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# DRAG REDUCTION EXPERIMENTAL ANALYSIS USING *OPUNTIA COCHENILLIFERA* MUCILAGE IN ROTATING GEOMETRY

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**Abstract.** *The drag reduction (DR) by the addition of high molecular weight polymers in turbulent flows is an important phenomenon which has been extensively studied by many researchers since its discovery. The application of these additives represents a great benefit in industrial processes. However, most polymers currently used as drag reducing agents are synthetic, which are non-biodegradable and have low resistance to turbulent shear forces. These facts encourage research in the pursuit of more resistant and biodegradable natural polymers to replace existing artificial ones. This paper proposes the use of mucilage extracted from *Opuntia Cochenillifera* as a drag reducer agent using a rotating cylindrical rheometer device. In addition, a method to extract the mucilage was developed and used for drag reduction tests at a temperature of 25 °C. The results indicate that the *Opuntia Cochenillifera* mucilage is a potential drag reducer, reaching a drag reduction of around 14% for a solution with concentration of 1000 ppm under the Reynolds number of 7500. Furthermore, the application of *Opuntia Cochenillifera* mucilage as a drag reducing agent presents several advantages compared to commercially polymers, such as: the low cost of extraction, production, and refining; its biodegradability and the easy access as a natural abundant raw material in Brazil.*

**Keywords:** *Drag Reduction. Biopolymer. Opuntia Cochenillifera. Rotating geometry.*

## 1. INTRODUCTION

Since the first time that drag reduction (DR) by additives injection was reported by Toms (1948), many studies have been carried out on this phenomenon. The polymer drag reduction (PDR) consist by addition of a small amount high weight polymer in a solvent in turbulent flows and has aroused the interest of many researchers due to its wide applicability in engineering.

The main example of application of drag reduction by addition of polymer is the transport of crude oil known as the *Trans-Alaska* pipeline, a system of pipelines with a diameter of 1.20 meters, 1288 kilometers in length, 12 pumping stations, with capacity to transport 1.8 million barrels of crude oil per day. A small amount of the polyolefin polymer was added to the pumping stations, to increase the flow while keeping the pressure differential constant, resulting in an increase in production of approximately 30% and a friction factor reduction around 40%, as reported by Burger *et al.* (1980).

In order to increase the range of water jets, Figueredo and Sabadini (2003) investigated the effects of the application

of additives in drag reduction on firefighting systems. The use of additives is also presented as a viable solution for increasing water flow in irrigation and hydroelectric systems, as reported by Singh *et al.* (1985), in the transport of mud and suspensions portrayed by Golda (1986). The applications studied by Larson (2003) of drag reduction additives in ship hulls stand out to reduce friction between the hull and the water, increasing the vessel's speed. Applications in turbopumps, to prevent cavitation and suppress noise and in thermal systems, to reduce energy consumption, both applications presented by Gyr and Tsinober (1997).

Furthermore, a field of application of the technique of drag reduction is biomedicine, as reported by Greene *et al.* (1980), the use of additives may help prevent atherosclerosis (characterized by the accumulation of fat in blood vessels) and reduce the rate of hemolysis (the process of rupture of the red blood cell membrane).

However, most of the studies presented in the literature use synthetic polymers as additives, which becomes an obstacle for the application in areas which require the use of non-toxic materials, such as the food, environment, and medicine sectors. On the other hand, in addition to the characteristic of non-toxicity, natural polymeric additives have greater mechanical strength compared to synthetic ones (de Oliveira Barbosa, 2017; Coelho, 2016).

Experimental DR analysis performed in flow loop apparatus generally requires high test time and sample volumes. These difficulties are overcome by employing rotating geometry to carry out the tests. Therefore, this work aims to develop a method for producing mucilage extracted from *Opuntia Cochenillifera* and investigate its behavior as a potential drag reduction additive using a rotating cylindrical rheometer device.

## 2. METHODOLOGY

In this topic will be presented the experimental apparatus, the production methodology of the material studied and the procedure of the experiments performed.

### 2.1 Experimental apparatus

Most of the experimental results available in literature were obtained in flow loop apparatus due to their wide use in industrial transport processes. However, the use of pipe flow systems to analyze degradation is complex and takes a lot of time of experiments. An alternative to avoid these difficulties is the use of cylindrical double gap geometry in a rotational rheometer. This type of geometry, used by Pereira and Soares (2012), Pereira *et al.* (2013) and Andrade *et al.* (2015) provides good accuracy even for relatively small values Reynolds numbers due to their large contact area. A scheme of this cylindrical double gap geometry is shown in Fig. 1.

