



## DRAG REDUCTION INTO A ROTATING CYLINDRICAL DOUBLE GAP DEVICE BY POLYMER ADDITION: EFFECT OF REYNOLDS NUMBER, CONCENTRATION, TEMPERATURE AND DIFFERENT POLYMERS AT THE VERY BEGINNING OF THE TEST

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**Abstract.** *Polymer-induced drag reducing flow has been investigated for over 60 years. One reason for this is that the drag reducers in flow systems have been successfully applied and represent a great potential benefit to many industrial processes. However, the phenomenon is not completely understood and many aspects of the problem remain unclear. Some important issues are related to the development of turbulent structures and to the breaking of polymer molecules. These two phenomena impose a transient behavior on the polymer efficiency and the drag reduction (DR) can be clearly divided into three periods of time. Over time, at the very beginning of the test, DR assumes a minimum value (sometimes negative) before reaching its maximum efficiency. When the degradation becomes important, DR starts to decrease until it achieves its asymptotic value, time in which the polymer scission stops and the molecular weight distribution reaches a steady state. In the present work we study the drag reduction development from the very beginning of a turbulent flow into a rotating cylindrical double gap device. DR is induced by two different polymers: Poly (ethylene oxide) (PEO) and Polyacrylamide (PAM) for a wide range of Reynolds number, polymer concentration, molecular weight, and temperature. The goal here is to analyze drag reduction over time, paying particular attention on the very beginning of the test. Initially, DR presents negative values due to gain of extensional viscosity caused by polymer stretching. After reaching a minimum value, DR increases in response to the development of turbulent structures, achieving its maximum value.*

**Keywords:** *Turbulent flow, Drag reduction, Developing time, Double gap device.*

### 1. INTRODUCTION

Polymeric drag reducers have been successfully used in a number of applications for more than 60 years (see Fabula (1971), Burger and Chorn (1980), Greene et al. (1980), Sellin et al. (1982), and Golda (1986)). Over the years, researchers have been successful in analyzing this phenomenon and many remarkable papers with practical interest can be found (see Virk et al. (1967), Virk et al. (1970), Virk (1975a), Virk (1975b), and Moussa and Tiu (1994)). Up to now, there has been no generally accepted theory for the mechanism of drag reduction, despite the fact that many researchers have contributed with some very significant papers (see Lumley (1973), Tabor and de Gennes (1986), Benzi (2010) and Dubief et al. (2004)). White and Mungal (2008) is a good review of some recent progress in understanding the fundamentals of polymer drag reduction.

A huge obstacle to attempts to obtain an accepted theory of the phenomenon of drag reduction is the mechanical molecular degradation. This issue involves a strong interdisciplinary connection between chemistry and fluid mechanics. This issue has received deserved attention over the years and many aspects of the problem have been studied, such as the effect of concentration, molecular weight, Reynolds number and temperature on the efficiency of drag reduction (see Paterson and Abernathy (1970), Yu et al. (1979), Moussa and Tiu (1994), and Pereira and Soares (2012)). Using an experimental turbulent pipe flow apparatus, Vanapalli et al. (2005) performed some careful analyzes to show that drag reduction,  $DR$ , decreases as a consequence of polymer degradation but reaches a steady state after a certain number of passes through the pipe flow apparatus. In other words, the molecular scission stops after a long enough time. This tendency is supported by many other results, such as those reported by Nakken et al. (2001), Choi et al. (2001), Kalashnikov (2002), and Pereira and Soares (2012).

The dependence of drag reduction on time is not exclusively related to molecular degradation. As reported by Dimitropoulos et al. (2005), the turbulent structures take some time to rearrange following a polymer deformation and the  $DR$  does not achieve its ultimate level instantaneously. In fact,  $DR$  is a complicated function of time. Figure 1 shows schematically the development of a polymer induced near-wall drag reduction, defined as  $DR = 1 - f_p / f_0$ ,

where  $f_p$  is the friction factor of the polymeric solution and  $f_0$  that of the solvent. This kind of figure can be constructed by monitoring the drag reduction along a pipe or channel after the polymer injection or by using any rotating apparatus. The last strategy is evidently easier. As sketched in Figure 1, the available results concerning flexible polymers suggest that at the very start of the test,  $DR$  decreases from  $DR_0$  to  $DR_{\min}$  before achieving its top level of efficiency,  $DR_{\max}$ . Since polymers extract energy from the vortices and release energy to the mean flow in a coil-stretch cycle, we presume that the maximum drag reduction occurs when a sufficient number of the molecules are in this coil-stretch cycle (Dubief et al. (2004)) and a state of equilibrium with the turbulent structures has been achieved. We will refer to the time to achieve  $DR_{\max}$  as the developing time, denoted  $t_d$ . The increasing friction factor at the beginning of the process is related to an instantaneous increment of the local extensional viscosity after a high polymer stretching. Following  $t_d$ , we observe a constant value of  $DR$  for a period of time, which is denoted by  $t_r$ , the resistance time. Finally, after this period,  $DR$  begins to fall, reaching a minimum level after a long enough time, when the degradation process has reached its steady state and  $DR$  assumes an asymptotic value,  $DR_{\text{asy}}$ . The time to reach  $DR_{\text{asy}}$ ,  $t_a$ , is relatively large compared with the stretching time of a single molecule, because the molecules are stretched and degraded step-by-step (see Elbing et al. (2011)). Thus, we could presume that during  $t_r$  the increasing number of molecules in the coil-stretch cycle is balanced by the molecular degradation, and the ultimate level of drag reduction is sustained. Following that, with a continuous degradation, the turbulent structures depart from their equilibrium and start to increase until achieving the final steady state in which the level of drag reduction assumes a constant value,  $DR_{\text{asy}}$ .

