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Polymer induced turbulent drag reduction using pressure and gravity-driven methods

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Abstract−Drag reduction using polymer additives has been industrially important for enhancing the flow rates and hence the power consumption. In this study, various polymers like PEG, PAM, HPMC were employed with solvents like water and lubricating oil for drag reduction using gravity and pressure driven methods. The optimum set of parameters for maximum drag reduction--polymer concentration, nature of polymer, polymer combinations, exit pipe diameter, solvent-polymer combinations, experimental methodology--were obtained and then the results validated with well known concepts like the Toms effect and Virk's maximum drag reduction asymptote.

Keywords: Drag Reduction, HPMC, PAM, PEG, Pipe Friction Apparatus, Gravity-driven Method

INTRODUCTION

Drag refers to force acting on a solid object in the direction of the relative fluid flow. It is experienced whenever transportation of fluid occurs and hence a great deal of energy is lost to overcome these forces. Systems and techniques are being designed to combat these forces and among these is the phenomenal Toms effect.

The Toms effect was first discovered by Toms [1,2] and Mysels [3] separately. It is the reduction in drag in a turbulent flow upon addition of very small quantities of high molecular weight and linear chain polymers. Since then a large number of experiments have been conducted based on this effect, resulting in a large amount of data, but ironically no concrete theory has been reported, till date, which is able to explain all of these data.

Drag reduction is initiated only when boundary layer is turbulent and it increases with increasing polymer concentration saturating beyond a certain concentration [4]. This bound is called Virk's asymptote or maximum drag reduction and was first discovered by Virk [5]. He also pointed out that as the molecular weight of the additive is increased the onset of drag reduction occurs at lower Reynolds number [4]. Moreover, drag reduction of a polymer solution becomes more pronounced as pipe diameter is reduced [6].

With the advancement of technology researchers are trying to investigate the mechanism of the Toms effect on different rheological parameters using direct numerical simulation (DNS) of turbulent channel flow in which different polymer models are used, (such as finitely extensible and elastic dumbbells [7,9], FENE-P and Giesekus models [8], Oldroyd-B model [10], Anisotropic Maxwell model [11]). Laser Doppler anemometry (LDA or LDV) techniques have been reported, to be used, to measure velocity of these flows and thus understand the interaction of turbulent structure with polymer which will further throw light on this effect [11-13].

This phenomenon of drag reduction has been implemented successfully to reduce pumping cost for oil pipelines, to increase the flow rate in fire fighting equipment and to aid irrigation and drainage in an effective manner [14,15]. It also has potential applications in the design of ship and submarine hulls to achieve an increased speed and reduced energy cost.

In this work, experiments have been conducted using HPMC (Hydroxypropyl Methylcellulose), PAM (Polyacrylamide) and PEG (Polyethylene Glycol) as additives, with water and lubricant oil as solvents, to estimate the maximum drag reduction and to determine the parameters affecting this phenomenon.

MATERIALS AND METHODS

1. Materials and Preparation

Three polymers/additives, namely Hydroxypropyl Methylcellulose (HPMC-M.W=22000, viscosity 40-60 cP), Polyacrylamide (PAM-M.W=5×10^6) and Polyethylene Glycol (PEG-M.W=6000) (supplied by SIGMA ALDRICH), have been employed with water and lubricant oil (Source: MAK lubricants, Grade: SAE 20W-40; Viscosity Index:108, specific gravity 0.889, kinematic viscosity 121 mm^2/s at 40 °C) as the two solvents. The polymer solutions were prepared by measuring polymers by weight and then dissolving them into the appropriate solvent using a magnetic stirrer at room temperature. For ensuring the homogeneity of the solutions, they were kept undisturbed for 24 hours to reach steady state.

2. Experimental Setup and Procedure

Two different experimental setups, gravity-driven method and pipe friction method, were employed to measure the reduction in drag.