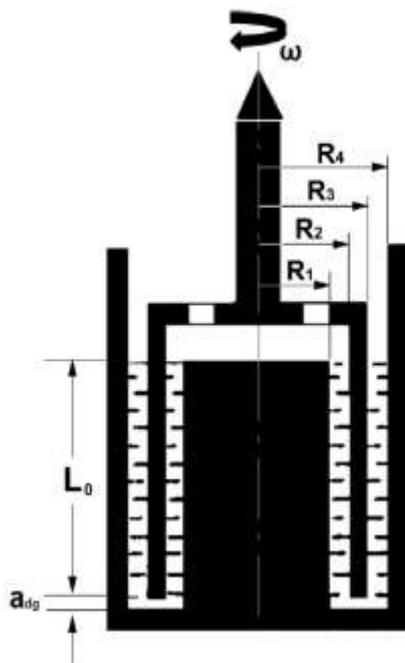


Figure 1. Schematic illustration of the axial symmetric double gap geometry.  
Source: de Oliveira Barbosa (2017).

In this work, the drag reduction tests were carried out using a commercial rheometer model HAAKE MARS 60, manufactured by Thermo Scientific, Germany. All tests were performed at a temperature of 25 °C.

In the double gap geometry used, the sample is located between two coaxial surfaces that are rigidly interconnected and

stationary, which have axial symmetry. The rotor is a thin-walled coaxial tube located between these two fixed cylindrical surfaces that can rotate over the sample holder's axis of rotational symmetry at a certain angular velocity. The geometry has the following dimensions of radius and rotor length:  $R_1 = 17.75$  mm,  $R_2 = 18.00$  mm,  $R_3 = 21.40$  mm,  $R_4 = 21.70$  mm and  $L = 55.01$  mm. The sample volume is 7.00 ml.

For the double gap geometry, for a certain angular velocity ( $\omega$ ), the mean shear rate ( $\dot{\gamma}$ ) is determined by Eq. (1), as a function of the rotor speed of rotation ( $n$ ) and a geometrical factor ( $K$ ), which is given by Eq. (2)

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

$$K = \frac{2R_4^2}{R_4^2 - R_3^2} = \frac{2R_2^2}{R_2^2 - R_1^2} \quad (2)$$

The Fanning friction factor based on the characteristic radius, which is the mean radius  $\bar{R}$  for the double gap geometry, is determined according to Eq. (3), where  $\tau_w$  is the nominal wall shear stress (related to the measured torque on the rotor),  $\rho$  is the density and  $\omega\bar{R}$  is a characteristic velocity.

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

$$\bar{R} = \frac{R_2 + R_3}{2} \quad (4)$$

The Reynolds number is defined according to Eq. (5), where  $\eta$  is the viscosity and  $\tau_w = \eta\dot{\gamma}$ .

$$Re = \frac{8\rho\bar{u}^2}{\tau_w} = \frac{8\rho\omega\bar{R}^2}{\eta K} \quad (5)$$

According to Lumley (1969), in relation to the Fanning friction factor, drag reduction occurs when the polymer solutions friction factor ( $f_p$ ) is lower than friction factor of solvent ( $f_s$ ) flowing at same Reynolds number. Thus, the equation that defines the drag reduction is given by Eq. (6).

$$DR = 1 - \frac{f_p}{f_s} \quad (6)$$

## 2.2 Mucilage extraction method and storage

*Opuntia Cochenillifera* undergoes four stages before obtaining the final product, which is the mucilage. First, the plant was washed to eliminate possible impurities. Subsequently, the leaves goes through the grating process to increase the contact area of its internal surface with the water to extract the largest amount of gum. Then it is placed in the sauce. After 40 minutes of rest of the mixture, the first stage of the coarse sieving is carried out, sequentially the fine sieving takes place. The solution resulting from the sieving process is filtered using a thin fabric made of lycra and this process is repeated twice.

Figure 2 illustrates the steps of the procedure detailed above, which are: (A) cleaning the leaves; (B) properly sanitized *Opuntia Cochenillifera*; (C) grating process; (D) extracted gum; (E) soaking process; (F) coarse sieving; (G) fine sieving; (H) tissue filtration.

