Effect of Reynolds Number and Concentration of Biopolymer (Gum Arabic) on Drag Reduction of Turbulent Flow in Circular Pipe

Kamaljit Singh Sokhal, Gangacharyulu Dasoraju, Vijaya Kumar Bulasara

Abstract**—**Biopolymers are popular in many areas, like petrochemicals, food industry and agriculture due to their favorable properties like environment-friendly, availability, and cost. In this study, a biopolymer gum Arabic was used to find its effect on the pressure drop at various concentrations (100 ppm – 300 ppm) with various Reynolds numbers (10000 – 45000). A rheological study was also done by using the same concentrations to find the effect of the shear rate on the shear viscosity. Experiments were performed to find the effect of injection of gum Arabic directly near the boundary layer and to investigate its effect on the maximum possible drag reduction. Experiments were performed on a test section having i.d of 19.50 mm and length of 3045 mm. The polymer solution was injected from the top of the test section by using a peristaltic pump. The concentration of the polymer solution and the Reynolds number were used as parameters to get maximum possible drag reduction. Water was circulated through a centrifugal pump having a maximum 3000 rpm and the flow rate was measured by using rotameter. Results were validated by using Virk's maximum drag reduction asymptote. A maximum drag reduction of 62.15% was observed with the maximum concentration of gum Arabic, 300 ppm. The solution was circulated in the closed loop to find the effect of degradation of polymers with a number of cycles on the drag reduction percentage. It was observed that the injection of the polymer solution in the boundary layer was showing better results than premixed solutions.

Keywords**—**Drag reduction, shear viscosity, gum Arabic, injection point.

I. Introduction

FLOW through the pipelines are very common in a number of industries like petrochemical, district cooling & heating, hydraulic fracturing, and irrigation etc. Most of these industries are working in a turbulent flow regime where Reynolds number of flowing liquids are quite high. When Reynolds number is more there is sufficient reduction in the pressure at the outlet as compared to the inlet pressure. A number of methods are implemented to reduce the pressure drop and maintain the flow rate as a change in pipe materials, coated surfaces etc. but most of these methods were led to the more equipment cost. A few decades ago, during the transportation of the wood fibres, it was observed that there was a considerable amount of pressure drop reduction. This accidental discovery lead to open a way to find a new solution to the energy lost in the form of pressure drop. A number of authors worked hard to develop this phenomenon which is nowadays known as “drag reduction phenomenon” [1]-[10]. Initially, the drag reduction was observed by using various types of fibers like natural and artificial fibers. But the use of the long chain polymers leads to a drastic change in the equipment design as well as commercialization of the drag reduction.

Many authors like Virk, Lumley, and others [1]-[4] have done severe work to establish the fundamentals of the drag reduction phenomenon. Many laboratories, as well as numerical simulations, were done to find the effect of various polymers and other additives on the maximum possible reduction [5]. It was observed that a small amount of long-chain polymer was able to reduce the pressure drop in the significant amount which in turn saving of pumping power. Drag reduction is a boundary layer phenomenon because a significant effect of the polymer addition has been found near the boundary layer. Many theories and models were developed to explain this phenomenon but still, the exact answer is unknown [6], [7]. A number of experimental evidence is available in which various authors have performed an enormous amount of experiment to find the effect of various parameters on the drag reduction. Some studies have shown the effect of concentration and Reynolds number on the percentage of drag reduction [8]. Similarly, the effect of the premixed polymer solution, as well as directly injected near the boundary layer, was also investigated [9].

In the present study, the effect of a biopolymer, gum Arabic, was investigated on the maximum possible drag reduction. For that, the concentration of the polymer solution was varied with respect to Reynolds number to find the best possible concentration with maximum possible drag reduction. The same concentrations of the polymer solution were circulated in the closed loop for 1400 cycles to find the effect of the shear degradation on the effectiveness of the polymer solution.