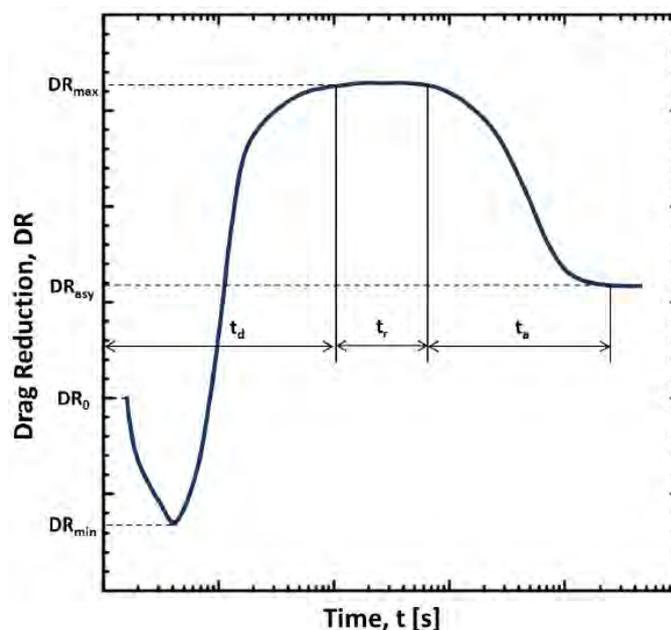


Figure 1. Sketch of the evolution over time of the polymer-induced drag reduction.

There have been a number of papers treating  $DR$  as a function of time. Recently, Pereira and Soares (2012) showed a great number of data in an attempt to understand the effect of the temperature, Reynolds number, concentration, and molecular weight on  $t_d$ ,  $t_r$ , and  $t_a$ , but it is not show the behavior of  $DR$  at the very beginning of the test. Direct numerical simulations computed by Dimitropoulos et al. (2005) indicate that after the polymer injection the friction factor of the polymeric solution increases and the drag reduction can assumes a minimum value (sometimes negative) before reaching its maximum efficiency. However there are no experimental results evidencing such behavior. In the present paper we study the drag reduction development from the very beginning of a turbulent flow into a rotating cylindrical double gap device. The experiments were conducted for a range of Reynolds number, polymer concentration, molecular weight, and temperature for different polymers in an attempt to understanding the beginning of the phenomenon.

## 2. EXPERIMENTAL APPARATUS AND PROCEDURE

The majority of the experimental results on drag reduction by polymer additives available in the literature have been obtained for pipe flow systems, obviously, because they are widely used in many industrial transport processes.

However, the use of pipe systems to analyze drag reduction is extremely difficult and time consuming. A way to overcome this difficulty is by using a rotational apparatus, such as coaxial cylinders (Kalashnikov (1998) and Kalashnikov (2002)), a rotating disk (Peysen and Little (1971), Choi et al. (1999), Choi et al. (2001), and Lee et al. (2002)) or a double-gap cylindrical geometry (Nakken et al. (2001), Bizotto and Sabadini (2008), and Pereira and Soares (2012)). This last geometry has a large contact area, which provides measurements with a quite good accuracy, even for small values of the Reynolds number. As in our previous work (Pereira and Soares (2012)), we use here this kind of apparatus, shown in Figure 2, to obtain our results.

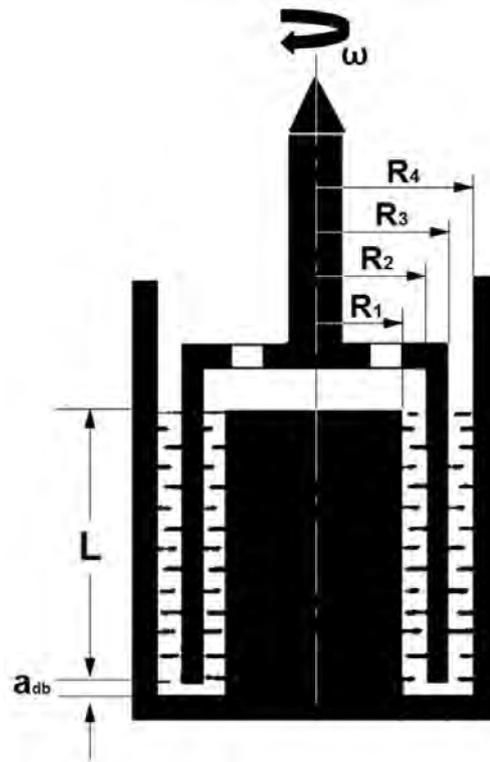


Figure 2. The axial symmetric double gap geometry.

The tests were carried out using a commercial rheometer, model Haake Mars II, manufactured by Thermo Scientific, Germany. The sample was located between the two rigidly interconnected coaxial and stationary surfaces, which have an axial symmetry. The rotor is a thin-walled coaxial tube located between these two fixed cylindrical surfaces which can rotate over the sample holder's axis of rotational symmetry at a given angular velocity. The radii  $R_1 = 17.75$  mm,  $R_2 = 18.00$  mm,  $R_3 = 21.40$  mm, and  $R_4 = 21.70$  mm, and the rotor height  $L = 55.00$  mm, shown in Figure 2, are the important scales of our test section. The sample volume is 6.3 ml.