For the analysis of the main parameters of drag reduction it is necessary to have a standardization of the samples in a way that allows the comparison of the results. Therefore, it is crucial that the samples used in the tests come from the same batch. As the volume required of double gap geometry is 7 ml, it was necessary to produce small volumes of samples. Therefore, 1360 grams of grated *Opuntia Cochenillifera* were used, diluted in 2 liters of water, resulting in 1455 grams of mucilage after the last filtration step. The final product was filled into nine 50 ml containers for drag reduction tests and the excess amount was used to determine the batch concentration. To preserve the integrity of the samples the freezing method was chosen. However, to make sure that freezing would not affect the rheological characteristics the mucilage properties and, consequently, the drag reduction efficiency, one of the samples was tested without freezing to obtain a reference for comparison. Such analysis will be presented later in Section 3.1.

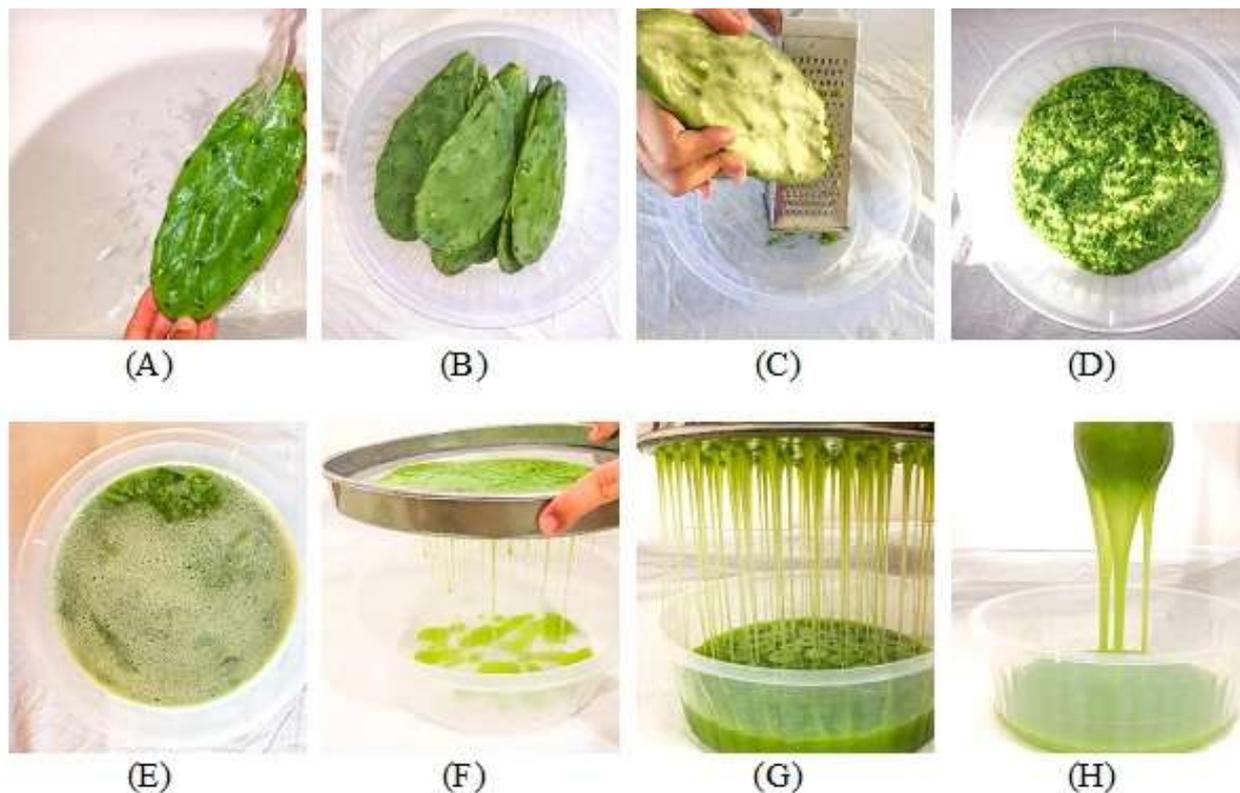


Figure 2. Steps of the *Opuntia Cochenillifera* mucilage extraction procedure.

