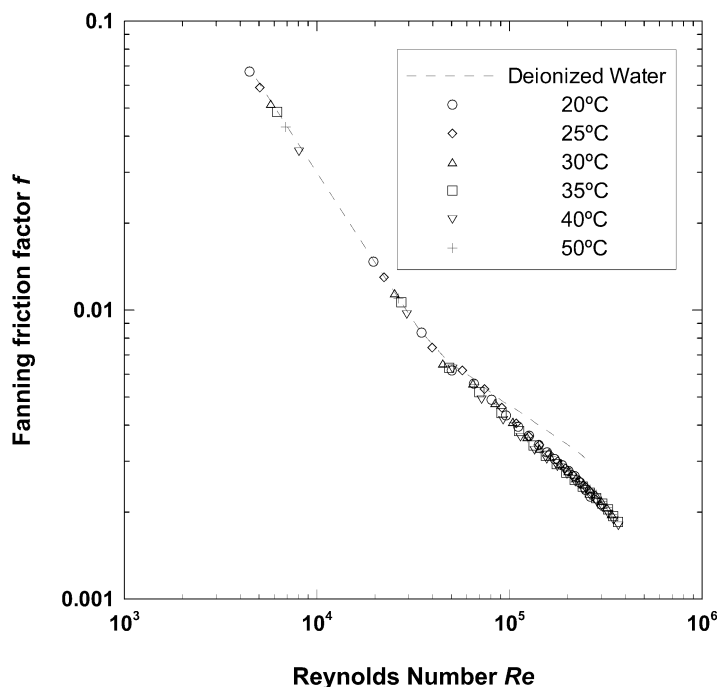

Figure 8. Fanning friction factor as function of Reynolds number. The tests were carried out for a polymer concentration of 30 ppm in deionized water and a range of temperature from 20°C to 50°C.

3.3. Polymer scission

A factor associated with the drag reduction by polymer additives is the scissions of polymeric chains caused by large fluid flow shear fields. Theoretical and experimental results show that the total energy dissipation decreases as flow becomes more turbulent and the polymer chains become more stretched (White and Mungal, 2008). Nevertheless, in intense turbulent flows the polymer chains are fragmented and the drag-reduction capability decreases to an asymptotic value (Solomon et al., 2005) as shown in Fig. 9.

It is well-known that polymer scission is function of Reynolds number, polymer solution concentration and polymer molecular weight. The plots in Fig. 9 show the induced drag reduction as function of time. The tests were carried out for fixed polymer concentration solutions of 30 ppm in deionized water. The temperature was maintained at 25°C during 1,800 seconds (time of each test). As can be seen, both initial drag reduction and drag reduction asymptotic value are related with the Reynolds number and polymer concentration. With time the polymer drag reduction capability reduces, as consequence of polymer chain scission, to an asymptotic value. Although there is a value of Reynolds number (Re = 110,000) from which turbulent shear stresses are not capable to cause polymer chain fragmentations and the induced drag reduction remains constant in time.

The data presented in Fig. 10 show the effects of temperature on polymer induced drag reduction as function of time. The measurements were carried out for both fixed polymer concentration (30 ppm in deionized water) and Reynolds number (Re = 230,000). At first, equal values of drag reduction are observed for all investigated temperatures. During the first seconds of test the perceptual drag reductions are considerably close. This fact is in agreement with that shown in fig. 8 in which polymer degradation is insignificant. With time the polymer drag reduction capability decreases, as consequence of polymer chain scissions. Although, is noted a different asymptotic drag reduction value for each temperature. A decrease of temperature reduces the polymer degradation. Therefore, the induced drag reduction achieves a greater asymptotic value in less time.