In the gravity-driven method (Fig. 1), with Reynolds number ranging from 15,000 to 38,000 for water, depending on the pipe diameter, the solution was collected in a transparent cylindrical glass tank fitted with a ball valve and a drain pipe at the bottom. The tank is calibrated by 1 cm markings from top to bottom. The tank was first filled with the solvent and then drained under gravity. The time required to drain 1 cm of solvent was measured using a stopwatch. The experiment was repeated again by using the polymer solution

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Fig. 1. Gravity-Driven Method (Reynolds number range-15000-35000 for water as a function of pipe diameter).

of the same solvent. Time taken to drain out a given volume of the fluid, a parameter indicative of drag reduction is inversely proportional to the velocity and hence the flow rate (for a drain pipe of given diameter). Thus the formula for drag reduction (DR) in this case becomes (Eq. (2)). This estimation methodology of drag reduction has been employed by Subba Rao et al. and Toonder et al. [16,17]:

$$\frac{Q_w}{Q_p}=\frac{\text{Area}\times\text{Height}/t_w}{\text{Area}\times\text{Height}/t_p} \quad (1)$$

$$\%DR=\left(1-\frac{Q_w}{Q_p}\right)\times 100=\left(1-\frac{t_p}{t_w}\right)\times 100 \quad (2)$$

In the pipe friction apparatus [Fig. 2] with Reynolds number ranging from 50,000 to 75,000 (for water, depending on pipe diameter), first pure water and then its polymer solution were used to evaluate the drag-reduction. The apparatus consisted of four different pipes of different diameters and roughness fitted with a ball valve for each pipe. The solution was filled in a sump tank and the motor was turned on. The motor drives the solution into a pipe fitted with by-pass valve and then into the four pipes. The valve corresponding to the pipe being used was kept open and the rest all were closed. The solution from these pipes goes back to the sump tank or measuring tank for measuring the flow rate. The flow rate is controlled using the by-pass valve. The pressure drops for both pure water and polymer solution are noted with the help of differential pressure sensors fitted to the pipe. With this set-up, both diameter and pressure difference is varied with different concentrations of polymer to understand the drag reduction phenomena. Now for a given reading, the radius R, density ρ, velocity V, and pipe length L being constant, the friction factor f is proportional to ΔP and hence the drag reduction. Hence the friction factor becomes the critical parameter to assess drag reduction as mentioned in Eq. (4).

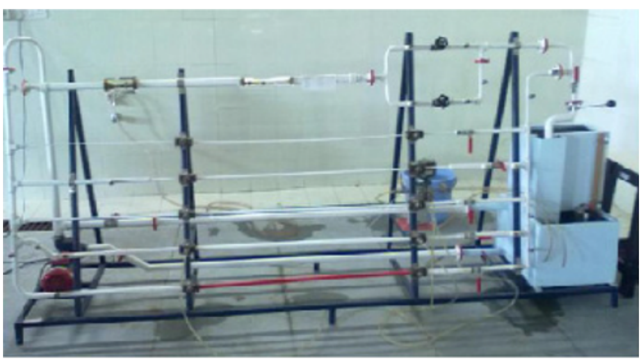

Fig. 2. Pipe Friction Apparatus (Reynolds number range, 50000-75000 for water as a function of pipe diameter).

$$f=\frac{\Delta PR}{\rho V^2 L} \quad (3)$$

$$\%DR=\left(1-\frac{\Delta P_p}{\Delta P_w}\right)\times 100=\left(1-\frac{f_p}{f_w}\right)\times 100 \quad (4)$$

RESULTS AND DISCUSSION

1. Effect of Solvent Selection

Experiments were carried out with water and lubricant oil separately with HPMC as the common polymer additive to evaluate the dependence of DR on the nature of solvent.

Drag reduction experiments were conducted employing both apparatus: pipe friction apparatus and gravity-driven method. As can be seen from Table 1, there is either no change or a slight increase in pressure difference (in case of pipe friction method) with the addition of polymer and drag is either constant or increasing. This observation is reinforced by the fact that in gravity-driven method, the time taken by the solution to drop by 1 cm in height is increased (flow rate is decreased and hence increase in drag) with the increase in the concentration of polymer [Fig. 3]. Therefore, HPMC solution with water is not a good system as far as DR is concerned.