II. Materials and Methods

A. Materials

A biopolymer gum Arabic was used during the experimentation which is also known as Gum acacia. It is a water-soluble biopolymer used in many industries like food, ceramics, textile, and pharmaceutical etc. it has very good

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emulsion stability, water holding and microencapsulation properties. Gum Arabic used in this study was 100 mesh size powder and purchased from Alpha Aesar (Thermo Fisher Scientific Inc., USA)

B. Polymer Solution Preparation

The polymer solution was prepared by using mechanical impellor controlled by a speed regulator. Initially, the speed was set on 200 rpm as low speed to form the vortex as well as to avoid the scission of the polymer molecules. By using speed regulator impellor speed was set to 200 rpm in water and the polymer powder was added in the vortex. The powder was added in the small portion at different time intervals to avoid lumps formation in the solution [10]. After addition of the polymer, speed was set to 400 rpm when the solution gets viscous. The solution was stirred for 7 hours and then left overnight for proper hydration. The master solution was prepared with 10000 ppm concentration and during experimentation, the solution was diluted as per the required concentration (100 – 300 ppm).

C. Shear Viscosity

Shear viscosity of each concentration was measured to characterize the flow behavior of the polymer solution under the shear rate. A rotational rheometer was used to measure the viscosity of the polymer solution with cone and plate geometry with 1° angle (Anton Paar, MCR 52 series, Germany). Rheometer consists of a Peltier system to control the decrease and rise in temperature. The shear rate was varied from 0.1 to 1000 s^{-1} with temperature 25 ± 0.5 °C.