Source: Authors.

### 2.3 Measurement of sample concentration procedure

As mentioned, after the mucilage was extracted, a sample was taken and used to determine the concentration of the batch. This sample was divided into two glass containers (petri dishes). Subsequently, the mass of the mucilage contained in each of these containers was measured by weighing and then the samples were taken to drying in an oven. After 3 days keeping the samples at a temperature of 60 °C, the mass of the completely dehydrated mucilage was measured also. The concentration was calculated from the mass of the sample before and after drying. Table 1 presents the results obtained. The batch concentration of *Opuntia Cochenillifera* was about 11176 ppm.

To weigh the mucilage extracted from the *Opuntia Cochenillifera* an electronic analytical balance with capacity of 320 g was used, model ABT 302-4M manufactured by the company KERN & SOHN GmnH, which precision of 0.1 mg.

Table 1. Masses measured and the respective concentration of the batch.

<i>Opuntia Cochenillifera</i>	Mass		
	Mucilage [g]	Dehydrated mucilage [g]	Concentration [ppm]
Sample 1	162.1108	1.81180	11176.3043
Sample 2	162.1074	1.81175	11176.2325
Average	-	-	11176.2684

## 3. RESULTS AND DISCUSSION

### 3.1 Analysis of solution storage methodology

To verify if the freezing storage method would be impact the drag reduction, a test was carried out varying the rotational speed of rotor from 0 to 1200 rpm. Was used a natural sample and another subjected to freezing (both at the same concentration) to obtain a comparison between the behavior of the Fanning friction factor.

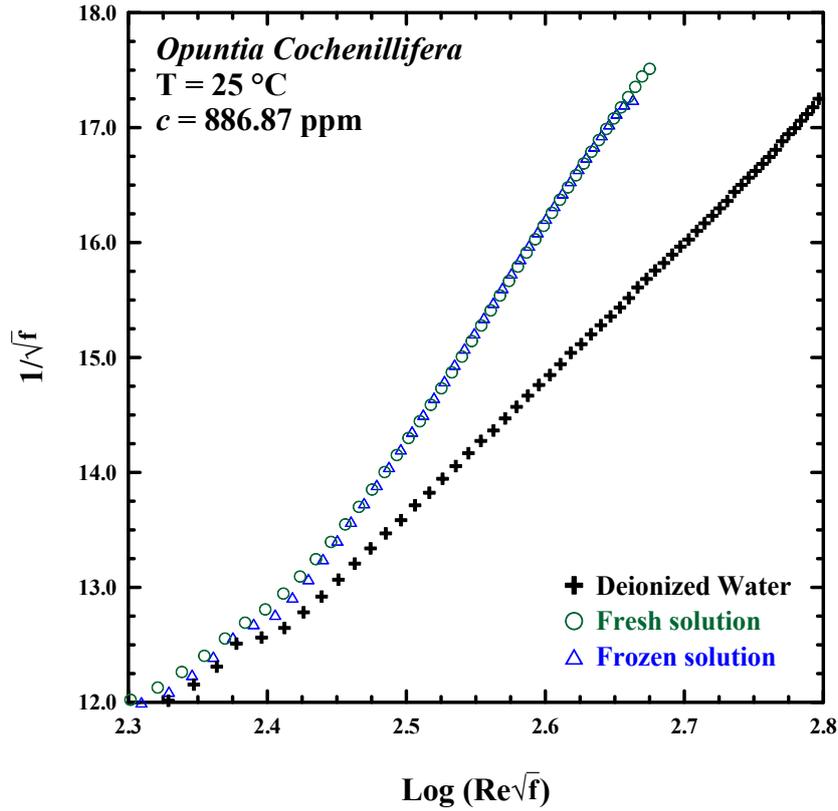


Figure 3. Fanning friction factor in Prandtl-von Kármán coordinates of frozen *Opuntia Cochenillifera* mucilage solution and natural *Opuntia Cochenillifera* mucilage solution.  
 Source: Authors.

