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Complex Behavior of Polymers as Drag Reducing Agents Through Pipe Fittings

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ABSTRACT

Polymer induced turbulent drag reduction has significant industrial importance and finds application in industries, oil and gas, fire-fighting, marine, irrigation, biomedical etc. Most of the reported literature is focused on the skin drag reduction in pipe flow employing drag reducing additives (DRAs) like polymers, surfactants, fibres and suspensions. In this work, the effect of polymeric addition on the total drag reduction (skin and form) is studied for turbulent flow of water through various fittings like 45 degree elbow, 90 degree miter, sudden expansion and sudden contraction. Different polymers like PAM, PEO, HPMC have been employed as DRAs at various concentrations and pressure drops. The results indicate a complex and interesting behavior. When compared to the results reported for pipe flow, even in this case polymers are found to give total drag reduction (TDR) though less relative to skin drag alone. The extent of TDR is found to depend on the nature of fitting, polymer and its concentration and the pressure drop used. From the results, it is also clear that there is a strong need to further investigate the problem using sophisticated analytical tools on rheometry and polymer degradation.

Keywords: Form drag; Total drag; Skin drag; Polymers; Turbulent flow; Pipe fitting; Pressure drop.

NOMENCLATURE

DR	Drag Reduction	*MW*	Molecular weight
DRA	Drag Reducing Additive	*PAM*	Polyacrylamide
FFA	Fluid Friction Apparatus	*PEO*	Polyethylene Oxide
g	gravitational constant, 9.8	*ppm*	parts per million
h	head friction loss	*SR*	Short Radius
HPMC	Hydroxypropyl Methylcellulose	*TDR*	Total Drag Reduction
K_L^W	friction loss coefficient for a fitting using flow of water without polymer	v	average velocity of fluid in a pipe
		V_L	average velocity in larger pipe for Sudden Expansion
K_L^P	friction loss coefficient for a fitting using flow of water with polymer	V_s	average velocity in smaller pipe for Sudden Expansion
LR	Long Radius		

1. INTRODUCTION

Drag can be defined as the force exerted by the fluid on the solid in the direction of flow. By Newton's third law, the fluid also experiences an equivalent force from the solid in the direction opposite to that of flow. This drag is experienced in all cases of relative motion balween a solid and fluid (McCabe, Smith, and Harriott, 2005).

Applications of fluid flow such as flow of crude oil through pipelines, in fire-fighting equipment, in irrigation, biomedical applications, piping systems for domestic uses etc. face the problem of drag. Energy requirement is significant to overcome drag forces in such cases, especially in a turbulent flow, which significantly adds to the operation costs. Thus, the transportation costs, which are the major investment if it were long pipelines that consisted of fluids flowing in turbulent regimes, could be significantly reduced if the drag forces were decreased.

It has been found that upon the addition of very

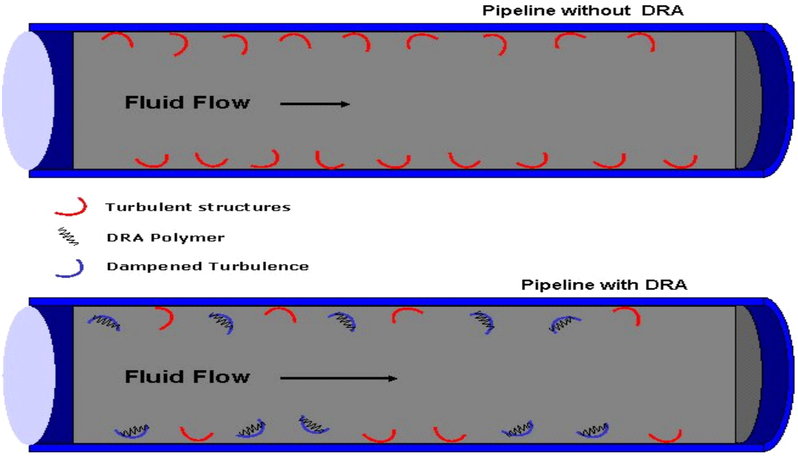

Fig. 1. Effect of Drag reducing Agent in a pipeline.

small quantities of substances called Drag Reducing Additives (DRAs), the fluid flowing in a turbulent regime experiences a reduction in drag. First result reported on drag reduction was for the flow of gasoline where skin friction was significantly reduced by adding aluminium disoap, an anionic surfactant (Mysels, 1971). Most commonly employed DRAs include anionic surfactants, fiber suspensions, high molecular weight polymers and nano-fluids (Pouranfard, Mowla, and Esmaeilzadeh, 2014; Radin, Zakin, and Patterson, 1975; Virk, 1975). Polymers have been used extensively as DRAs and the phenomenon of drag reduction by using polymers is known as the Tom's effect, after Tom, a pioneer in this field (Toms, 1977).

Extensive studies have been reported to understand and utilize this drag reduction phenomenon which was found to occur only when applied shear stress is above a minimum threshold value called the "Onset Shear Stress". At this value, the polymer length reaches certain value with reference to turbulent length as per length scale model and Deborah number (ratio of polymer relaxation time to turbulent time) reaches unity as per time scale model (Gold, Amar, and Swaidan, 1973; Toms, 1977; Virk, 1975). It has also been widely observed that there is an optimum or saturation concentration of DRA, which gives maximum DR, which is referred to as Virk's asymptote (Virk, Merrill, Mickley, Smith, and Mollo-Christensen, 1967). When the concentration is less than this value, DR increases due to more dampening of eddies by increasing polymer molecules that dominates/offsets the decrease in DR due to increase in solution viscosity until the concentration reaches the saturation value beyond which the predominant phenomena mentioned above gets reversed.