Next, experiments were conducted using a solution of HPMC and lubricant oil in the gravity-driven method, which is more suitable for lubricating oil due to the high viscosity of the oil. Contrary to the previous case, DR was observed (Fig. 4) from which it is evident that 7-14% DR is obtained using varying concentrations of polymer with an exit pipe of diameter of ¼ inch. Similar experiments were repeated with exit pipe of ½ inch diameter and a DR of 18% could be achieved.

Table 1. Pressure difference in different diameter pipes for water and 10 ppm HPMC solution in case of pipe friction apparatus

Diameter of the pipe (mm)	ΔP of water (mm)	ΔP of 10 ppm HPMC solution[a] (mm)
d1=7.5	5277	5328
d2=9.5	1899	1925
d3=15.7	387	387
d4=15.7	463	463

[a]Solution with water as solvent

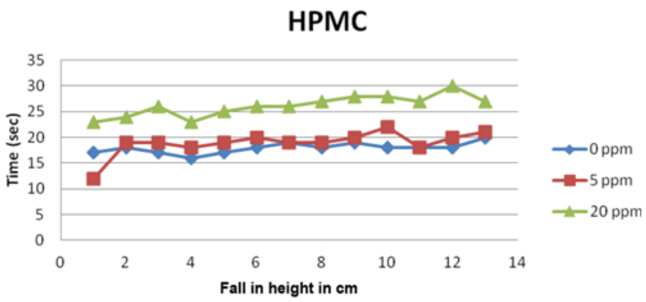

Fig. 3. Time taken to drop 1 cm under gravity for various concentrations of HPMC in water in case of gravity-driven method.

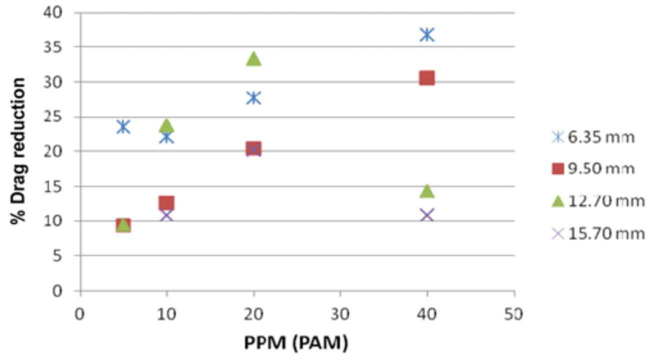

Fig. 5. Effect of PAM concentration (ppm) on %DR of water for different pipe diameters using pipe friction apparatus.

These experiments where drag reduction was achieved in one solvent but not in another using the same additive indicate that the choice of additive is crucial with reference to the solvent and vice versa. Even the drag-reduction achieved by HPMC in lubricant oil is as high as 18%, which is significant in spite of its hydrophilic nature, which indicates a polymer if forms a stable dispersion in a solvent could achieve drag reduction. Thus, it can be concluded that HPMC is a good drag reducing agent achieving 18% DR at a very low concentration and hence could be successfully employed as an additive.

2. Effect of Concentration and Nature of Polymers

To evaluate the effect of concentration of polymers the following systems were used:

2-1. HPMC with Lubricant Oil

Though HPMC is hydrophilic, it forms a highly stable dispersion in non-aqueous systems when more than 5 : 1 ratio of solvent and polymer has been employed. In our case too, the stability of the dispersion remained intact even after 24 hours as we have taken a much higher solvent-polymer ratio. Gravity-driven method was used for this system and the concentration of the polymer was varied from 10 ppm to 70 ppm and the time taken to drain 1 L of oil through ¼ inch diameter pipe was noted. As can be seen from Fig. 4, the %DR first increases with concentration till 20 ppm, after which it decreases with increase in polymer concentration. Thus, the optimum or saturation concentration is 20 ppm with a DR of 14%. Similar results were obtained when the diameter of the drain pipe was changed from ¼ to ½ inch, but was accompanied by an increase in DR to 18% at the same concentration, i.e., 20 ppm. Thus, the saturation concentration was 20 ppm in both the cases.

