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EXPERIMENTAL ANALYSIS OF POLYMER SOLUTIONS FLOWING IN ANNULAR SPACE

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Abstract. *The axial flow in annular space occurs in many industrial applications and it is relevant in several processes in the drilling industry. Considering this importance, an experimental setup was developed to study the axial flow in the annular space and to analize the drag reduction phenomenon. In this work it is intended to analize the behavior of the drag reduction capacity using polymer solutions with different concentrations. Furthermore, an additional analysis of polymer degradation is presented to investigate the lifetime of the polymer used. For this analysis volumetric flow and the temperature control can be ensured.*

Keywords: *drag reducion, polymer solution, annular space, friction factor.*

1. INTRODUCTION

Many studies have been done to find a way to reduce the energy loss of a fluid flowing from one point to another with the injection of additives. These additives can be polymers, surfactants, cotton fibers, nylon and asbestos, paper pulps and gas bubbles.

This paper studies the drag reduction by the addition of polymers. Toms (1949) observed that in turbulent flow in pipes, under certain conditions, the polymeric solutions require a lower specific energy related to the pure solvent.

According to Virk (1966), there are two situations using polymer additives: (i) it is possible to keep the same volumetric flow with a smaller pressure gradient; (ii) to achieve a greater volumetric flow with the same pressure gradient. Both situations are related to the pure solvent. The drag reduction induced by a series of equivalent polymers in a pipe is function of the concentration, the flow rate and the molecular weight; and the maximum drag reduction possible is limited by an asymptote which is independent of the polymer and the pipe size (Virk, 1975).

The friction factor for a circular pipe is well known, but as studied by Jones Jr and Leung (1981), the correlations for circular pipes can not be used to an annulus space, since they have a dispersion from -25% up to 35% of the value. It was observed that the hydraulic diameter was not enough to describe exactly this behaviour and no correlation was accepted (Jones Jr and Leung, 1981). This disagreement is well known and has been the subject of many studies. From this, Jones Jr and Leung (1981) proposed the Colebrook correlation using a modified Reynolds number, reaching the dispersion of $\pm$5% of the value, accepted for practical experiments.

This work aims to study the reduction of the friction factor in annular space by adding rigid polymers, investigating the influence of the concentration of the polymer solution and the Reynolds Number.

2. LITERATURE REVIEW

The drag reduction is a phenomenon widely studied since the last century. As quoted by Lumley (1969), to avoid confusion, the drag reduction is defined as the reduction of the friction factor in turbulent flow of the solution relative to the solvent only. Algebraically, this definition can be written as shown in the Eq. (1).

$$DR(\%) = \left(\frac{f_{solvent} - f_{mixture}}{f_{solvent}}\right) \times 100 \quad (1)$$

Toms (1949) noted that the reduction of the friction factor is more evident for a greater Reynolds number and that the phenomenon only occurs in the turbulent flow. Toms demonstrated that the additions of small amounts of polymers with high molecular weight in a fully developed turbulent flow would reduce the friction factor compared to solvent only (Silva, 2014).

Several studies about drag reduction have been made by Fabula (1971), Savins (1964), Metzner and Park (1964), Hershey and Zakin (1965), as quoted by Virk (1966), with many polymer solutions in turbulent flow through pipes with internal diameter of 0.5 to 5.0 cm. From these experiments, two general aspects have been recognized:

i. The start of the drag reduction occurs in a well-defined manner; and

ii. Qualitatively, the drag reduction increases with the Reynolds number, with the molecular weight of the polymer and, within limits, with the concentration.

Despite several studies, many questions are not answered yet, among them, the interaction of the polymer and the vortexes caused by turbulence (Silva, 2014). As reported by Lee (2010), two theories have been proposed to explain the drag reduction phenomenon, one is related to viscous effects, called the theory of viscous forces proposed by Lumley (1969), and the other is the elastic theory, proposed by Tabor and De Gennes (1986).

In viscous forces theory, the drag reduction is attributed to additional dissipation introduced by the polymer (Lumley, 1973), it means, the polymers act directly on the vortexes created by turbulence. According to Tabor and De Gennes (1986), as proposed in the elastic theory, the kinetic energy of the vortexes is entirely converted into elastic energy by the polymer, then this energy is transferred to the flow.