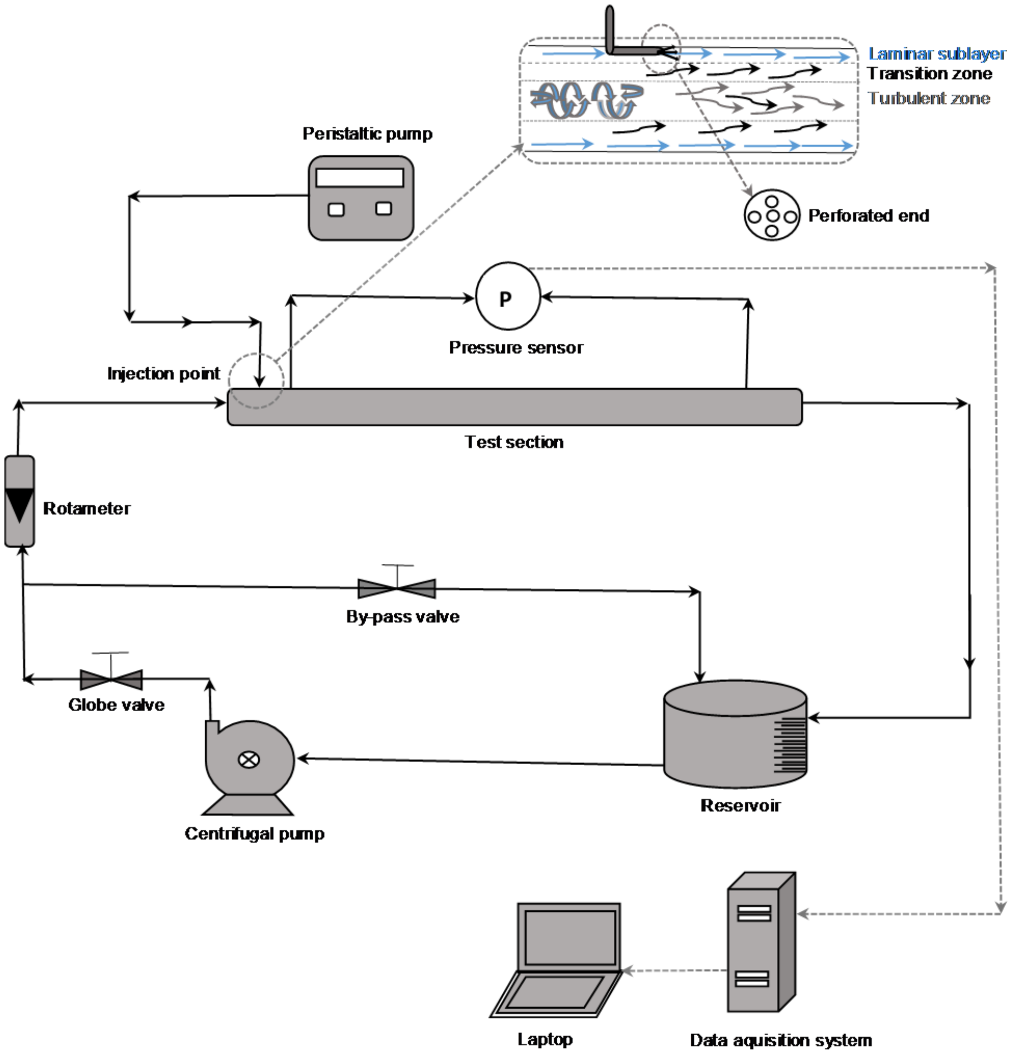

Fig. 1 Schematic diagram of the experimental set-up

III. Experimental Set-Up

The experimental set-up used to perform all experiments is shown in Fig. 1. A circular galvanized iron pipe having inlet diameter 19.05 mm and of length 5040 mm was used as a test section. The distance between the two-pressure tapping was kept as 3048 mm. A digital pressure transducer (Honeywell STD730, USA) was used to continuously monitor the pressure drop around the test section. The pressure transducer was having accuracy 0.05% and range from -7 to 7 bar connected with a continuous data acquisition system to record the readings. The polymer solution was injected continuously by using a peristaltic pump (400 mL/min) through the hole before the first pressure tapping. To achieve the proper mixing of the polymer the length of the pipe was kept accordingly. There was no other inline mixing device was used to enhance the mixing. The speed of the injection of the polymer solution was controlled according to the speed of the bulk fluid so to avoid any disturbance in the flow. A small diameter tube having 5 mm diameter was used inside the test section with the perforated end for the polymer solution to be injected in the form of the sprinkler to enhance the mixing in small length.

The polymer solution was injected in the bulk solution for a time period continuously and then it was stopped to observe the effect of the shear degradation on the effectiveness of the polymer. Continuous degradation of the polymer was observed in the form of the pressure drop. The maximum drag reduction was observed during the continuous injection of the polymer. A centrifugal pump (3000 rpm) was used to maintain the required Reynolds number in the test section. A variable area type flowmeter was used to measure the flow rate (800 L/h to 2400 L/h) with an uncertainty of ±1.5%. Water was collected in the reservoir in which an impeller was fitted for continuous rotation at 30 rpm to keep the polymer solution mixed in the bulk fluid properly during the degradation study. The speed of the impeller was kept low to eliminate the chance of mechanical degradation of polymer molecules due to shear.

Initially, the fresh water was circulated through the test section for the steady-state and thereafter the injection of the polymer was started. The solution was again circulated from the reservoir to the test section by using the centrifugal pump for 1400 cycles to observe the continuous degradation. Tap water was used during the experimentation. The values of the concentration of the polymer solution given are as per the values corresponding to the bulk solution. All the experiments were performed at 25 ±0.5°C. A proper length was kept before and after the test section to avoid the entrance losses for water. Experiments were performed three times for each concentration to check the reproducibility of the values. A bypass valve is connected before the flowmeter to ensure the fully developed flow and to adjust the required flow through the test section. Some of the parameters used during the experimentation are given in Table I.