For a given angular velocity ( $\omega$ ), the mean shear rate ( $\dot{\gamma}$ ) is determined by Eq. (1) as a function of the rotation speed of rotor,  $n$ , and  $K = \frac{2R_4^2}{R_4^2 - R_3^2} = \frac{2R_2^2}{R_2^2 - R_1^2}$ , a geometrical factor:

$$\dot{\gamma} = K\omega = K \frac{2\pi}{60} n \quad (1)$$

The measured torque on the rotor is related to the nominal shear stress,  $\tau$ , by Eq. (2):

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

Here,  $\delta = R_4/R_3 = R_2/R_1$  is the aspect ratio. Thus, we can calculate the Fanning friction factor based on the characteristic radius, which is given by the mean radius ( $\bar{R} = \frac{R_2 + R_3}{2}$ ):

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$$f = \frac{2\tau}{\rho u^2} = \frac{2\tau}{\rho(\omega\bar{R})^2} \quad (3)$$

The Reynolds number is defined by Eq. (4):

$$\text{Re} = \frac{\rho \bar{h} u}{\eta} = \frac{\rho \bar{h} (\omega \bar{R})}{\eta} \quad (4)$$

where  $\eta$  is the solution's viscosity,  $\omega\bar{R}$  is a characteristic velocity and  $\bar{h}$  is the average gap given by  $\bar{h} = \frac{(R_2 - R_1) + (R_4 - R_3)}{2}$ .

In order to distinguish the distinct flows in the double-gap geometry, for a range of analyzed Reynolds numbers, we used the Taylor number given by Eq. (5).

$$T_a = \frac{\bar{R} \bar{h}^3 \omega^2}{\nu^2} \quad (5)$$

where  $\nu$  is the cinematic viscosity.

We have tested solutions with three different molecular weights of Poly (ethylene oxide) ( $M_{v1} = 6,0 \times 10^5$  g/mol,  $M_{v2} = 4,0 \times 10^6$  g/mol and  $M_{v3} = 5,0 \times 10^6$  g/mol). Solutions of Polyacrylamide were restricted to just one molecular weight ( $M_{v4} = 5,0 \times 10^6$  g/mol). All our chemical supplies were provided by Sigma–Aldrich. We obtained the molecular weight by calculating the intrinsic viscosity,  $[\eta]$ , using the Huggins equation (for details see Flory (1971)) and our measurements were very close to the values quoted by Sigma–Aldrich. The measured intrinsic viscosity was also used to estimate the overlap concentration by means of the relation  $c^* [\eta] = 1$ :  $c_1^* = 26000$  ppm,  $c_2^* = 3900$  ppm,  $c_3^* = 3125$  ppm,  $c_4^* = 100$  ppm. The maximum polymer concentration used in this work was 100 ppm which suggests we are working with diluted solutions. Using deionized water as a solvent, the polymer powders were gently deposited on the solvent surfaces. Each test was carried out after 24 hours, time for complete natural diffusion. This procedure was adopted to avoid any polymer degradation before the beginning of the test.

The maximum rotational speed of the rotor used was  $n = 3000$  rpm (revolution per minute). The flow field becomes unstable in  $T_a$ , Eq.(5), close to 1700. This value of  $T_a$  is achieved when  $n$  is close to 500 rpm. This corresponds to  $\text{Re} \geq 350$ . Drag reduction is only observed for values of  $T_a$  beyond this critical value. In the main tests, the rotational speed was kept constant to display the drag reduction as a function of time which was extended over 600 seconds, time to achieve  $DR_{\max}$  in all tests, and around 600 shear stress values were measured.

The kind of geometry used here can, eventually, exhibit some laminar instabilities, such as Taylor-vortices. Thus, someone could question whether our results are related to Taylor instabilities or to turbulence. In an attempt to quantify the real importance of laminar instabilities on the drag reduction and degradation, Pereira and Soares (2012) performed a sequence of tests using the double gap and a standard Taylor-Couette geometry for a range of Taylor numbers. The author's analysis conducted for flexible polymers showed that, the drag reduction and, principally, the degradation, in the double gap are predominantly related to turbulence instead of any kind of laminar instability.

### 3. RESULTS AND DISCUSSION

The tests were conducted in attempt to better understand the drag reduction over the time, paying a particular attention on the very beginning of the test. The results are displayed considering variations in the Reynolds number, concentration, molecular weight, and temperature. We present our results in two parts. In subsection 3.1 we show the Fanning friction factor in Prandtl-von Karman coordinates for a range of molecular weight of PEO and concentrations of each polymer. Subsection 3.2 presents  $DR$  over time from the very beginning of the test until reaching its maximum value, denoted developing time,  $t_d$ .

#### 3.1 Fanning friction factor in Prandtl-von Karman coordinates

Figure 3 shows the Fanning friction factor for a range of concentration,  $c$ , and molecular weight,  $M_v$ , of PEO and PAM in Prandtl-von Karman coordinates with the temperature fixed at 25°C. In these tests the rotation speed was gradually increased from 0 to 3000 rpm over ten minutes.