2.1 Used additives

The polymer used in this work is the polyethylene oxide (PEO) with a molecular weight equals to 7×10^6 g/mol. Due to the concentration used in the solutions they do not have pseudoplastic characteristics and the fluids were modeled as newtonian fluids.

2.2 Influence parameters

According to Fox and McDonald (1984), the distributed pressure losses can be calculated both for laminar and turbulent flow, but in turbulent flow it is not possible to evaluate the pressure drop analytically in the fully developed flow. So, the experimental data and the dimensional analysis are used to correlate them. In fully developed turbulent flow, the pressure drop Δp, due to friction, on a horizontal pipe of constant area, depends on the pipe diameter, D, on the length, l, on its roughness, e, on the mean velocity of the flow, V, on the fluid properties as density, ρ, and viscosity, μ, as shown in Eq. (2).

$$\Delta p = \phi(D, l, e, V, \rho, \mu) \quad (2)$$

Using the Buckingham's Pi Theorem, the dimensionless groups that can be used to correlate the data are shown in Eq. (3).

$$\frac{\Delta p}{\rho V^2} = \phi\left(\frac{\mu}{\rho V D}, \frac{l}{D}, \frac{e}{D}\right) \quad (3)$$

Developing the Eq. (3), and knowing that the pressure drop is directly proportional to the third dimensionless group, the pressure loss, h_l (m^2/s^2), can be written as the Eq. (4).

$$h_l = f \frac{l}{D} \frac{V^2}{2} \quad (4)$$

Where f is the Darcy friction factor. Thus, the experimental friction factor is obtained from Eq. (5).

$$f_{exp} = \frac{2 D h_l}{V^2 l} \quad (5)$$

It is important to note that for circular pipes, D is the internal diameter of the pipe, while for the annulus space, D is the hydraulic diameter. So, the experimental friction factor for annulus space may be calculated as shown in the Eq. (5).

$$f_{exp,annular} = \frac{2(D_o - D_i) h_l}{V^2 l} \quad (6)$$

Jones Jr and Leung (1981) believes that the behavior described by the flow into an annulus space is similar to the flow in a circular pipe and the Colebrook correlation can be used with a Reynolds number, Re. The theoretical friction factor can be found by Eq. (7), and the Reynolds is found by Eq. (8).

$$\frac{1}{\sqrt{f}} = 2\log_{10}(Re\sqrt{f}) - 0.8 \tag{7}$$

$$Re = \frac{\rho V d_{eq}}{\mu} \tag{8}$$

In this paper it was used the Blasius correlation to find the friction factor, Eq. (9), once the difference compared to the Colebrook correlation in the tested Reynolds Number range was 2%.

$$f = \frac{0.316}{Re^{0.25}} \tag{9}$$

The equivalent diameter can be found by Eq. (10), according to Jones Jr and Leung (1981).

$$d_{eq} = [D_o(1-a)]\phi^* \tag{10}$$

Where ϕ^* is the form factor, Eq. (11), and a is the diameter ratio, Eq. (12).

$$\phi^* = \frac{1}{(1-a)^2}\left[1 + a^2 - \frac{1-a^2}{\ln\left(\frac{1}{a}\right)}\right] \tag{11}$$

$$a = \frac{D_i}{D_o} \tag{12}$$

To compare the drag reduction between different Reynolds it is used the dimensionless time, Eq. (13). Every time the fluid pass through the pump it suffers mechanical degradation, then if the data is analysed at the same Δt, the solution at a higher Reynolds Number would have passed more times through the pump. The dimensionless time represents the number of times that the fluid pass through the experimental circuit. Where V_o is the initial volume, Q is the volumetric flow rate and t_i is the time on the instant "i".

$$t^* = \frac{Qt_i}{V_o} \tag{13}$$

3. METHODOLOGY

This section details the sample preparation procedure and the experimental setup.

3.1 Mixture preparation

The stock solution is prepared in a closed container and allowed to solubilize for 48 hours by brownian motion. After this time, the test fluid is placed in the tank and the test begin.

3.2 Experimental setup

An experimental assembly is used to determine the friction factor, consisting of a closed circuit to ensure the circulation of the fluid, according to the model shown in Figure 15. The elements of the assembly are: one frequency inverter CFW- 08 -RS-485, one magnetic type flow meter (1) and three pressure transducers Warme with 0.01% uncertainty. The assembly is fixed to a wooden frame (2) attached to a metal frame. The prepared solution is stored in a stainless steel tank (3). The suction of the fluid (4) is made by using a screw pump Weatherford (5), model WHT40F.