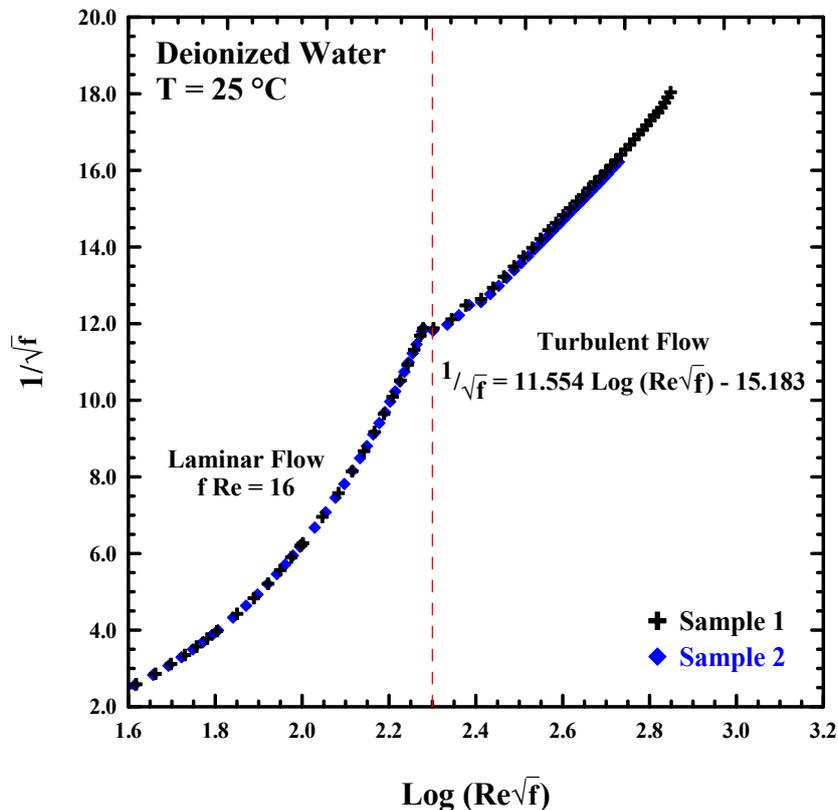


Figure 4. Fanning friction factor in Prandtl-von Kármán coordinates of deionized water (solvent).  
 Source: Authors.

As shown in Fig. 3 in Prandtl-von Kármán (PVK) coordinates, it is evident the behavior of the solution curves is quite similar. Besides, can be observed that the beginning of drag reduction (onset) for both samples occurs simultaneously at the same point. According to Virk *et al.* (1967), onset is related to the wall shear stress or minimum strain stress necessary to initiate the drag reduction. Therefore, it is concluded that the freezing storage methodology does not significantly impact the drag reduction.

### 3.2 Analysis of concentration on the Fanning friction factor

To realize the analysis the behavior of the concentration of solution on the Fanning friction factor in the the laminar and turbulent flow, tests were performed varying gradually the rotational speed of rotor from 0 to 1800 rpm in a period of 1200 seconds. Figure 4, Figure 5 and Figure 6 presents the results obtained.

Figure 4 shows the results of tests performed used the solvent (deionized water). The behavior of the water Fanning friction factor is verified in Prandtl-von Kármán coordinates. It is possible to identify the laminar and turbulent flow regimes and the equations of  $fRe$  for each regime. Note that the turbulent flow regime begins at about  $\text{Log}(Re\sqrt{f}) = 2.3$