2-2. PAM with Water

For this system, both apparatus were used for evaluation. Fig. 5 shows that the %DR for 12.7 mm and 15.7 mm diameter pipes increases with increasing concentration until a saturation point is reached, after which it decreases. However, for the other two smaller diameter pipes, drag reduction was much more pronounced, reaching values as high as nearly 40% at 40 ppm concentration. These results are in accordance with the ones reported by Gasljevic et al. [6].

2-3. PEG with Water

For this system, pipe friction apparatus was used with an exit pipe of diameter 9.50 mm. Fig. 6 shows that %DR achieved employing PEG with water is relatively low and that the effect of its concentration is marginal as the average %DR achieved is found to vary between 4-5% only for the polymer concentration varying from 5-20 ppm.

It was reported that in turbulent flow, polymeric additives are exposed to elongational strain and strong shear stresses, and that this mechanical energy is responsible for the scission of the polymer chain, decreasing the drag reduction efficiency. This mechanical degradation in turbulent flow is known to be affected by various properties: molecular weight, molecular weight distribution, temperature, polymer solvent interactions, polymer concentration, turbulent intensity, method of preparation and storage and flow geometry [18]. Hunston and Zakin et al. [19] performed turbulent flow experiments with extremely dilute polymer solutions. As it is very difficult to

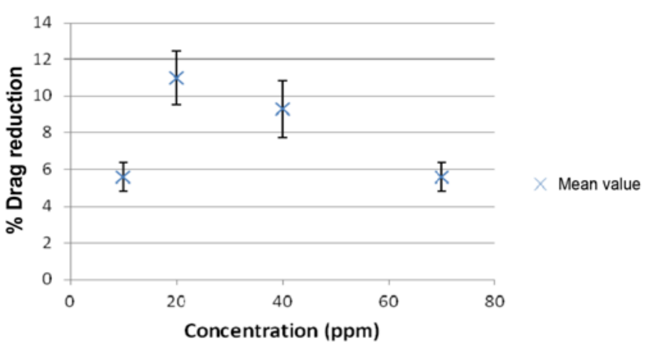

Fig. 4. Effect of HPMC concentration (ppm) on %DR of lubricant oil with an exit pipe of ¼ inch diameter using gravity-driven method (The black line represents the standard deviation for each data entry).

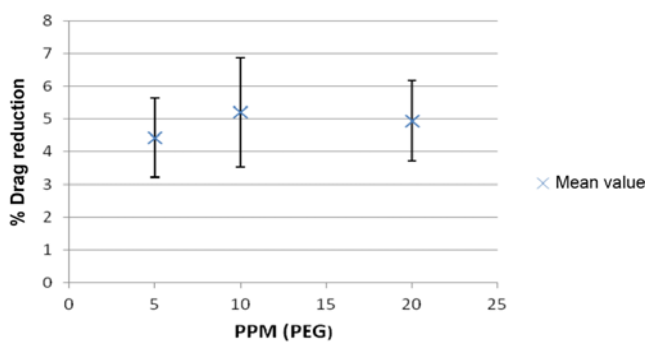

Fig. 6. Effect of concentration of PEG (ppm) on %DR of water for 9.50 mm diameter pipe using pipe friction apparatus (The black vertical line represents the standard deviation for each data entry).

measure changes in the molecular weight distribution for extremely dilute solutions, drag reduction measurements have been used to study the mechanical degradation. It was also reported that among all the parameters, the molecular weight plays a dominant role in the effectiveness of drag reduction by polymers, especially at low concentrations, and the drag reduction was reported to increase with molecular weight of the polymer additive for a given concentration, indicating that drag reduction depends to some degree on the length and extension of the polymer chains [20-22]. The above results are perfectly in agreement with the reported literature as the molecular weight of HPMC, PAM, and PEG is 2.2×10^4, 5×10^6 and 6000, respectively. Hence the drag reduction efficiencies achieved are also in proportion to the molecular weights, which is the critical influencing parameter on drag reduction at low concentrations. It was also reported that if the molecular weight is too low, the drag reduction will be negligible in spite of the nature of polymer-solvent interactions. The phenomenon of optimum concentration to achieve maximum drag reduction could be defined as that concentration below which the increase in concentration leads to increasing interaction of polymers with turbulent eddies, thus dampening them, and hence the turbulent drag thereby responsible for increase in DR [23-25]. Moreover, below this concentration, the effect of polymer viscosity is insignificant to that of the ongoing interaction, but above the saturation point, the role of viscosity dominates over polymer-eddy interactions and is thus responsible for the decrease in DR.