Two pressure accumulators (6) are in the pump discharge to reduce the pulsation of the flow caused by the pump. A by-pass (7) is also mounted to enable testing of low Reynolds number in order not to compromise the operation of the motor connected to the pump. The entire circuit is thermally insulated with an elastomeric foam. It is importante to note that the horizontal and vertical lenghts are sufficient to ensure a flow entirely developed in the pressure drop measurement region (8) as well as the flow measurement region (1). The fluid is pumped into the test pipe through a hydraulic hose with *1"* diameter (9).

Flange connections were used to connect the pipes and to facilitate the exchange of pipes. A sample of working solution can be collected for later analysis through a valve positioned after the measuring section of the pressure (10). The return pipe was dipped in the tank approximately 30 cm to avoid the fluctuation of the air-liquid interface in the tank and to prevent the formation of air bubbles. The temperature of the tank is adjusted from the flow of a secondary fluid coming from a thermostatic bath Lauda Proline RP1845, flowing through a copper coil mounted inside the tank. The experiment is controlled by a supervisory system developed under the platform LabView 2010 and the communication is made by an industrial network.

The temperature of the fluid present in the tank is obtained from an average of four T-type thermocouples mounted in the tank. The temperature signal from these thermocouples is acquired by a data acquisition card NI 4351 in order to assist the control of the temperature of the fluid in the tank. Fig. (1) shows a schematic of the experimental assembly.

The friction factor is obtained from the static pressure measurements obtained in three interchangeable points. For these measurements, it was performed eleven holes of 2.0 mm diameter and with a distance of 100.00 mm between their respective centers. A stainless steel tube of internal diameter of *1/8"*, with a length of 30 mm was welded in each hole for assembling the hoses to connect the pressure transducers. The pressure signal is acquired by the NI-6251 data acquisition board. A honing process was also done to guarantee the internal diameter of the pipe after the welding process of the pressure outlets, ensuring constant and known diameter.

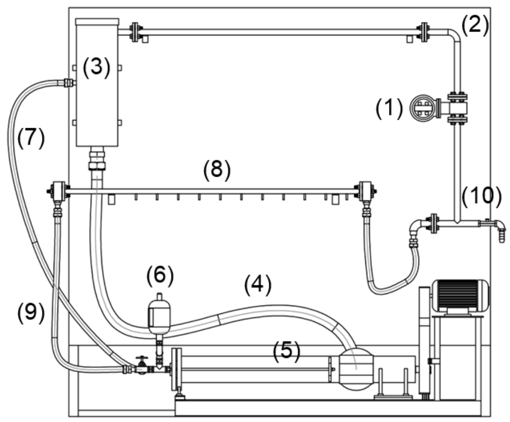


Figure 1: Schematic figure of the experimental setup.

4. RESULTS

To begin the tests in the annular space it is necessary to validate the experimental setup, in other words, to check if the experimental friction factor value aproximates the theoretical. To do so, three tests were made with water. Figure (2) shows the results of these tests. Through the figure it is possible to see that the experimental results has high concordance with the theoretical data, the maximum error is about 8%. The concentric annular space is formed by a *1/8"* axis inside a *3/8"* tube.

