DRAG REDUCTION BY A MIXTURE OF POLYMERS AND FIBERS EXTRACTED FROM OKRA PODS IN TURBULENT PIPE FLOWS

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Abstract: *Drag reduction by dilute addition of high molecular weight polymers in turbulent flow is an important phenomenon that has been extensively studied by many researchers in the last years. The application of this phenomenon represents a great potential benefit to many industrial processes. However, most of the polymers currently used as drag reduction agents are synthetic polymers, which are not biodegradable and have low resistance to turbulent shear forces. These facts encourage researches on natural biodegradable and more resistant polymers to replace the existing artificial ones. In the present work, the drag reduction efficiency of dilute aqueous solutions of a mixture of fibers and polymers extracted from okra pods is investigated. An experimental apparatus, consisting of a centrifugal pump and a loop pipe system, in which the main section of the test is made of stainless steel with polished treatment, is used. This apparatus has a magnetic flow meter and three pressure transducers for the acquisition of experimental data. The results are focused on the analysis of drag reduction effects produced by the variation of the solution concentration, namely 100, 200, 400, 800 and 1600 ppm. A maximum drag reduction capability of approximately 80% was observed for the 1600 ppm solution concentration. The drag reduction decrease due to material de-aggregation, as the flow passes repeatedly through the pipe apparatus, was also evaluated. The results confirm the efficient applicability of Okra as a drag reduction agent.*

Keywords: *drag reduction, polymers de-aggregation, turbulent flows, natural polymer, polymer concentration*

1. NOMENCLATURE

c polymer concentration, ppm
d inner pipe diameter, m
DR drag reduction
DR_{asy} asymptotic drag reduction
f Darcy friction factor
$f_{blasius}$ Blasius friction factor
f_{virk} Virk friction factor
f_0 Solvent friction factor
MDR maximum drag reduction

Np number of passes
Re Reynolds number
V_m average flow velocity, m/s

Greek symbols

η shear viscosity, Pa.s
ρ density, kg/m^3
Δp pressure drop, Pa

2. INTRODUCTION

Drag Reduction (DR) by polymeric additives is a phenomenon that has been analyzed since the pioneering works of Forrest and Grierson (1931), Toms (1948) and Mysels *et al.* (1949). Toms (1948) was the first to report this phenomenon scientifically and showed that the addition of small quantities of polymers of high molecular weight in a turbulent flow could reduce significantly the friction factor.

A few years later, Lumley (1969) defined drag reduction as the reduction of friction factor of the additive solution with respect to the solvent, measured in the same Reynolds number.

Virk (1975), noted the practical aspects of the problem, such as the effect of the Reynolds number, concentration, molecular weight, solvent quality, and type of polymer on the efficiency of the drag reduction agents. Thereafter, numerous experimental studies related to this phenomenon has been extensively conducted due to the great benefit reached for applications in several areas of engineering.

One of the most famous applications of Drag Reduction Agents (DRA) is the "Trans-Alaska Pipeline", where crude oil was carried by 1300 kilometers of extension, with approximately 40% of drag reduction by the addition of 10 ppm of polymer, as described by Burger *et al.* (1980). There are many other applications for polymer-induced DR, including long-distance transportation of liquids (Mysels *et al.*, 2003), firefighting (Fabula, 1971 and Figueredo and Sabadini, 2003), biomedical application (Kameneva *et al.*, 2004), irrigation (Phukan *et al.*, 2001) and transport of suspensions and slurries (Golda, 1986). However, most of the polymers currently used as drag reduction agents are synthetic polymers, which are not biodegradable, have low resistance to turbulent shear forces and are toxic. Therefore, these polymers cannot be used in some applications like medical and environmental areas.

Abdulbari *et al.* (2014) presented a good review on the use of biopolymers as Drag Reduction Agents Agents, including okra mucilage, and indicate that they are a good alternative to artificial drag reduction agents.

Hong *et al.* (2010) analyzed the effectiveness of Guar Gum (GG) as a drag reduction agent, using a rotating disk apparatus. They concluded that the polymer resistance to shear forces increases with increasing concentration.

In another work, carried out by Ogata *et al.* (2014), *Nata de Coco* suspensions was used as DRA for a pipe flow system. They found that drag was reduced up to 25% with a concentration as low as 50 ppm. The DR effect appeared only when a network of *Nata de Coco* fibers was formed in the suspension and DR increased when fibers size increased.