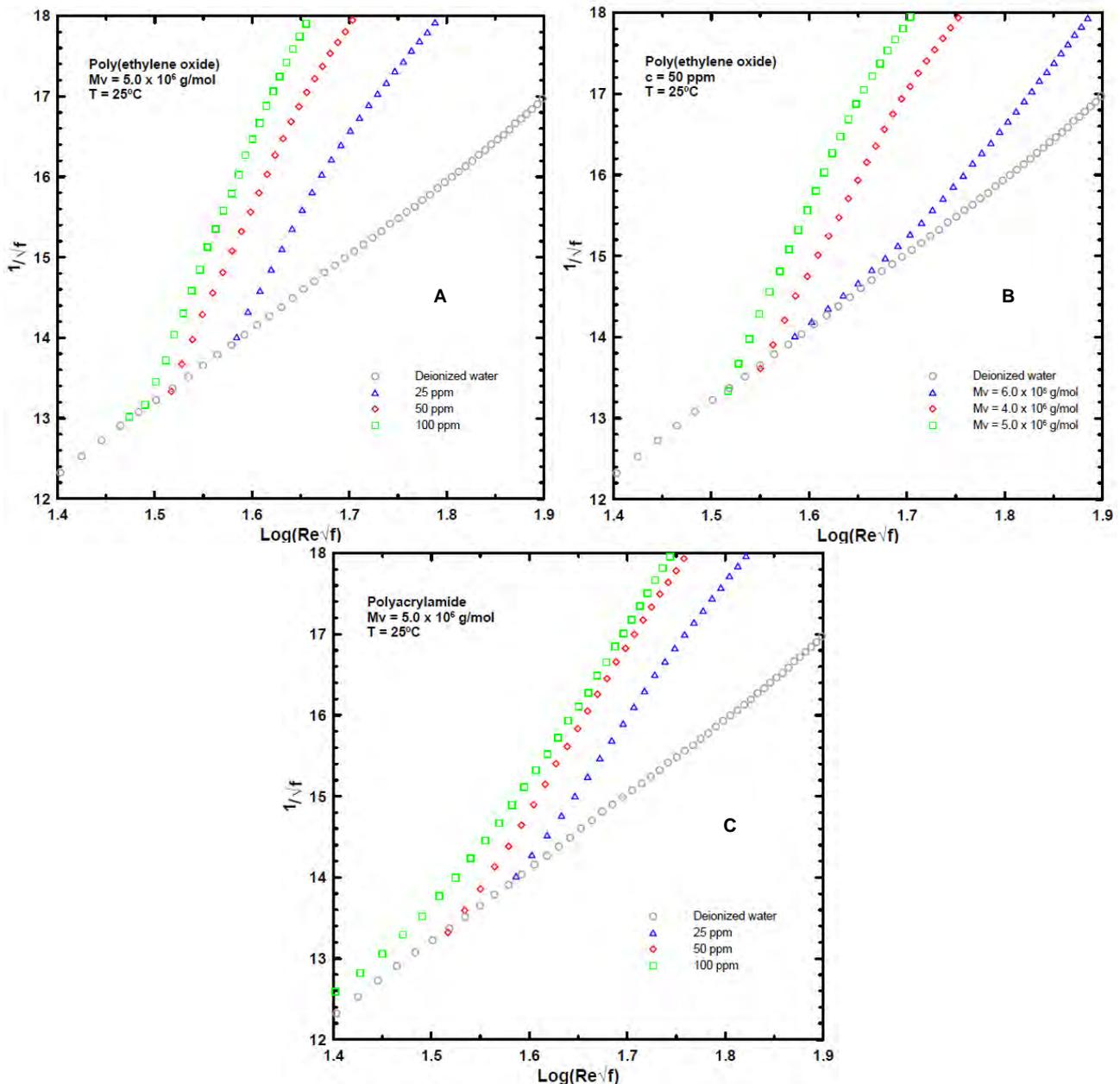


Figure 3. Effects of concentration and molecular weight on Fanning friction factor,  $f$ , as a function of Reynolds number,  $Re$ .

We can observe a similar behavior of the Fanning friction factor between PEO and PAM solutions. As widely reported by a number of researchers (Hershey and Zakin (1967), Virk et al. (1967), Burger and Chorn (1980), Moussa and Tiu (1994), Vanapalli et al. (2005) and Pereira and Soares (2012)), the friction factor falls faster and the onset of drag reduction occurs at smaller values of Reynolds numbers with increasing concentration. It is also clear that the values of the coefficient  $1/\sqrt{f}$  are more pronounced in the PEO than the PAM solutions with same molecular weight. The increasing molecular weight produces similar effects to increasing concentration. In other words, the friction factor falls faster and the onset of drag reduction occurs at smaller values of Reynolds numbers with increasing molecular weight, as observed by Hershey and Zakin (1967), Virk et al. (1967), Kalashnikov (1998), Vanapalli et al. (2005), and Pereira and Soares (2012).

### 3.2 Drag reduction decay

The tests shown here are carried out with constant rotational speed ( $n > 500$  rpm, sufficient to produce turbulent flow) to display the drag reduction as a function of time. The rotation speed is quickly increased until achieved the final rotation imposed, thereafter it is kept constant until the end of the test. We made many experiments (not shown here) to evaluate how long it takes to rheometer achieve the final rotation. We saw that, when the imposed rotation is less than

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1500 rpm, the rheometer achieves it half-second after the beginning of the test. This value is independent the rotation imposed and the viscosity of the sample. Based on these results, the range of Reynolds number tested here is limited for the onset of drag reduction shown in Figure 3 ( $Re > 640$ ) and for maximum  $Re$  obtained with 1499 rpm ( $Re < 860$ ).

Figure 4 displays drag reduction against the time for a range of Reynolds number for PEO and PAM solutions,  $M_v = 5,0 \times 10^6$  g/mol. The temperature was kept at 25°C. Values of drag reduction obtained before half-second are not shown, as mentioned previously.