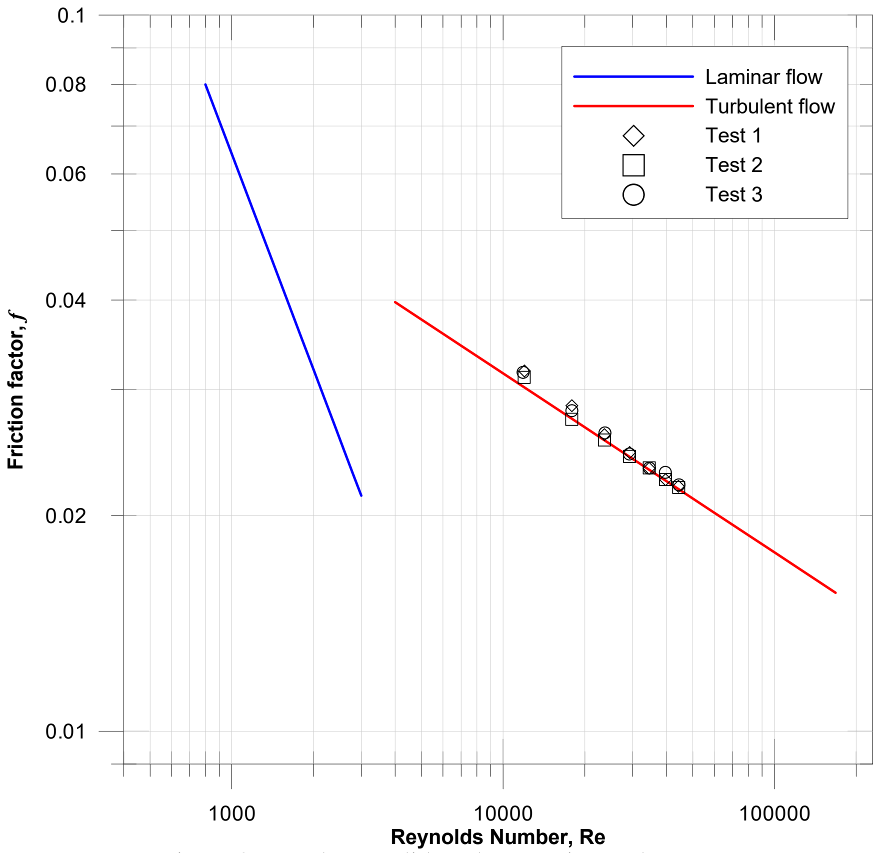
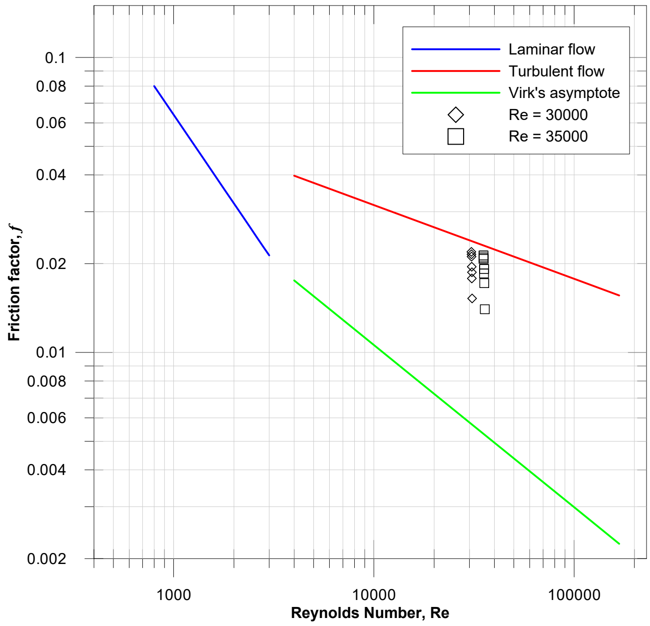


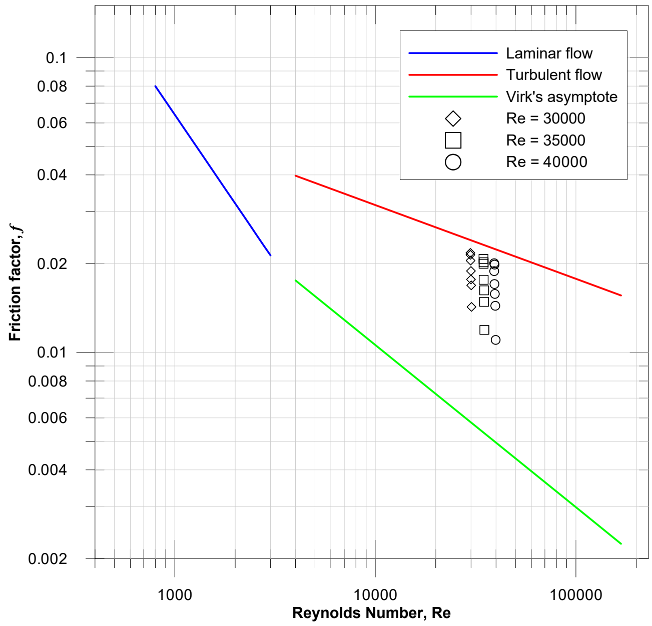
Figure 2: Results to validate the experimental setup.