3. Effect of Pipe Diameter

While observing the effect of diameter of the drain pipe on DR two contradicting results were observed. These could be due to the difference in the two systems employed for study.

3-1. PAM and Water Solution

For this system of PAM with water, both apparatus, gravity and pressure driven methods, were employed to study the effect of pipe diameter on %DR achieved. Fig. 7 employing gravity-driven method shows that %DR decreases with increase in diameter, while in Fig. 8 employing pressure-driven method this effect is not significant, though the trend observed is similar to the above. The above results are in agreement with those reported by Gasljevic et al. [6]. This trend can be explained by the fact that with increase in diameter, the roughness parameter decreases (e/D ratio), thereby the turbulence and hence %DR. It can also be explained that with increase in diameter, the wall shear stresses decrease for a given velocity and hence pressure drop too which is related to wall shear [25-27].

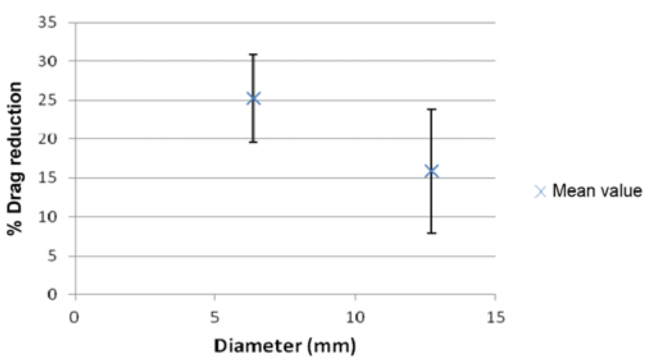

Fig. 7. Effect of Pipe diameter (mm) on %DR of water with PAM for gravity-driven method (The black line represents standard deviation for each data).

3-2. HPMC and Lubricant Oil

For this system, experiments using gravity-driven method have been conducted to study the effect of initial volume on % drag reduction. The results in Fig. 10 clearly show that %DR increases with initial volume fraction for both exit pipes and our results agree with those reported by Yaari et al. [27] for oil water system in a horizontal pipe. Also, DR_{max} was reduced with increase in pipe diameter, contrary to the results with water as a solvent. This might be due to high viscosity of lubricant oil, which decreases the Reynolds number of the lubricant system (R_l) when compared with that of water (R_w). Now when the diameter increases in both cases, R_l value increases and it comes into the early turbulent regime, and as the critical Reynolds number (corresponding to Virk's maximum drag reduction asymptote [4,5]) is quite far from this; therefore, there is an increase in DR with increase in diameter until this point is reached, whereas on the other hand, R_w is already present close to the corresponding critical Reynolds number (because of low viscosity of water) and thus a little increase in diameter leads to the Reynolds number to be greater than the critical value thus leading to a decrease in DR value.

Also, with the increase in diameter of the pipe in case of PAM and water as the system, the concentration required for maximum drag reduction decreases from 40 ppm to 20 ppm, as shown in Fig. 9, the trend similar to that observed in Fig. 4 and hence the same

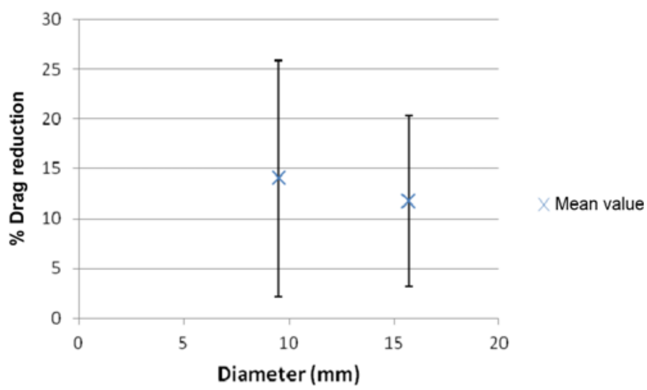

Fig. 8. Pipe diameter (mm) vs. %DR for PAM with water as solvent for pipe friction apparatus (The black line represents standard deviation for each data).