TABLE I
VARIOUS PARAMETRIC CONDITIONS USED DURING THE EXPERIMENTATION

Parameter	Unit	Range/type
Flow rate of water	L/h	800 – 2400
Reynolds number	-	17000-45000(approx.)
Biopolymer	-	Gum Arabic (100 mesh powder)
Concentration of biopolymer	ppm	50-300

As the flow of the water through the test section is turbulent, all the calculations for the outcomes were calculated as follows. The mean shear stress (τ_w) at the wall can be calculated by using (1):

$$\tau_w = \frac{D\Delta P}{4\Delta x} \quad (1)$$

ΔP is the pressure drop along the pipe length Δx and D is the internal diameter of the pipe. To calculate the friction factor (f) from calculated shear stress (τ_w) from (2):

$$f = \frac{\tau_w}{\frac{1}{2}\rho u_m^2} \quad (2)$$

ρ is the density and u_m are the mean velocity of the fluid circulating through the pipe. Reynolds number can be calculated for laminar and turbulent flow by using (3) and (4) respectively:

$$f = \frac{16}{\mathrm{Re}} \quad (3)$$

$$\frac{1}{\sqrt{f}} = 4\log_{10}(\mathrm{Re}\sqrt{f}) - 0.4 \quad (4)$$

Reynolds number was calculated on the basis of the bulk fluid properties circulating through the test section. Equation (5) was used to find the optimization of the observed values which is known as the maximum drag reduction asymptote.

$$\frac{1}{\sqrt{f}} = 19.0\log_{10}(\mathrm{Re}\sqrt{f}) - 32.4 \quad (5)$$

Pressure drop obtained with and without the polymer was continuously observed and friction factor was calculated then drag reduction value was found out by using (6):

$$\text{Drag reduction } DR(\%) = \left[\frac{f_s - f_p}{f_s}\right] \times 100 \quad (6)$$

f_s and f_p are the friction factor values without and with polymer respectively.

IV. Results and Discussion

A. Viscosity Measurements

Rheological measurements were done with the help of the rheometer at 25 °C for the concentration of the polymer solution from 50 ppm to 300 ppm. Observed values were plotted on the shear viscosity graph with corresponding to the shear rate as shown in Fig. 2.

The shear rate was maintained from 0.1 to 1000 s^{-1} for all the polymer concentrations (50-300 ppm). It can be seen from Fig. 2 that for the very low concentrations of 50 and 100 ppm the behavior of the polymer solution viscosity was almost Newtonian. For the lower concentrations of the polymer, the increase in the viscosity was less as compared to the higher concentrations (150-300 ppm). For higher concentration, the shear thinning behavior was observed [11], [12]. As compared to the 50 and 100 ppm of the polymer solution, there is a rapid increase in the viscosity of the solution for higher concentrations. For higher concentrations like 100-300 ppm, there was a continuous decrease in the viscosity with respect to shear rate. It was found that the continuous decrease in the viscosity of the solution was up to 100 s^{-1} shear rate, then a Newtonian behavior and no further decrease in the viscosity was observed.

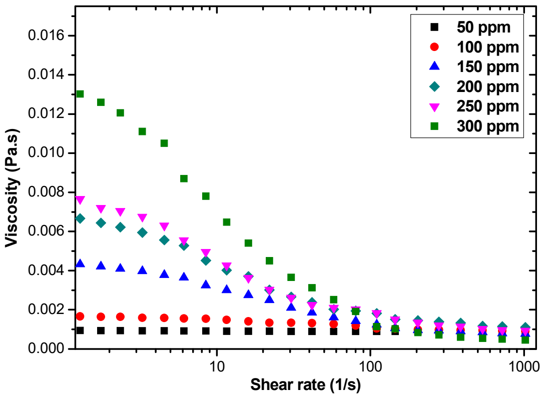

Fig. 2 Shear viscosity of the different polymer solutions with respect to shear rate