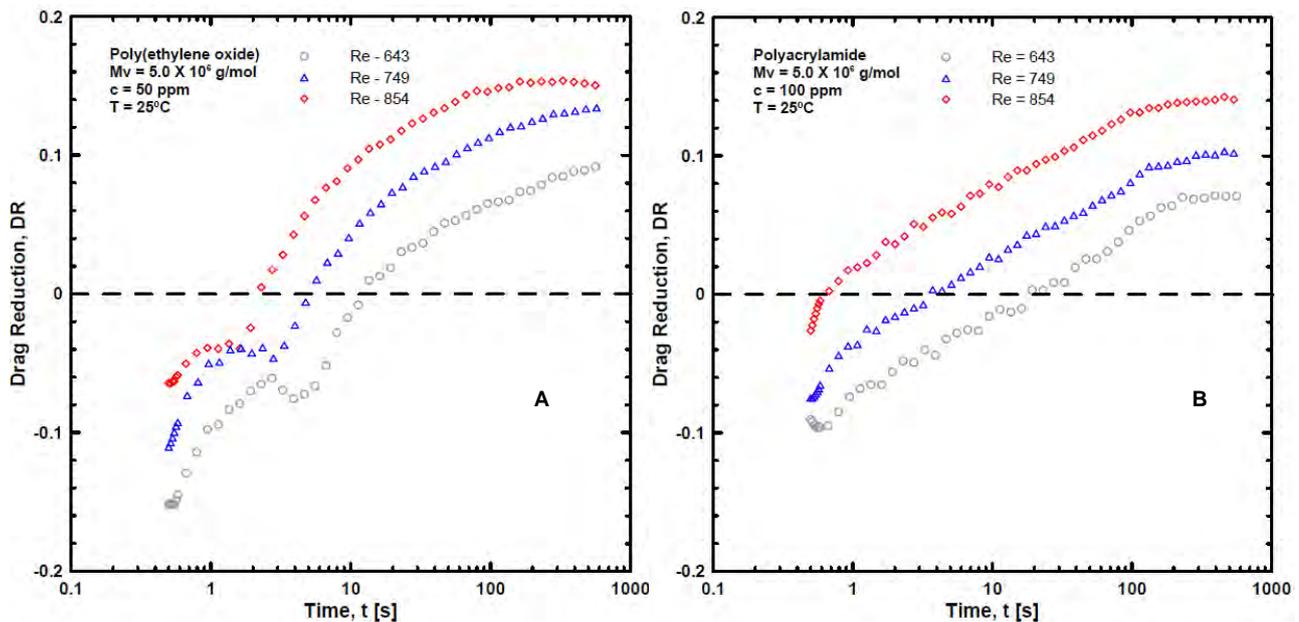


Figure 4. Effect of Reynolds number on  $DR$  as a function of time at the very beginning of the test.

We can see, at the beginning of the test, a significant increase of the friction factor, producing negative drag reduction,  $DR$ . This behavior is also observed by Dimitropoulos et al. (2005) in direct numerical simulation. The authors argue that the increasing friction factor is related to an instantaneous increment of the local extensional viscosity after a high polymer stretching. We also see that the time to achieve  $DR_{max}$ , developing time,  $t_d$ , increase with decreasing Reynolds Number. It is known the drag reduction is associated to stretching of macromolecules. Winkel et al. (2009) report that the time to stretch a macromolecule is proportional to the time to polymer relaxing,  $t_z$ , on the order of  $10^{-3}$ s, based on the zimm model. However, we observed that the time to reach  $DR_{max}$  is significantly longer than the time stretch of individual molecules. This is supported by many other results, such as those reported by Dimitropoulos et al. (2005), Dimitropoulos et al. (2006), Somandepalli et al. (2010), Elbing et al. (2011), and Pereira and Soares (2012). Dimitropoulos et al. (2005) also observe that  $DR_{max}$  is achieved moments after the medium stretch of macromolecules reach its maximum, in other words, the polymer stretch and  $DR_{max}$  is asynchronous. The authors suppose that the turbulent structures require a period of time for arrange after the high degree of polymer deformation at the very start of the test. We also note an increase of  $DR_{max}$  with increasing  $Re$ , as noted by Kalashnikov (1998), Sohn et al.(2001), and Pereira and Soares (2012) using a rotating cylinders apparatus. Comparing PAM and PEO, the negative drag reduction noted in PAM solutions is less apparent than the PEO solutions. These behaviors are better analyzed when we evaluate the effect of concentration of each polymer. Figure 5 displays drag reduction as function of the time for a range of concentration for PEO and PAM solutions,  $M_v = 5,0 \times 10^6$  g/mol, with temperature fixed at 25°C.

