

POLYMER DEGRADATION IN TURBULENT DRAG REDUCING FLOWS IN PIPES

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ABSTRACT

The drag reduction by addition of high molecular additives has been investigated by a number of researchers since it was reported by Toms more than 60 years ago. One of the most significant limitations in drag reduction is the polymer degradation, which is caused by the turbulent structures. Researches have demonstrated that many parameters affect the polymer efficiency, as: molecular weight, Reynolds number, concentration and temperature. In the present work we investigate this degradation phenomenon in a pipe flow apparatus device, for aqueous solutions of three different polymers: Polyethylene Oxide (PEO), Polyacrylamide (PAM) and Xanthan Gum (XG). The first two are known as flexible molecules while the last one is considered rigid. The dependence of polymer scission on molecular weight, concentration and Reynolds number is analyzed. We report how the drag reduction decreases when the flow pass repeatedly through the pipe and how the pressure loss measured in the apparatus increases, despite to the fact that the experiment was conducted at a fixed inlet pressure. It is worth noting that the mechanism of loss of efficiency for the XG solutions seems to be completely different from that observed for PEO and PAM, the flexible materials.

Keywords: drag reduction, polymer degradation, turbulent flows, polymer molecular weight, polymer concentration

NOMENCLATURE

c	polymer concentration, ppm
d	inner pipe diameter, m
DR	drag reduction
f	non-Newtonian friction factor
f_D	Darcy friction factor
f_0	Newtonian friction factor
l	length of the test section
MDR	maximum drag reduction
M_v	molecular weight, g/mol
N_p	number of passes
PAM	Polyacrylamide
PEO	Polyethylene Oxide
P_{in}	inlet pressure, kPa
Re	Reynolds number
V_m	average flow velocity, m/s
XG	Xanthan gum
T	temperature, K

Greek symbols

η	shear viscosity, Pa.s
ρ	density, kg/m ³
$\dot{\gamma}_w$	shear rate in the wall, 1/s
Δp	pressure drop, Pa

INTRODUCTION

The friction factor reduction in turbulent pipe flows by addition of additive has been studied since

mid-century and has aroused abroad scientific and industrial interest until nowadays. Among the additives most utilized stand out the polymers (Polyacrylamide, Polyethylene Oxide and Xanthan gum), surfactants, fibers (nylon, cotton and asbestos), also paper pulp and gas bubble. The drag reduction using polymeric additives is a phenomenon that was first reported by Toms (1948). The author showed that the addition of small quantities of polymers of high molecular weight in a turbulent flow could reduce significantly the friction factor. Later, Lumley (1969) defined the drag reduction as the reduction of friction factor of the additives solution with respect to the solvent, measured in the same Reynolds number. Thenceforth, the phenomenon has been extensively studied, due the great benefit reached in practical applications in several areas of the engineering. The most famous example is the transport of crude oil in the "Trans-Alaska Pipeline" with 1300 kilometers of extension, in which the addition of 10 ppm of polymer additive reduces the drag by 40%, as is describe by Burger and Chorn (1980). The phenomenon is also used in other pipelines around the world, such as in the Iraq-Turkey, in the Bass Strait in Australia, Mumbai inter alia (Nijs, 1995). The polymer drag reduction technique is also used in firefighting systems (Fabula, 1971), biomedical applications, (Kameneva et al. 2003), irrigation systems, operations in oil wells, etc. However, an important limitation of this technic concerns the polymer mechanical degradation due to exposition of the macromolecules to the shear forces, which are

generated by the turbulent flow. Researches have demonstrated that degradation of polymers is very dependent on: concentration and molecular weight, Reynolds number, temperature, geometry and solvent properties. Recently, these parameters have been studied by numerical simulations (Dimitropoulos, 2005) and experimental procedures (Pereira and Soares 2012, and Pereira et al. 2013). Despite these experiments have shown some qualitative progress on the understanding of the phenomenon, the results can vary according to the level of turbulence and a number of different properties. The goal of the present work is to analyze the phenomenon of drag reduction in turbulent pipe flows by addition of flexible and rigid polymers, using an experimental apparatus in which both the inlet pressure and the flow rate are carefully controlled.

EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus used to conduct the experiments is compound by a thermally insulated galvanized steel pipes (inside diameter 16.35 mm), one magnetic flow meter and three static pressure transducers which are connected in the tube in a position where the flow is fully developed as it is shown in figure 1. Especially, the test section (where is located the pressure transducer) is composed of stainless steel previously polished to improve the quality of the pipe's surface. The solution was driven through a compressor, which is connected pneumatically to a vessel with fixed inlet pressure, 250 kPa.

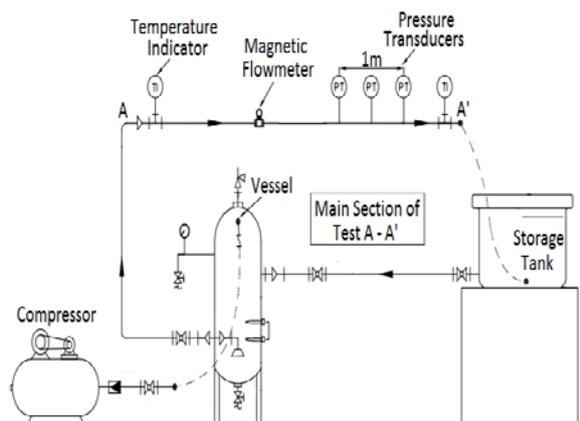


Figure 1. Diagram of experimental turbulent pipe flow.

We used filtered water as our solvent. The reduced friction factor was compared with that obtained for flows into smooth pipes (in our experiments, we used the Blasius friction coefficient for turbulent pipe flow as our reference). Using pure water, the maximum difference observed between our measured friction factor and the Blasius one was 6%, as it shown in figure 2.

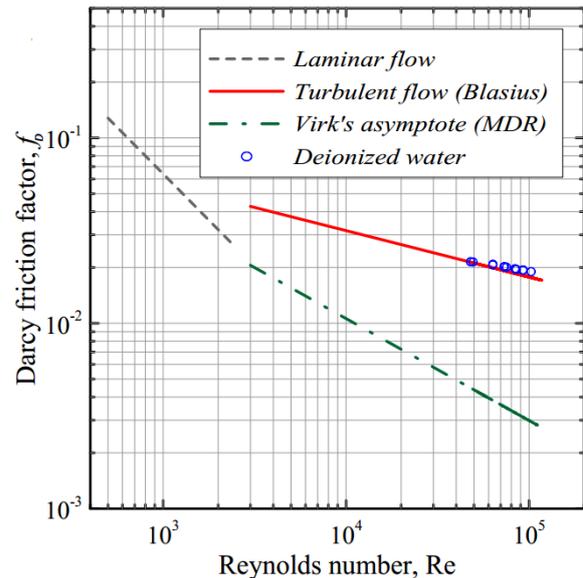


Figure 2. Comparison between the friction factor of experimental apparatus with the Blasius friction coefficient.

The first step of the test is to dilute small quantities of polymer in filtered water, which is later deposited in a reservoir. The solution (water with polymer) is driven through the pipe repeatedly until the final values of drag reduction is reached, when the polymer reaches its minimum molecular weight caused by the mechanical degradation. The tests are conducted at fixed inlet pressure. Our data was acquired by using the program of the National Instruments called LABVIEW. The polymer degradation was analyzed by changing the additive concentration (c ; from 25 to 200 ppm), Reynolds number (Re ; from 60.000 to 110.000) and molecular weight, M_v , of PEO (from 4×10^6 and 5×10^6 g/mol), PAM (5×10^6 g/mol) and XG (2×10^6 g/mol). All our chemical supplies were provided by Sigma-Aldrich. The data acquired during the test (pressure, temperature, viscosity and flow) was analyzed to calculate the drag reduction with the Eq. (4).