B. *Effect of Addition of Gum Arabic in Water Flow*

The polymer solution was injected in the pipe flow at different concentrations in the pipe flow. The effect of the Reynolds number and concentration was observed to find out the maximum drag reduction. As shown in Fig. 3 it can be seen that there was a significant effect of the concentration as well as Reynolds number on the drag reduction. When the concentration of the polymer solution was 50 ppm the value of the decrease in the pressure drop was found to be more than 40% at 45000 Reynolds number, and the minimum was 25% at 17000 Reynolds number. With the further increase in the Reynolds number, the observed value of the drag reduction percentage was also higher. The maximum drag reduction during all the concentrations was observed to be 62.15% at 300 ppm of concentration for 45000 Reynolds number, which was due to the significant decrease in the pressure drop due to the polymer addition. When Reynolds number was high, there was the continuous formation of turbulent eddies near the boundary layer. When the polymer solution was injected in the boundary layer, the molecules of the polymer starts interacting with the turbulent eddies and it suppresses the eddies [13], [14]. The suppression of the eddies leads to decrease the loss of energy in the form of pressure drop [15].

A rapid increase in the value of the drag reduction was observed from 17000 to 30000 Reynolds number. After 30000 Reynolds number for the particular concentration, the change in the value of the drag reduction was less as compared to former Reynolds numbers.

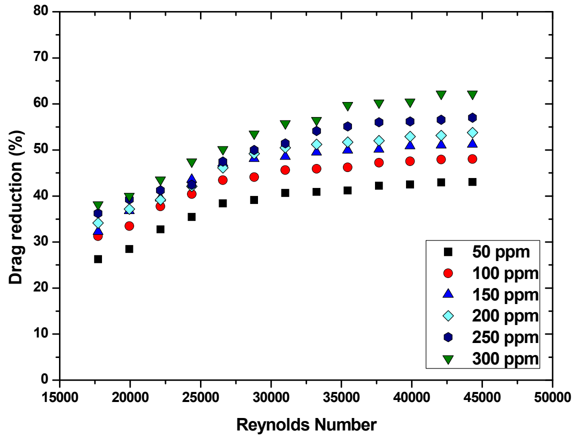

Fig. 3 Effect of concentration and Reynolds number on drag reduction percentage

C. *Effect of Shear Degradation on the Drag Reduction*

To check the effectiveness of the polymer under the high shear produced by the centrifugal pump, the solution was circulated in the closed loop for 14000 cycles. During all experiments, the maximum Reynold number was maintained (45000). Initially, the water was circulated through the test system and after steady state, the polymer solution was started injected. The polymer solution was injected until the desired concentration in the circulating fluid was not attained. During the injection type, the maximum possible drag reduction was maintained. When the injection of the polymer solution was stopped the shear degradation of the polymer solution was noted continuously to observe the effect of the shear on the effectiveness of the polymer with a number of cycles.

Effect of the shear degradation of the number of cycles with polymer concentration is shown in Fig. 4. It can be seen from Figs. 4 (a)-(f) that these were a continuous decrease in the effectiveness of the polymer with a number of cycles. For the 50 ppm of the polymer solution the maximum value of the drag reduction was 43.02% and starts degrading rapidly and after 1400 cycles it remained 10.05%. Similarly, for the 100 ppm, it was decreased from 48.07% to 13.93% and for 150 ppm it remained 20.21% from 51.22%. When the concentration of the polymer was more (200-300), there was a 45% reduction in the effectiveness of the polymer's ability to reduce drag. This may be due to the break of the polymer molecules due to the turbulent eddies continuously [10], [15]-[20].

V. Conclusions

A water-soluble polymer was injected in the boundary layer of the flowing fluid to find the effect of the concentration and Reynolds number on drag reduction and the following conclusions were made:-

1) A significant effect of the concentration and Reynolds number was found on the drag reduction value.
2) With the injection of the polymer solution, the maximum drag reduction was observed to be 62.1% at 45000 Reynolds number with 300 ppm of concentration.

3) Shear degradation of the polymer effectiveness was observed with a number of cycles in a closed loop.
4) For lower concentration 50-150 ppm the average reduction in the value was found to be 30% from its initial value. And for the higher concentrations from 200-300 ppm the average reduction in the effectiveness was observed almost 45%.