Figures (3a), (3b) and (3c) show the results for the tests with Polyethylene Oxide for the 50 ppm, 75 ppm and 100 ppm concentrations, respectively. For all concentrations it is possible to see the same phenomenon, that is, a more evident drag reduction at the beginning of the test than at the end. Each figure shows the degradation of the solution, therefore, at the end of the test the solution still shows some drag reduction compared to the solvent, in this case the solvent is water. As reported by Pereira and Soares (2012), the degradation causes the decrease of the polymer molecular weight reducing the drag reduction.

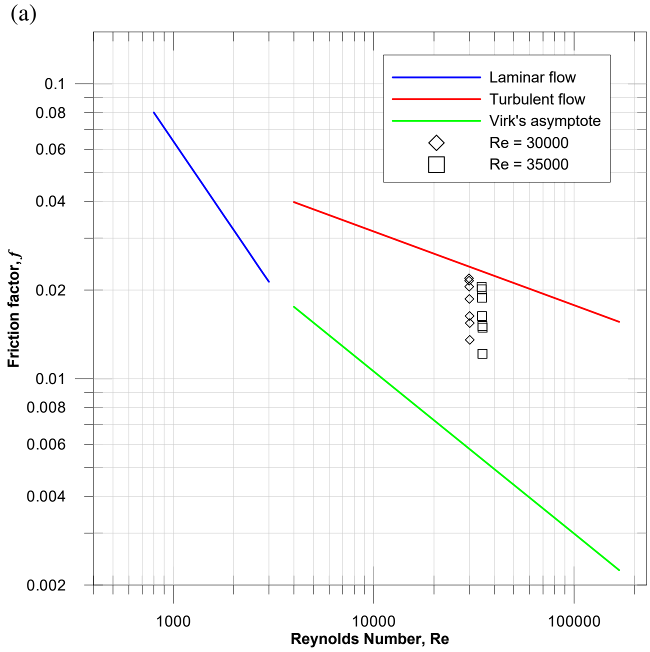
The time increase occurs from below to above. E.g. for Re = 40000, Fig. (3b), at the beginning of the test the friction factor was approximately 0.0115 and at the end 0.02.



(a)



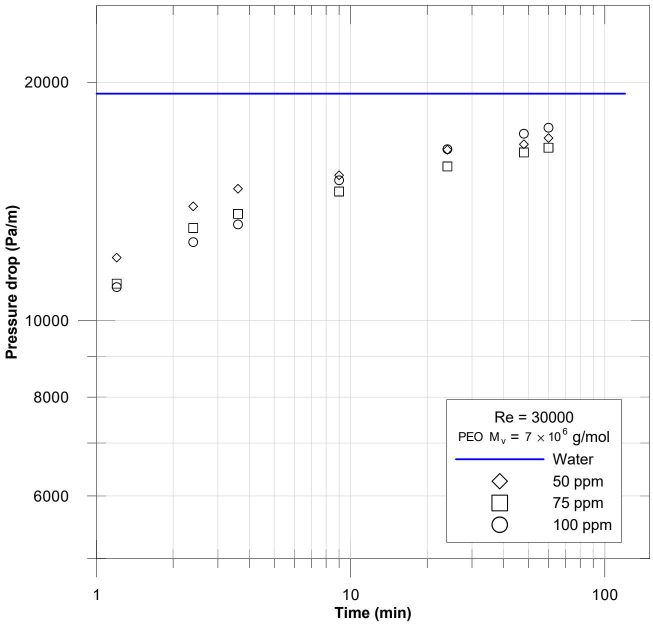
(b)



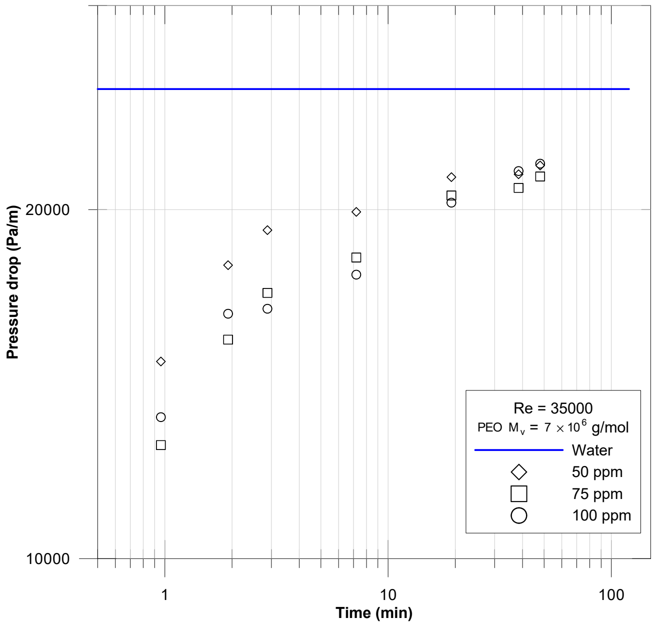
(c)