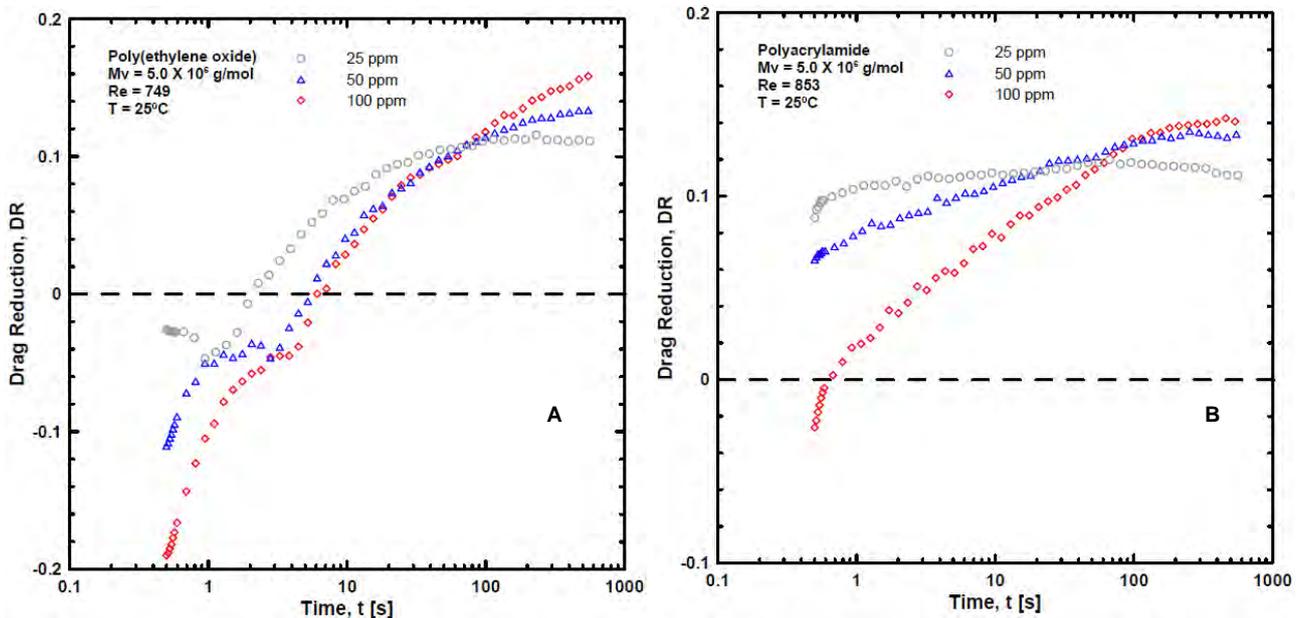


Figure 5. Effect of concentration,  $c$ , on  $DR$  as a function of time at the very beginning of the test.

Figure 5 show an increase of friction factor at the beginning, developing time, and  $DR_{max}$  with increasing of concentration. Since the number of molecules increases, a large amount of energy is removed of the flow at the start of the test for stretch them, causing an increase of the friction factor. Such conditions cause higher disturbance on the flow and the turbulent structures require a larger period of time for arrange. The same concentration effect was reported by Somandepalli et al. (2010) who analyzed a turbulent drag reducing flow over a flat plate. They measured the distance from the injection point to where the maximum drag reduction is observed. This distance is clearly an increasing function of concentration. We can also observe that  $DR_{max}$  is an increasing function of concentration, as widely reported by a number of researchers (Hershey and Zakin (1967), Virk et al. (1967), Burger and Chorn (1980), Moussa and Tiu (1994), Vanapalli et al. (2005), and Pereira and Soares (2012)). Comparing PEO and PAM is clear to see that the increase of friction factor at the beginning, developing time, and  $DR_{max}$  noted in PAM solutions is less significant than in PEO solutions. The developing time with 25 ppm of PAM is very short ( $t_d \approx 3s$ ) and we can see negative drag reduction only with concentration of 100 ppm. In order to highlight a comparison between both polymers, we display in Figure 6 the drag reduction against the time for PEO and PAM solutions,  $M_v = 5,0 \times 10^6$  g/mol,  $c = 50ppm$ .

We clearly note a significant difference between PEO and PAM solutions at the beginning of the test. Solution of PEO shows a considerable increase of friction factor before reaching its maximum efficiency. On the other hand, the result of PAM presents a very short developing time, rendering the negative drag reduction imperceptible. We also observe that  $DR_{max}$  is higher in the PEO solution. We suppose that this behavior is related to two effects. First to the elasticity of each polymer and second to the molecular conformation of each one. Pereira and Soares (2012) verify that  $G'$  (elastic modulus), is higher in PEO solutions,  $M_v = 5,0 \times 10^6$  g/mol, than in PAM solutions,  $M_v = 5,0 \times 10^6$  g/mol, suggesting that the first is more elastic than the second. On the other hand, PAM molecules, when solubilized, possible can expand more freely in the solution (less coiled) than the PEO molecules. Since the PEO molecules are more elastic and less stretched, a greater amount of energy is removed of the flow for stretch them, causing an increase of the friction factor and higher initial disturbance on the flow.

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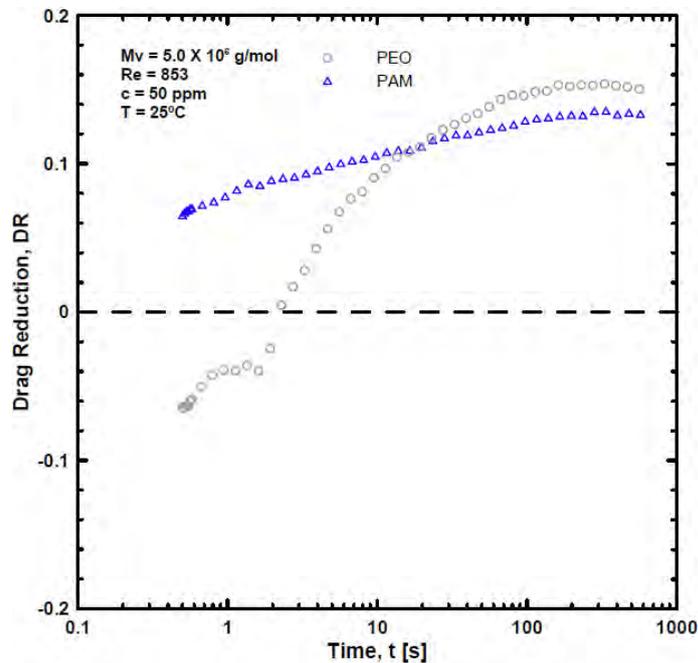


Figure 6. Comparison of  $DR$  as a function of time between PEO and PAM at the very beginning of the test.