Another biopolymer used as DRA is produced by marine microalgaes, this biopolymer was studied by Gasljevic *et al.* (2008), where they conducted a series of experiments and observed a great drag reduction effectiveness. These facts encourage researches on the searching for natural biodegradable and more resistant polymers to replace the existing artificial ones.

The goal of the present work is to analyze the phenomenon of drag reduction in turbulent pipe flows of dilute aqueous solutions of a mixture of fibers and polymers extracted from okra pods, using an experimental apparatus in which the pump rotation and the flow rate are carefully controlled.

3. EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus consists of a loop pipe system, composed by thermally insulated stainless steel pipes (inside diameter 16.35 mm), a centrifugal pump, a magnetic flow meter and three static pressure transducers, which are connected to the test section, where the flow is fully developed, as shown in Figure 1. The test section is made of stainless steel with polished treatment to improve the quality of the pipe surface. The solution was driven through a centrifugal pump with fixed rotation of 3000 rpm.
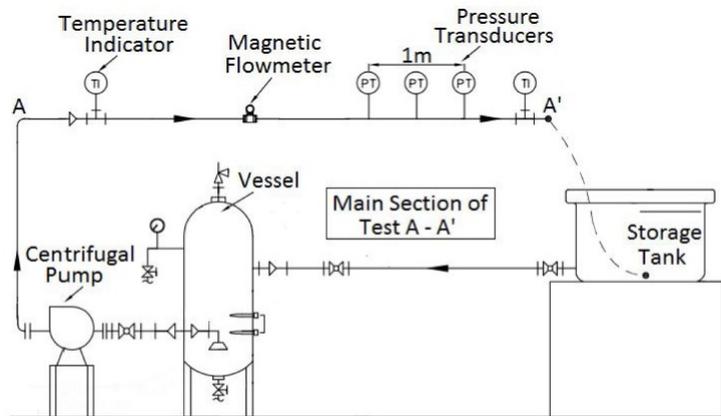

Figure 1: Diagram of experimental turbulent pipe flow apparatus.

Initially, 100 liters of the polymer solution is prepared inside a storage tank. For the total dilution of the polymer in the solvent, the solution remains at rest for two hours and after this time it is smoothly mixed for ten minutes. Then, the solution (water with polymer) is driven through the pipe test by a pump and when all the solution has passed through the pipeline apparatus, one pass is completed. This process is repeated until it reaches an asymptotic value of DR, when the molecular weight is minimum for the flow parameters, caused by de-aggregation of the polymer.

All tests were carried out at a constant temperature of 27 °C. The flow rates and the values of the static pressures at the test section were collected simultaneously by a data acquisition system (LabVIEW from National Instruments). The polymer de-aggregation was analyzed by changing the additive concentration (100 ppm $\leq$ c $\leq$ 1600 ppm) and Reynolds number (65000 $\leq$ Re $\leq$ 87000). The additive used (a mixture of polymer and fibers) was produced in our lab, where the okra pod was cleaned (removing the seeds), totally dried, floured and sifted.

4. VALIDATION AND MATHEMATICAL FORMULATION

Filtered water was used in our experiments as solvent. The validation of our apparatus was done by the comparison between the experimental data, obtained by the test with solvent, and results calculated considering the flow in a smooth pipe (Blasius friction coefficient for turbulent pipe flow was used as reference). The maximum difference observed between the measured friction factor and the Blasius one was 3% as shown in Figure 2.
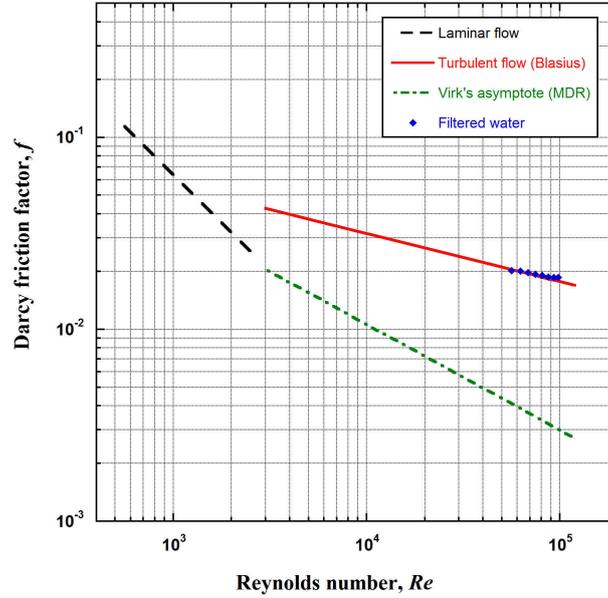
Figure 2: Comparison between the measured friction factor for the water test in the experimental apparatus and the friction factor calculated using Blasius friction coefficient.