Using the density, ρ , and the solution viscosity, η , the mean velocity of the flow, V_m , and with the respectively inner pipe diameter d , then the Reynolds number is calculated as

$$Re = \frac{\rho V_m d}{\eta} \quad (1)$$

As mentioned previously, the friction factor for pure water was calculated using the Blasius correlation,

$$f = \frac{0.316}{Re^{0.25}} \quad (2)$$

Through the pressure difference in a the section test, $\frac{\partial p}{\partial x}$, with constant diameter, where the flow is fully developed, the friction factor of the experimental apparatus is calculated by the Darcy definition,

$$\frac{\partial p}{\partial x} = f_D \frac{\rho V_m^2}{d} \quad (3)$$

The percent Drag Reduction, %DR, was determined following the relation

$$\%DR = \left(1 - \frac{f}{f_0}\right) * 100 \quad (4)$$

where f_0 and f are respectively the friction factor of Newtonian and non-Newtonian turbulent flows.

RESULTS AND DISCUSSION

The main results obtained are presented in terms of drag reduction as a function of the number of passes (N_p) through the pipe line. The tests were conducted at a fixed inlet pressure.

The drag reduction is analyzed taking into account the friction factor of the polymeric solution for each pass. Such a friction factor is compared with the solvent one and DR (drag reduction) is calculated, as defined by Lumley (in the same Reynolds; see Equation 4).

Figure 3 shows the DR as a function of N_p , for the solution of PAM, with molecular weight ($M_v=5 \times 10^6$ g/mol). The range of concentration used was from 25 to 100 ppm, while the temperature and pressure were fixed. The drag reduction decreases when the number of passes through the pipe line increases, until its minimal value is reached at N_p close to 40. Such a number of passes is equivalent to a fluid displacement of 450 m, along the pipeline.

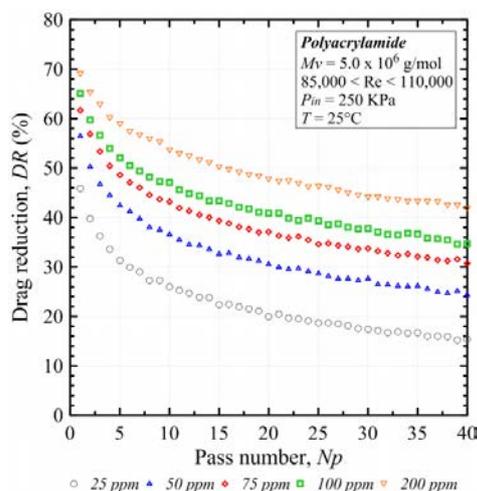


Figure 3. The DR over the N_p through the system for a range of concentrations of PAM.

The referred reduction in efficiency is caused by mechanical polymer degradation with was also observed by Vanapalli et al. (2005). In addition, we observe that the polymer efficiency is an increasing function of its concentration.

For PAM, the results are qualitatively the same that PEO (DR increases with the addition of polymer concentration), as shown in figure 4. Undoubtedly the loss of efficiency in PAM solutions is considerably smaller that in PEO solutions, which suggests that the polymer scission is more intense for the latter. Moreover, the rigid polymer (XG) shows a particular behavior, different from solution of PEO and PAM. The DR abruptly falls in the first steps and keeps constant. Using a different geometry, a rotational apparatus, Pereira et al. (2013) showed the same tendency. It is interesting to note that the asymptotic limit reached by using XG is almost the same than that for PEO (approximately 22% of DR for $c=50$ ppm).