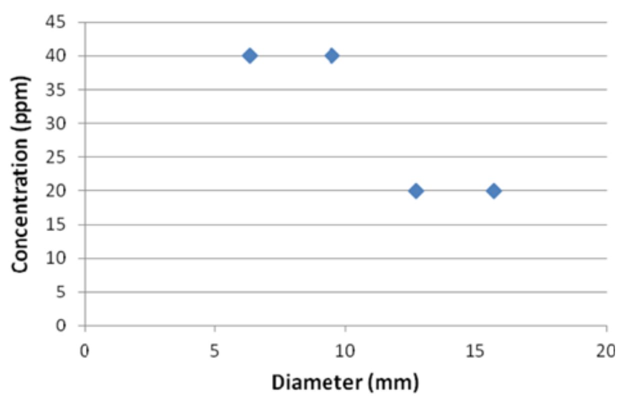

Fig. 9. Pipe diameter (mm) vs. Concentration (ppm) for PAM with water as solvent.

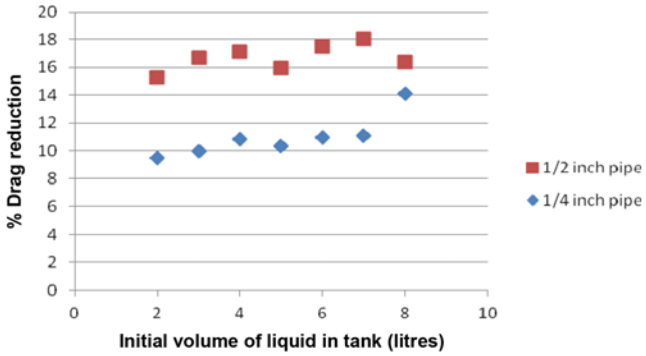

Fig. 10. Comparison of %DR of 20 ppm HPMC with lubricant oil for two exit pipes of ¼ inch and ½ inch diameter using gravity-driven method.

explanation that the drag reduction becomes more pronounced at lower diameters holds good and hence requires greater optimum polymer concentration and vice versa.

4. Potential Drag Reducing Polymers

From all the studies conducted, PAM is the best drag reducing additive for water, while it is HPMC for lubricant oil, and maximum DR could be achieved in both the cases by using the optimum concentrations with appropriate sizes of the drain pipe. Further, PEG is found to be a potential drag reducing agent that has given a consistent drag reduction of 6-7% till 20 ppm by weight in water.

5. Mixing of Polymers as Drag Reducers

Studies have also been conducted using the combination of polymers with an objective of utilizing the positive aspects of both. But our experiments with the combination have given a contrary result than anticipated. PAM and HPMC were mixed in different concentrations and used as additive with water and it was found that their combination increased the drag rather than otherwise. This might be due to a possible reaction or coagulation between the two polymers, which led to an increase in the viscosity of the solution. We assert this reason because of the following observations:

Drag of 20 ppm HPMC<Drag of (20 ppm HPMC+40 ppm PAM).

Drag of 40 ppm (PAM+HPMC)>Drag of (20 ppm HPMC+40 ppm PAM).

These observations can be visualized in Fig. 11.