It is also interesting to investigate the polymer degradation at the very beginning of the test. It is known that maximum level of efficiency is sustained for a while, the resistance time,  $t_r$  (Pereira and Soares (2012)). Supposedly, when the degradation becomes important,  $DR$  starts to decrease until it achieves its asymptotic value,  $DR_{asymt}$ , a time during which the polymer scission stops and the molecular weight distribution reaches a steady state, as reported by Choi et al. (2000), Nakken et al. (2001), Vanapalli et al. (2005), and Pereira and Soares (2012). However it is still not clear the importance of polymer degradation at the beginning of the test. In order to investigate such effect, four samples of PEO,  $c = 50\text{ppm}$ , in different degradation state, in other words, with different molecular weight, are submitted to the same type of test, displayed in Figure 7. The gray circles are our original sample of  $M_v = 5,0 \times 10^6$  g/mol. The another curves are obtained with samples of  $M_v = 5,0 \times 10^6$  g/mol previously submitted to flow at  $Re=749$  to different periods of time. The sample represented by blue triangles is previously submitted to flow at  $Re=749$  for 10s, time required to  $DR=0$ ; the red lozenges is previously submitted to flow at  $Re=749$  for 600s, time required to  $DR = DR_{max}$ ; the green squares is previously submitted to flow at  $Re=749$  for 3600s, time required to  $DR = DR_{asy}$ . Before start each test, the samples were kept at rest for 60s to the macromolecules relax back ( $60s \gg t_z$ ).

We can see a great difference between each sample at the start of the test. Only 10s (blue triangles) of previously flow causes a significant change of  $DR$  over the developing time, the negative drag reduction, clearly seen in original sample (gray circles), is no longer observed. However, the samples previously submitted to flow for 10s (blue triangles) and 600s (red lozenges) not present loss of efficiency, since  $DR_{max}$  is not change.  $DR_{max}$  is lower only in green squares, previously submitted to flow for 3600s, in other words, as we assumed,  $DR_{max} = DR_{asy}$  in this case. These observations indicate that polymer degradation doesn't play an important role at the beginning of the test. What is not clear is the reason for the samples not degraded (gray circles, blue triangles and red lozenges) present different behavior. In an attempt to understand the effect of molecular weight at the beginning of the test, we conducted some experiments with samples of different molecular weight of PEO,  $c = 50\text{ppm}$ , displayed in Figure 8.

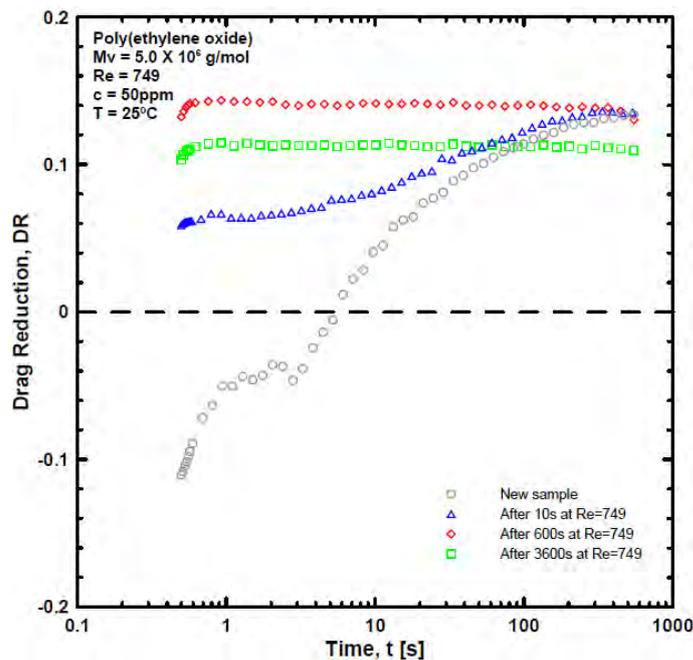


Figure 7. Drag reduction on PEO samples previously submitted to flow at  $Re=749$

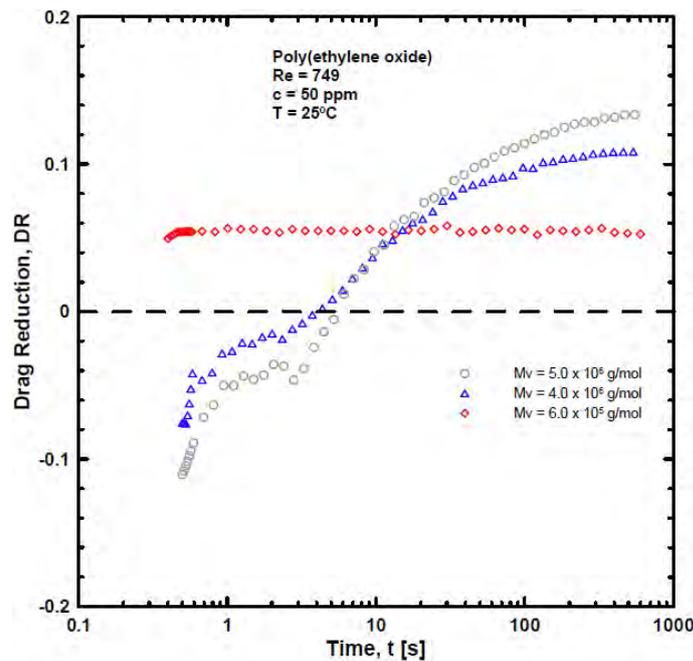


Figure 8. Effect of molecular weight,  $M_v$ , on  $DR$  as a function of time at the very beginning of the test.