The results presented in fig. 10 show that temperature has relevant function on degradation mechanism. Nevertheless, further studies are needed to consistent theoretical arguments about this mechanism.
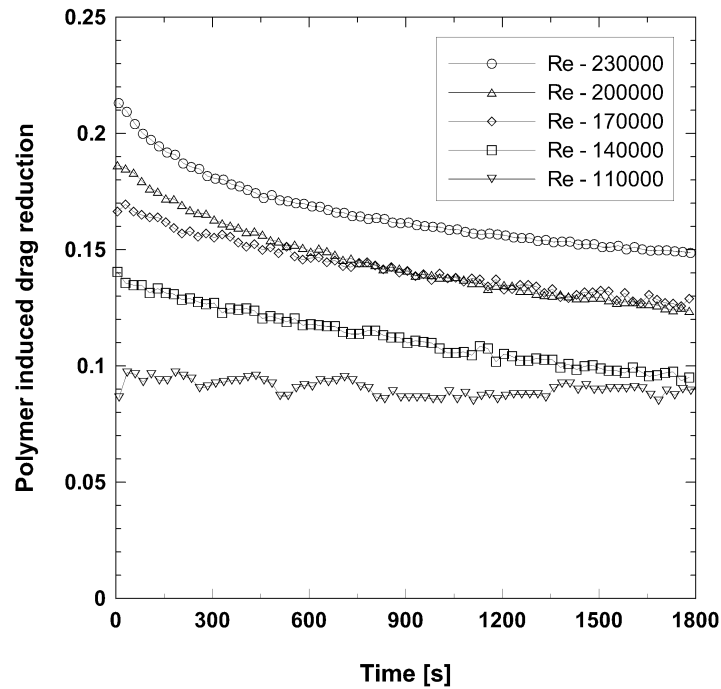
Figure 9. Induced drag reduction as function of time. The tests were carried out for fixed polymer concentration solutions of 30 ppm in deionized water and several Reynolds numbers. The temperature was maintained at 25°C during 1800 seconds (time of each test).
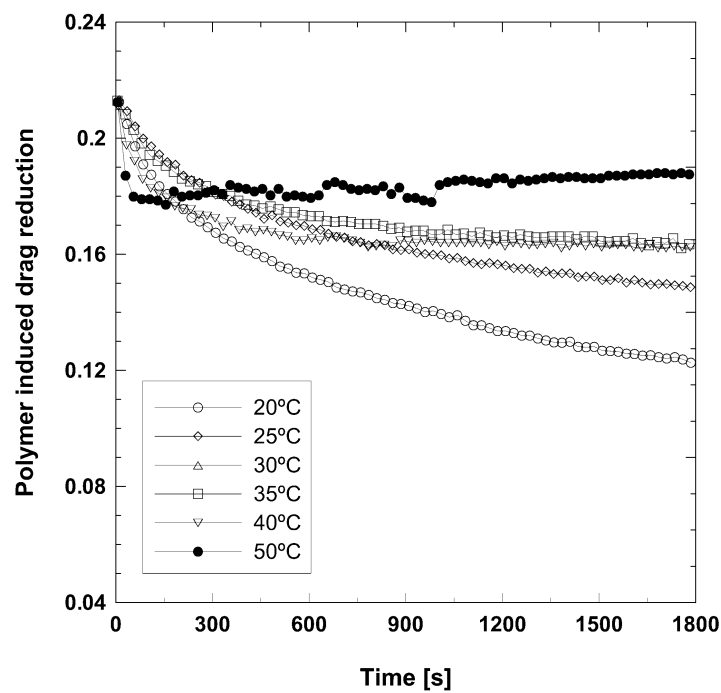

Figure 10. Effects of temperature on polymer induced drag reduction as function of time. The measurements were carried out for both fixed polymer concentration (30 ppm in deionized water) and Reynolds number (Re = 230,000)

4. FINAL REMARKS

An experimental investigation of drag reduction of aqueous Polyacrylamide solution (Sigma Aldrich - 5.0 X 10^6 g/mol) in turbulent flow for a range of temperature from 20ºC to 50ºC was conducted. A commercial rheometer equipped with a standard double-gap sample holder was used to study the phenomenon.

Two solvents were used: deionized water and concessionaire water (provided by the local concessionaire, Companhia Espírito Santense de Saneamento - CESAN). The drag reduction percentages obtained for both solvents are considerably close. A maximum induced drag reduction of 26% was observed.

The degradation experiments reported here demonstrate that the temperature has relevant function on degradation mechanism. The scission scaling may be incorporated into direct numerical simulations of turbulent flow to obtain accurate estimates of polymer drag reduction. Nevertheless, further studies are needed to consistent theoretical arguments about the polymer degradation mechanism.

5. ACKNOWLEDGEMENTS

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