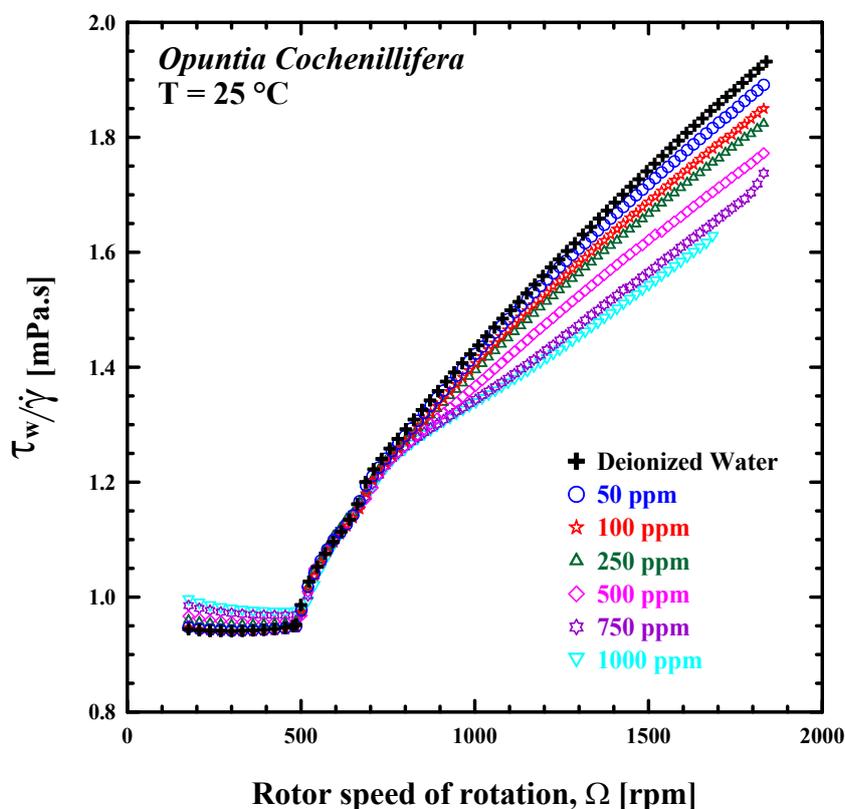


Figure 5. Nominal shear viscosity of *Opuntia Cochenillifera* mucilage solutions as function of rotor speed of rotation for different concentrations.

Source: Authors.

In Figure 5, it is observed that until a rotation approximately of 500 rpm for the all *Opuntia Cochenillifera* solutions the flow regime is laminar and no instabilities. Then, the sharp slope of the curves is observed, indicating the beginning of instabilities in the flow. The phenomenon of drag reduction can be noticed when the nominal shear viscosity curves of the solutions become lower than the water (solvent) curve. This behavior occurs for rotation higher than approximately 1100 rpm for the 50 ppm concentration, 800 rpm for the 100 ppm solution and 700 rpm for the concentrations of 250 ppm, 500 ppm, 750 ppm and 1000 ppm. These results are interesting because they allow a previous qualitative analysis of drag reduction of the solution, simply by observing the characteristics of the behavior of nominal shear viscosity of solution as function of rotor speed of rotation.

The results illustrated in Fig. 6, presented in Prandtl-Von Karman coordinates, demonstrate the influence of concentration of solution on the Fanning friction factor and onset of drag reduction. Note that the point where drag reduction starts varies according to the concentration of the solution. Following the analysis realized by Pereira and Soares (2012), it is possible to conclude that the increase in concentration anticipates the beginning of the drag reduction (onset).

Furthermore, it is possible to observe that increase the concentration causes a significant reduction of the Fanning friction factor of the solution compared to the solvent. This fact is observed by the behavior of  $1/\sqrt{f}$  as a function of

$\text{Log}(Re\sqrt{f})$  in Fig. 6 varying the concentration, where the curves shift upwards showing the reduction of friction.