6. Estimation of Threshold Pressure Difference

It was observed that using 15.7 mm diameter drain pipe, there exists a particular pressure difference of 185 mm with drag reduction achieved being 0, and below this pressure difference, drag increases with decrease in pressure head, irrespective of the concentration of polymer. At this pressure difference, calculations showed that it is in turbulent range as the corresponding Reynolds number= 20,096>2300. This "phenomenon of Threshold pressure difference" or onset shear stress [4,29] or shear rate [30,31] has been reported earlier. But White [32], Virk [4] and Hershey [33] reported it to be independent of pipe diameter [25], while our results showed that this threshold pressure difference is a function of diameter (about 866-841 mm for a 9.50 mm diameter pipe).

7. Effect of Concentration of Polymer Additives on Pressure Head, Flow Rate & Velocity

The results of the effect of concentration of polymer additives on drag reduction can also be translated to the increase in flow rate/velocity which are linked to drag, and Fig 12 shows the results which are in line with that of Figs. 5 and 6 earlier.

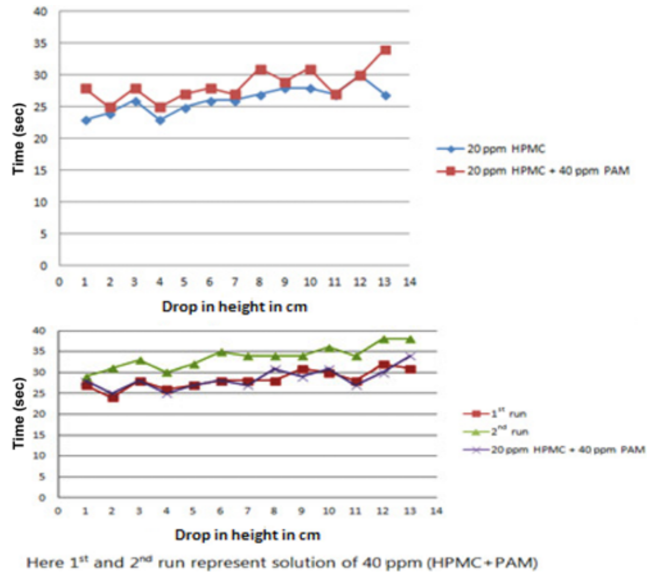

Fig. 11. Drop in height (cm) vs. Time (sec) for combination of HPMC and PAM in water using gravity-driven method. *1st and 2nd run are equivalent in meaning to two rounds of experiments.

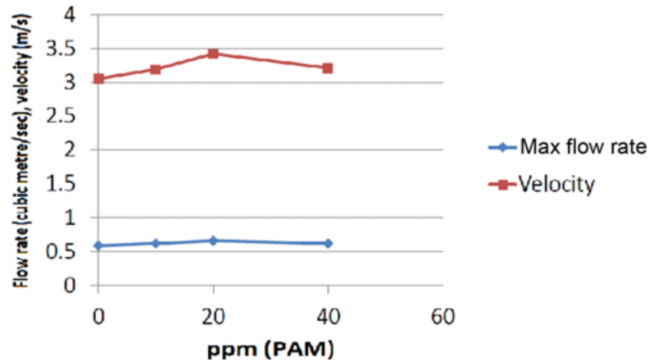

Fig. 12. Variation of flow rate, velocity with concentration (ppm for PAM) with water as solvent using pipe friction method.

CONCLUSIONS

Drag reduction phenomena or the Toms effect has been studied by conducting various experiments with HPMC, PAM and PEG as polymers and using water and lubricant oil as solvents. It was found that the polymer additives of PEG and PAM could reduce drag in water, while for lubricant oil HPMC was found to be effective drag reducer. For a given polymer-solvent system, the pipe diameter and the concentration of polymer are critical in achieving maximum drag reduction. The studies also reinforced the fact that the additives should be selected as per the nature of solvent for drag reduction.

NOMENCLATURE

DR : drag reduction
M.W : molecular weight in daltons/g/mol

Q_p : volumetric flow rate of polymer solution
Q_w : volumetric flow rate of water
t_p : efflux time of polymer solution
t_w : efflux time of water
f_p : friction factor of polymer solution
f_w : friction factor of water
HPMC : hydroxypropyl methylcellulose
PAM : polyacrylamide
PEG : polyethylene glycol
V : velocity
L : length of the pipe

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