Figure 3: Results for the
(a) 50 ppm, (b) 75 ppm and (c)100 ppm solutions.

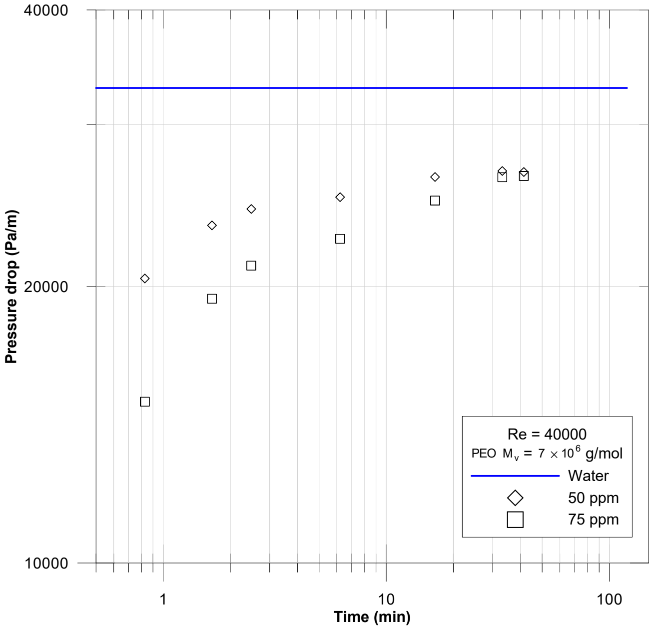
Figures (4a), (4b) and (4c) show the pressure drop during the test. It is possible to observe a decrease in the pressure drop with the concentration increase but with the polymer degradation this pressure drop increases again. The pressure drop has influence on the friction factor, as seen in Eq. (6), where the plotted pressure drop is $h_l \rho / l$.



(a)



(b)



(c)

Figure 4: Pressure drop versus times for
(a) Re = 30000, (b) Re = 35000 and (c) Re = 40000.

The lower the pressure drop, the lower the friction coefficient and, consequently, the greater the drag reduction. The results are in agreement with the ones obtained by Kenis (1971), Vanapalli *et al.* (2006) and Sandoval (2015).

Figures (5) and (6) show the drag reduction as a function of the Reynolds Number and the concentration, respectively. For both cases, the higher the concentration and the Reynolds number, the greater the drag reduction, such as the results reported by Pereira and Soares (2012), Pereira *et al.* (2013), Silva (2014) and Sandoval (2015). The blue line on the next figures represents the point which the flow is developed.

Besides the maximum drag reduction (I) other region of interest is where the drag reduction decreases significantly less with time, this region is called the asymptote of drag redution (II)