The mathematical formulations used on the analysis of the drag reduction phenomenon are given below.

The Reynolds number is given by the following equation,

$$Re = \frac{\rho V_m d}{\eta} \tag{1}$$

where ρ is the density, η is the solution viscosity, V_m is the bulk flow velocity, and d is the inner pipe diameter.

As previously mentioned, the friction factor for the filtered water is calculated using the Blasius correlation,

$$f_{blasius} = \frac{0.316}{Re^{0.25}} \tag{2}$$

According to Virk's law for the Maximum Drag Reduction (MDR) by polymers addictive, the friction factor is obtained by the follow equation,

$$f_{virk} = \frac{1.68}{Re^{0.55}} \tag{3}$$

The friction factor of the experimental apparatus is calculated by Darcy's definition,

$$\Delta P = f \frac{\rho}{d} \frac{V_m^2}{2} \tag{4}$$

The Drag Reduction percentage, %DR, is determined by,

$$\%DR = \left(1 - \frac{f}{f_0}\right) * 100 \tag{5}$$

where f_0 is the friction factor of of the Newtonian solvent and f is the friction factor of non-Newtonian solution flow.

5. RESULTS AND DISCUSSION

Our main results are presented in terms of drag reduction as a function of the number of pass (Np) through the pipeline. For each pass, the drag reduction is analyzed taking into account the friction factor of the polymeric solution compared to the solvent one, thus, DR is calculated as defined by Lumley (in the same Reynolds number).

Figure 3 shows the DR values as a function of Np for the solution of fibers and polymers extracted from the okra pods. As expected, the drag reduction increases with concentration. It is observed that the first value of DR, for the 1600 ppm concentration, was closed to the Maximum Drag Reduction value (MDR) given by the Virk's law. The efficiency falls step-by-step until an asymptotic value (DR_{asy}) is reached after a large enough Np. The number of passes necessary to find the final value of DR, increases with concentration. To reach DR_{asy}, it was required 10 passes for c = 100, 30 passes for c = 400 ppm and around 40 passes for c = 1600 ppm. Since this material is considered rigid, we believe that the loss
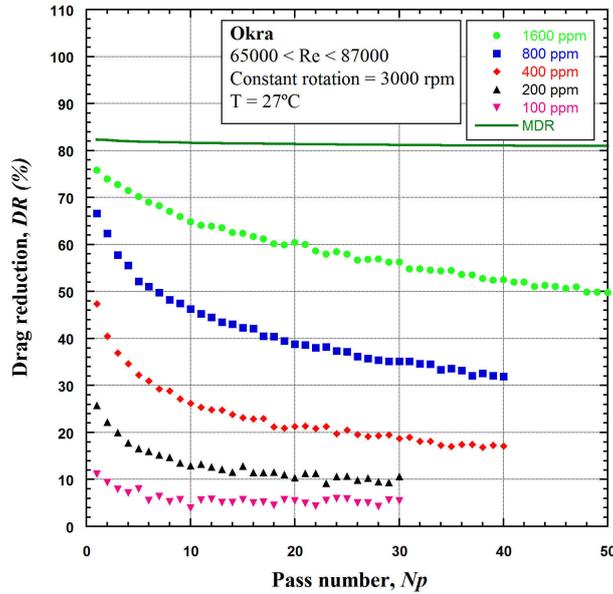
Figure 3: Influence of concentration on Drag Reduction.

of efficiency is not caused by mechanical degradation (mechanical scission of the fibers or polymers), but by material de-aggregation, as noted by Soares *et al.* (2015) for rigid materials like Xhantam Gum. The authors argue that the mechanism of loss of efficiency for rigid materials is related to material de-aggregation and not to mechanical degradation.

Figure 4 shows the flow rate as a function of the number of passes through the pipeline for the fiber and polymers solution of the powder extracted from the okra pods. Obviously, the flow rate for the polymer and fiber solution is larger than that observed for the solvent, which is represented by the black solid line in the figure. As expected, the difference between the flow rate for the solvent and solution cases increases with the concentration and falls with the increase of Np. This falls of flow rate with Np is also associated to the de-aggregation phenomenon. In terms of flow rate for the fixed pump rotation and 1600 ppm of solution concentration, the maximum gain was approximately 1.7 m^3/h (near to 48%) compared to the solvent at the first pass. Concerning to the asymptotic values, this gain was approximately 0.7 m^3/h (near to 20%). In a practical point of view, for this case, it means an equivalent gain in production for the transportation of the fluid.