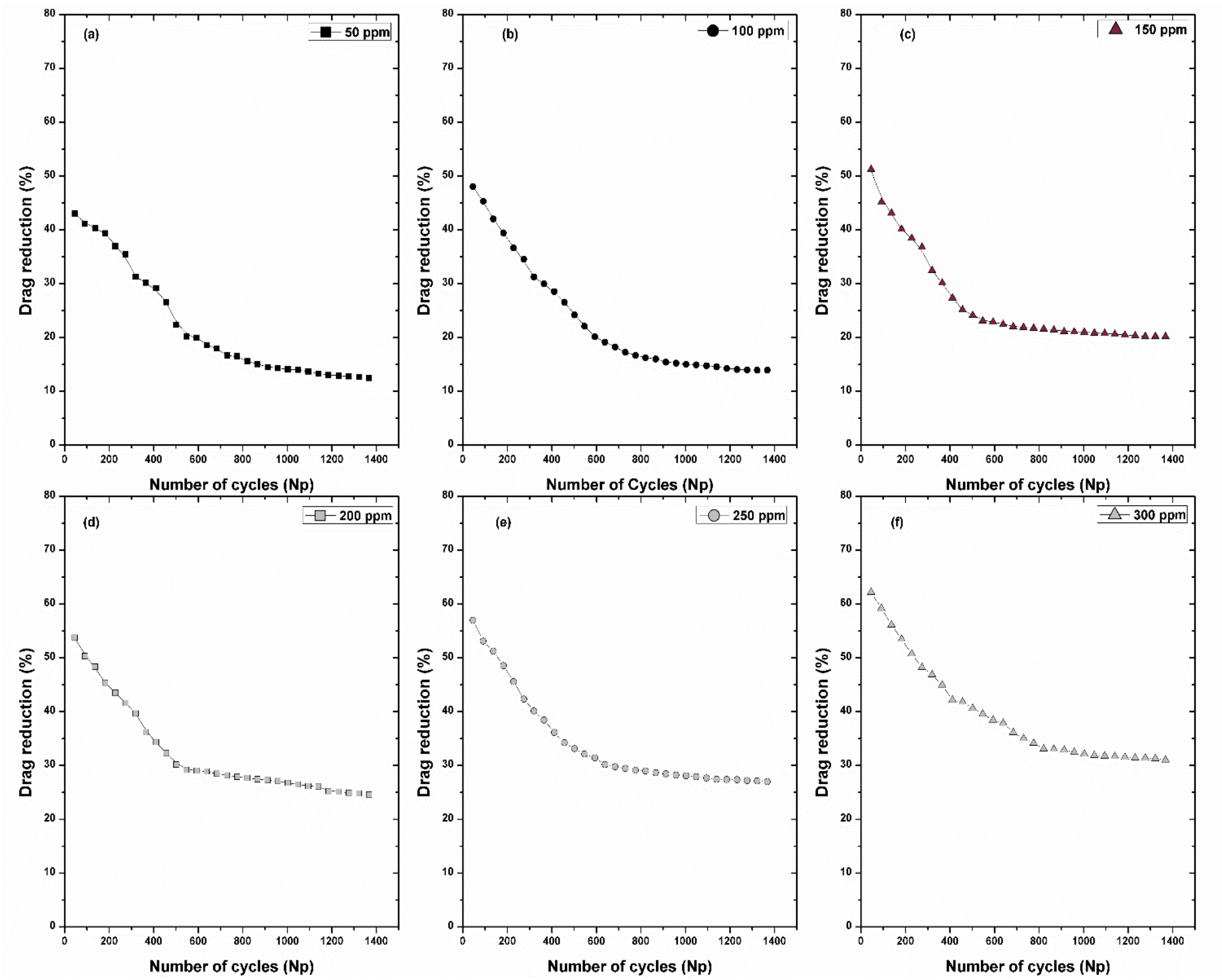

Fig. 4 Effect of shear degradation on different concentration of polymer solutions

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