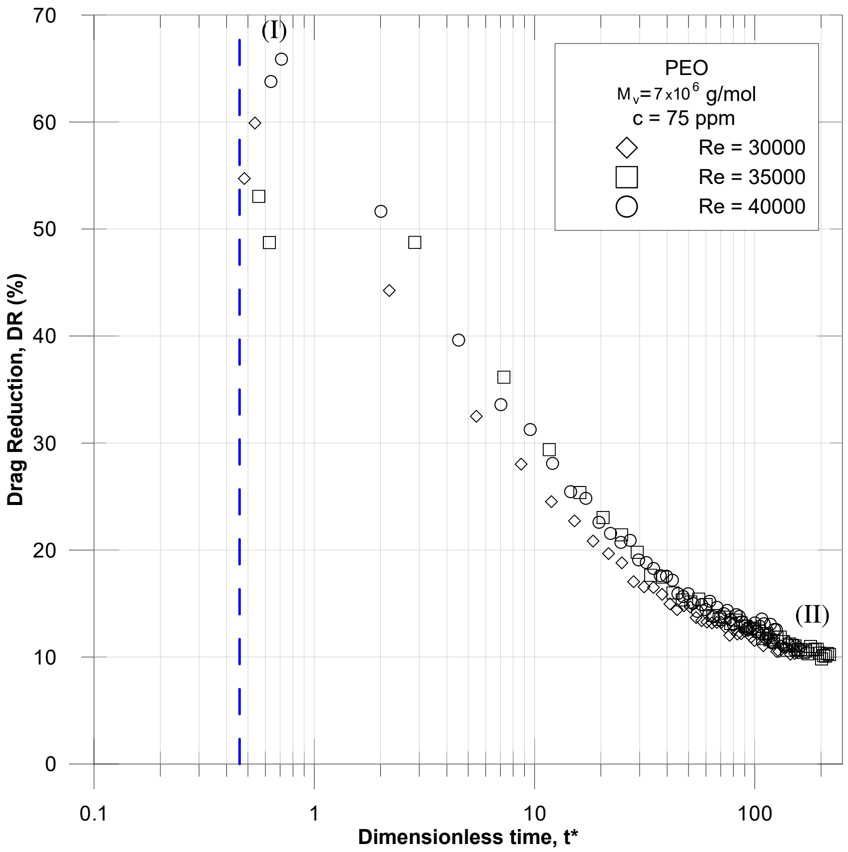


Figure 5: Drag reduction versus dimensionless time for 75 ppm solutions

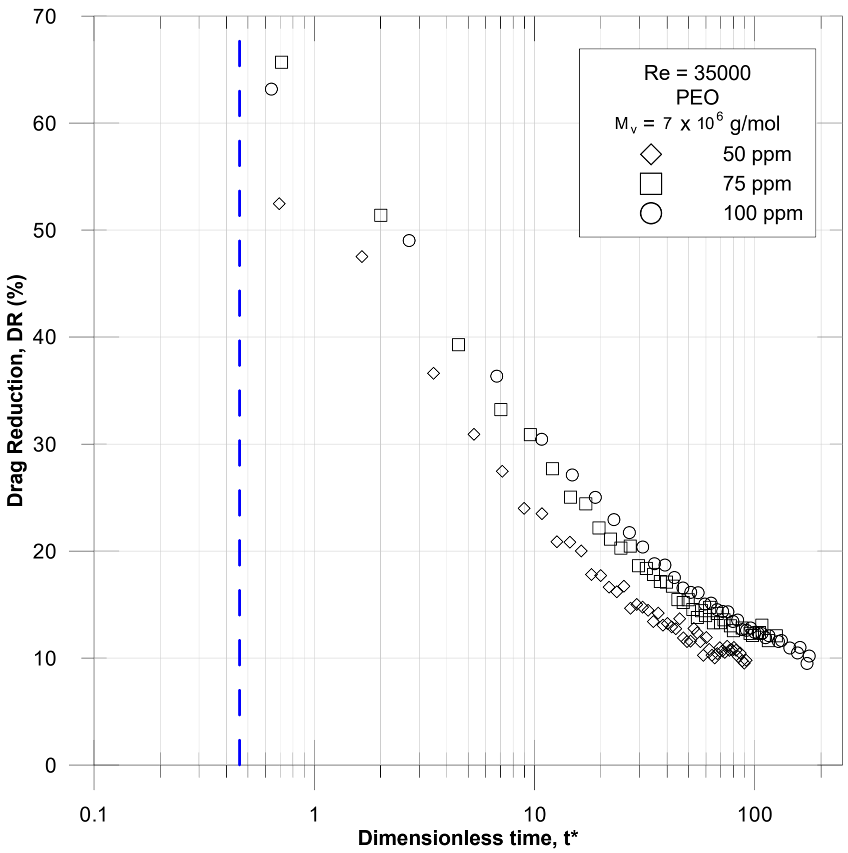


Figure 6: Drag reduction versus dimensionless time for Re = 35000

5. FINAL CONSIDERATIONS

It was observed high concordance between experimental tests and theory. The experimental and theoretical data had a maximum dispersion of 8% at lower Reynolds number and a minimum of 2% at higher Reynolds number. It is noteworthy that the tests realized with the polymers solutions has a maximum dispersion of 2%. Therefore, at the end of the test the solutions still show some drag reduction compared to the solvent only.

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7. RESPONSIBILITY NOTICE