We can clearly observe that decreasing of molecular weight causes a significant influence on drag reduction. The developing time and the increase of friction factor at the beginning are an increasing function of the molecular weight. Pereira and Soares (2012) verify that  $G'$  (elastic modulus), is higher in solutions with higher molecular weight, suggesting that the larger molecules are more elastic. Since the longer molecules are more elastic and stretch any further, a larger amount of energy is removed of the flow for stretch them, causing an increase of the friction factor and higher initial disturbance on the flow. Similar effect noted in Figure 7. However, we clearly note in Figure 8 that  $DR_{max}$  is also a function of the molecular weight, as also observe Hershey and Zakin (1967), Virk et al. (1967), Kalashnikov (1998), Vanapalli et al. (2005), and Pereira and Soares (2012). Such results indicate that the effects observed in Figure 7 is not caused by any change of molecular weight of the sample, in other word, any degradation is noted. The results suggest that the molecules in the original sample, before the beginning of the test, are tangled and to stretch they remove a greater amount of energy of the flow. On the other hand, it seems that the molecules do not entangled again

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after they stretch, they just retract or coil. Thus, when the flow is restarted the coiled molecules need smaller amount of energy to stretch than the first time, when they were tangled, causing a lower increase of the friction factor and lower initial disturbance on the flow. Since the molecules is not broken, the efficiency is not affect, providing same  $DR_{max}$ . It is know that higher temperature allow molecules to expand more freely. Then, a way to test this hypothesis is analyzing the drag reduction as a function of the time in different temperatures, as show Figure 9 wherein are tested solutions of PEO,  $M_v = 5,0 \times 10^6$  g/mol,  $c = 50$ ppm.

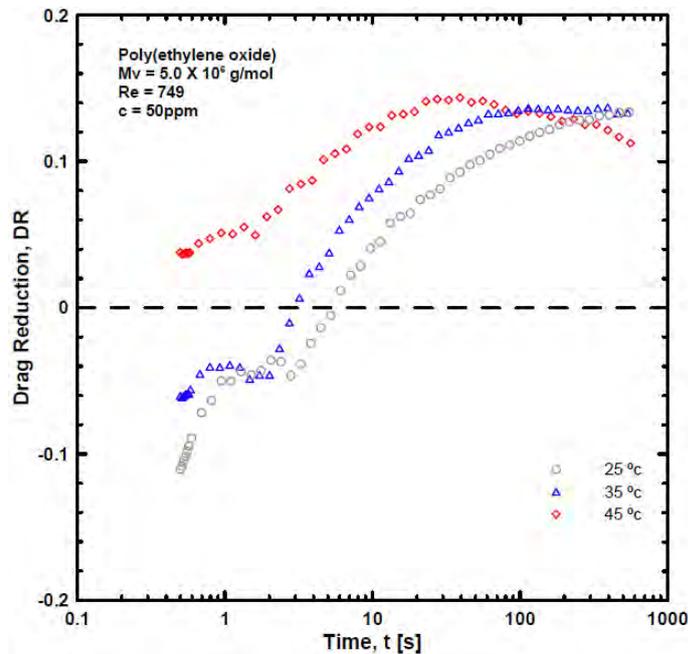


Figure 9. Effect of temperature,  $T$ , on  $DR$  as a function of time at the very beginning of the test.

Figure 9 shows clearly that the increase of friction factor at the beginning of the test is lower when the solution's temperature is increased. In this conditions the developing time decreases, as observe Pereira and Soares (2012). It is know that the higher temperatures causes an increase of the radius gyration of polymer, in other words, the macromolecules are naturally stretched. Therefore, less energy is absorbed of the flow to stretch them initially, causing a lower increase of the friction factor and lower initial disturbance on the flow. As we suppose, these effects are similar to those observed in Figure 7. These results support our hypothesis, but evidently, more tests must be conducted in order to verify such theory. Figure 9 also shows that  $DR_{max}$  is an increase function of temperature, as observe Sohn et al. (2001), and Pereira and Soares (2012).

#### 4. FINAL REMARKS

We presented an experimental approach developed to analyze the development of drag reduction by high-molecular weight polymers at the very beginning of the test using a cylindrical double gap rheometer device. The tests were conducted with dilute solutions of Poly (ethylene oxide) (PEO) and Polyacrylamide (PAM) for a wide range of Reynolds number, polymer concentration, molecular weight, and temperature.

First the Fanning friction factor,  $f$ , was displayed in Prandtl-von Karman coordinates to studied the effect of polymer concentration and molecular weight with increase of the Reynolds number (Figure 3). We verify that an increase of  $c$  and  $M_v$  hastens the on onset of drag reduction and cause a decay of friction factor more pronounced, tendency also observed in other researches. The tests to computing drag reduction as a function of the time were extended over 600 seconds, sufficient time to achieve  $DR_{max}$  in all tests. The results show that the flow stresses at the very start of the test cause an abrupt stretch of the macromolecules, which remove a large amount of energy of the mean flow. This quick removal energy at the beginning of the test cause an increase of friction factor, so  $DR$  decrease and assumes a minimum value (sometimes negative) before reaching its maximum efficiency. We also observed that polymer degradation not play an important hole at the beginning of the test, as presented in Figure 7. Then we suppose that  $DR_{max}$  occurs when the interaction between molecules and turbulent structures (the coil-stretch cycle) reaches a steady state before the degradation becomes important. This interaction is significantly influenced by the increase of concentration (Figure 5), polymer size (Figure 8), and entanglement of the macromolecules (Figure 7 and Figure 9),

making the development time longer. In these conditions the increase of friction factor at the beginning is higher, due the large amount of energy absorbed by the molecules when stretch. On the other hand, higher levels of  $DR_{max}$  are achieved. We also note that the increase of friction factor at the beginning, the developing time, and  $DR_{max}$  is higher in PEO than in PAM solutions. This indicates that PEO molecules are more elastic and less stretched, when the solution is at rest, then the second (Figure 6).

## 5. ACKNOWLEDGEMENTS

This research was partially funded by grants from the CNPq (Brazilian Research Council), the ANP (Brazilian Petroleum Agency), and Petrobras.

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