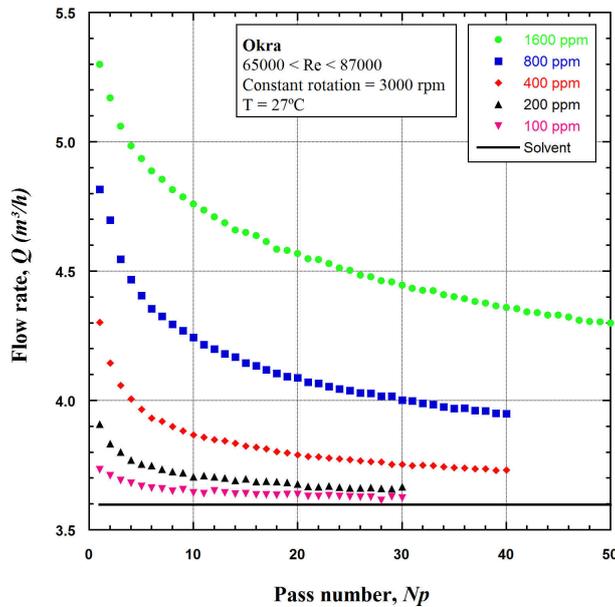

Figure 4: Flow rate over the Np for a range of concentrations of okra.

Figure 5 shows the pressure drop as a function of the number of passes through the pipeline for the okra solution. It's observed that the pressure drop falls with the increase of concentration. As expected, the pressure drop also increases with increasing the number of passes. This is also related to de-aggregation of the material. A pressure drop of almost 5900 Pa/m (near to 47%) smaller was observed for the first pass at 1600 ppm concentration compared to the solvent.

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The same analysis for the asymptotic value shows a 3200 Pa/m (near to 25%) decrease in the pressure drop. This means a gain of operation pressure.
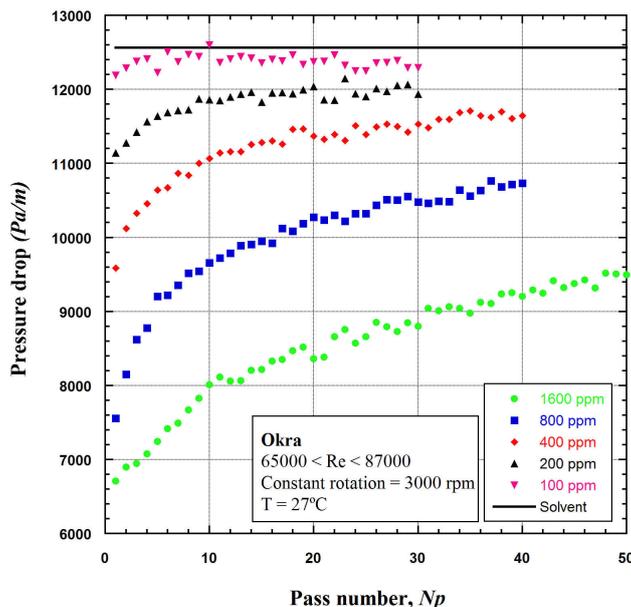

Figure 5: Pressure drop over the Np for a range of concentrations of okra.

It's worth noticing that, for a fixed pump rotation, the material de-aggregation causes an increase in the pressure drop and a reduction in the flow rate. It is also observed that part of the gain in efficiency provided by the use of the drag reduction agent is wasted in a system, where the pump rotation is fixed, if the aim of use is the flow rate. In fact, for a fixed pump rotation, the reduction of the friction factor is not totally transformed in improvement of the flow rate.

6. FINAL REMARKS

The dilute solutions of a mixture of fibers and polymers extracted from okra pods proved to be a good natural option as a drag reduction agent. It was capable to promote a satisfactory drag reduction in the pipeline flow. The results showed the effect of the variation of concentration in the drag reduction phenomenon, where the maximum value of drag reduction obtained was close to 80% for 1600 ppm. The material de-aggregation was also investigated step-by-step through the experimental apparatus, showing the loss of effectiveness of the material through the flow. Besides the satisfactory result, this material also have other advantages when compared to the synthetic one, because, being natural, they are environmental friendly and also cheaper and abundant in Brazil.

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