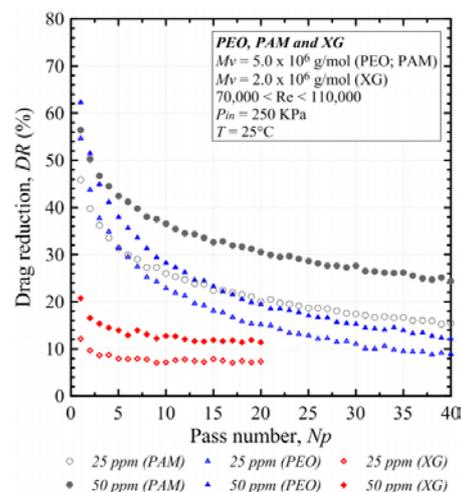


Figure 4. Comparison of DR between flexible polymers (PEO and PAM) and rigid polymer, XG.

Figures 5 and 6 show, respectively, the pressure drop and the flow rate at the test section as a function of the number of passes through the apparatus for PAM. At each figure, the black dashed line is related to the solvent, pure water, at the same inlet pressure. As expected, at a fixed inlet pressure, the flow rate is larger when the polymer solution flows through the pipeline. Obviously, the difference between the solution and water's flow rate increases with the concentration and falls as the number of passes N_p is incremented, which is also expected since the polymer is degraded or de-aggregated step-by-step, before reaching its final mean molecular weight when N_p is close to 40. Also, it is worth nothing that the polymer degradation causes an increase in the pressure loss besides a reduction in the flow rate when the inlet pressure, P_{in} , is fixed. (Note that the Reynolds number is not constant over the number of passes through the apparatus). In a practical point of view, it seems that part of the gain in efficiency

provided by the use of drag reducers is wasted in a system where the inlet pressure is fixed, since the reduction in the friction is not totally transformed in improvement of the flow rate. We believe this point deserves attention, because a quick look at the value of DR may induce to a false conclusion.

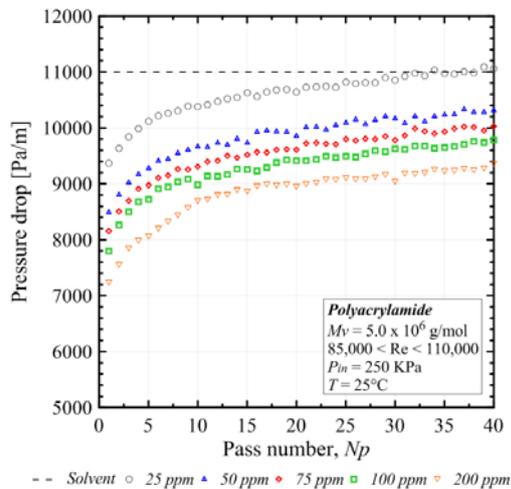


Figure 5. Pressure drop over the N_p for a range of concentrations of PAM.

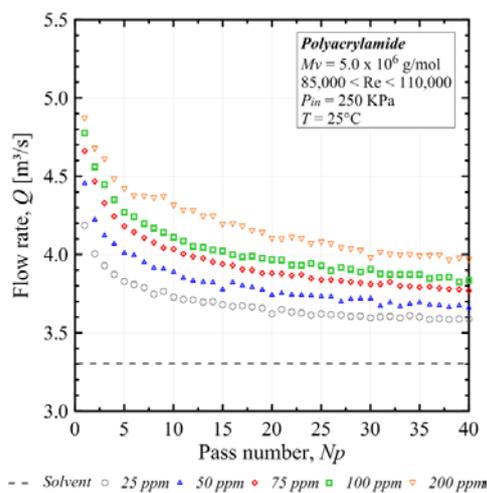


Figure 6. Flow rate over the N_p for a range of concentrations of PAM.

FINAL REMARKS

We analyzed the polymer degradation using an experimental turbulent pipe flow apparatus. The tests were carried out with solutions of PEO, PAM (flexible polymers) and XG (rigid polymer) for different polymer concentrations and molecular weights. The results showed the effect of the Reynolds number, the concentration and the molecular weight in the drag reduction phenomenon. The polymer degradation was computed step-by-step through the experimental apparatus. We also show that the pressure drop in the test section decreases in

spite of the fact that the tests were conducted with a fixed inlet pressure.

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