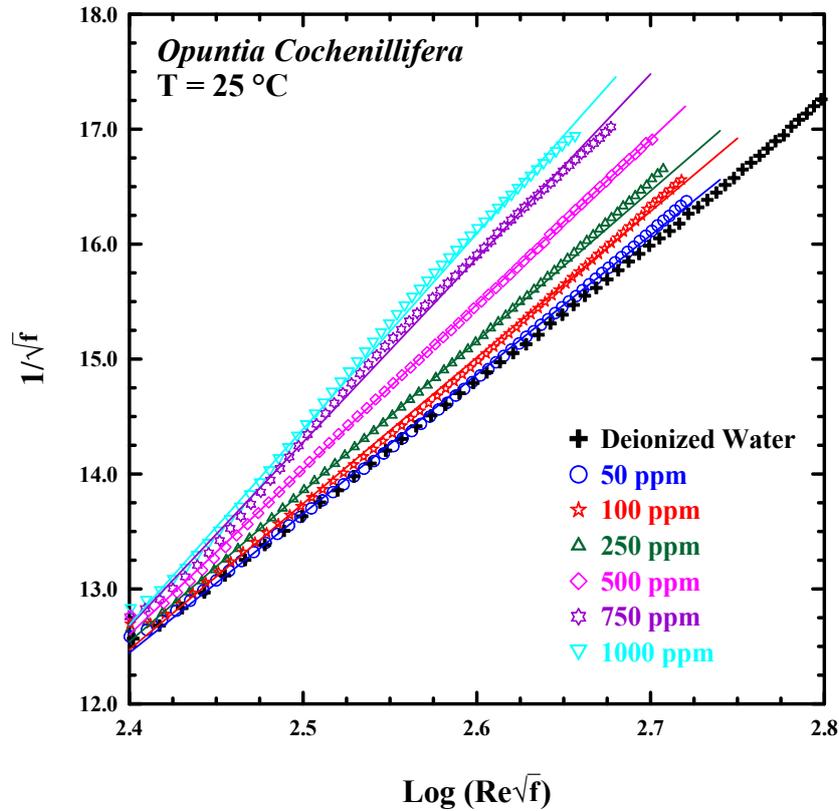


Figure 6. Fanning friction factor in Prandtl-von Kármán coordinates of *Opuntia Cochenillifera* mucilage solutions as function of concentration.

Source: Authors.

### 3.3 Analysis of concentration on the drag reduction for the same Reynolds

The Reynolds number of approximately 7500 was adopted for different concentration of *Opuntia Cochenillifera* mucilage solutions to estimate their influence on drag reduction. This Reynolds number corresponds to  $\text{Log}(Re\sqrt{f}) = 2.68$  for deionized water (solvent) in Fig. 5, which corresponds a turbulent flow regime. Table 2 presents the Fanning friction factors obtained for each *Opuntia Cochenillifera* solution at the same flow condition.

Table 2. Fanning friction factors and DR obtained for the *Opuntia Cochenillifera* mucilage solutions for different concentrations.

SAMPLE	Reynolds number = 7500	
	Fanning friction factor	Drag reduction [%DR]
Deionized Water	0.004084	-
50 ppm	0.004006	1.90%
100 ppm	0.003933	3.70%
250 ppm	0.003858	5.54%
500 ppm	0.003735	8.53%
750 ppm	0.003593	12.01%
1000 ppm	0.003524	13.71%

From the Fanning friction factor obtained by Eq. (3), the drag reduction is calculated by Eq. (6). Therewith, a DR of approximately 8.53% was obtained for the concentration of 500 ppm, 12.01% for the 750 ppm concentration and 13.71%

for the 1000 ppm solution. Therefore, the exposed results indicate that the increase of solution concentration increase the drag reduction, as reported by Pereira and Soares (2012).

#### 4. CONCLUSIONS

This work objectives to present the feasibility of using mucilage extracted from *Opuntia Cochenillifera* as a drag reducing agent (DRA). In addition, to obtain this new natural DRA, was necessary to develop a methodology for extracting and refining the mucilage, since it cannot be found commercially in the appropriate form for the application.

In fact, the analyzes obtained from experimental tests carried out in the rheometer indicate that the use of a small amount of mucilage in turbulent flows is capable of significantly reducing drag. Additionally, it is possible to infer from the results presented in Section 3.3 that increasing the concentration of the solution increase the drag reduction, which are theoretically limited by the Virk asymptote.

The application of mucilage extracted from *Opuntia Cochenillifera* as a drag reducing agent has several advantages over the polymers used commercially. Among these, we can highlight the low cost of extraction, production and refining; the fact that the mucilage is extracted from a plant, and therefore, considered biodegradable and natural, which can enable its application in critical areas, such as solutions that involve direct and indirect contact with the environment and even contact with living tissues in biomedical applications; abundant raw material, since the cultivation of this plant is widely spread in Brazil, especially in the northeast, north and center-west regions, where the cultivation is mainly intended for cattle feeding.

Furthermore, the results presented in Section 3.1 indicate that the storage of mucilage in frozen form (capable of delaying the effects of the biodegradability of mucilage) does not significantly impact the behavior of viscosity curves, indicative of minimal change in the properties of DR.

In view of this, it is possible to conclude that the results obtained in this research are considered satisfactory and promising. As a future work, it is suggested to carry out tests in flow loop apparatus for a more accurate measurement of drag reduction, a better characterization the flow behavior in higher Reynolds and verify the mechanical strength of this material. In addition, it is critical to understand the influence of temperature, flow and storage time and extraction methodology on the DR values, as well as, the influence that the extraction site and its environmental conditions exert on the experimental results. Additionally, tests using *Opuntia Cochenillifera* mucilage with other drag reducing polymer and the investigation of their synergistic effects are suggested.

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