Out of several models reported to predict and simulate Tom's effect, the highly validated and acceptable one was that proposed by Joseph (Joseph, 1990) and Gennes (De Gennes, 1990). According to them, the elastic properties of polymers which give their long chains the ability to propagate shear waves which in turn damp and suppress smaller eddies, which are responsible for turbulent shear, is the cause for drag reduction. Works of K. Hoyer, A. Gyr and A. Tsinober (Hoyer, Gyr, and Tsinober, 1995) also describe the elasticity of long chain polymers as the cause for drag reduction. A detailed mathematical model has been developed by Dong-HuynLee (Lee, 2010) to explain the mechanism of polymer induced drag reduction.

An image showing the role of DRA in decreasing the intensity of turbulent eddies, the main cause of turbulent drag is shown in Fig. 1.

(Image Source: http://flo-quest. Com/ pics/ mechanism. jpg)

Degradation of polymers under large shear stresses has been the major challenge in the use of polymers as DRAs though they have been the most effective drag reducers thus far, as reported by Patterson (Patterson, Zakin, and Rodriguez, 1969). This happens when scission of long chain polymer takes place, generally from the center, which becomes one of the weakest points in a high shear stress environment. Thus there is a trade-off to be done between high drag reduction achievable and easy degradation when using long chain polymers.

Drag reduction using polymers has been successfully implemented in the Trans - Alaska pipeline for the transportation of crude oil (Burger, Munk, and Wahl, 1982). Highly productive results have also been obtained in attempts to aid irrigation and drainage (Khalil, Kassab, Elmiligui, and Naoum, 2002; Sellin and Ollis, 1980). It also finds applications in marine and biomedical areas viz., in the design of submarine hulls to enhance the speed and thereby reduce energy costs and to increase the flow rate of blood through the arteries preventing serious health disorders like atherosclerosis, thrombosis etc. An ideal DR polymer is one that has high molecular weight, high resistance to mechanical degradation, high thermal resistance and good solubility with the solvent.

Most of the reported literature involves polymeric drag reduction in pipe flow. In this work, an attempt

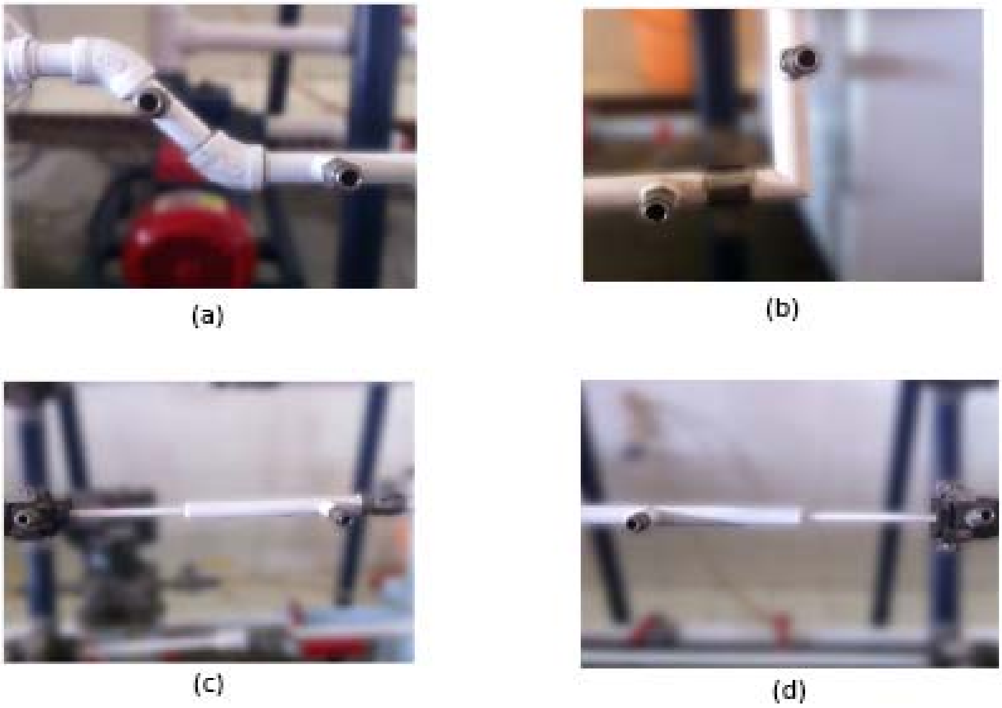

Fig. 2. (a) 45 degree elbow (b) 90 degree miter (c) Sudden Expansion (d) Sudden Contraction.

has been made to understand the influence of polymeric addition (PAM, PEO, HPMC) on the total drag (skin and form) for the turbulent flow of water through various fittings like 45 degree elbow, 90 degree miter, sudden expansion, and a sudden contraction (Fig. 2). Polymers at various concentrations ranging from 10 ppm to 70 ppm in water, flowing at pressure drops ranging from 205 mm Hg to 559 mm Hg have been considered to understand this phenomenon.

Drag is classified as skin and form drag. While skin drag is due to the wall shear, from drag is due to the fluid pressure normal to the surface. When a surface is parallel to the fluid flow, the total drag is the skin drag since the normal pressure has no component in the direction of flow. On the other hand, when the solid surface is perpendicular to the fluid flow, the total drag is form drag as the wall shear has no component in the direction of fluid flow. If the solid surface makes an angle between 0 to 90 degrees with respect to the flow, the total drag is contributed by both skin and form drag, as both wall shear and normal pressure have their components in the direction of flow contributing to drag. The form frictional losses are given by the following equations (McCabe *et al.*, 2005)

i) For 45 degree elbow : $h = K\frac{v^2}{2g}$ (1)

ii) For 90 degree miter : $h = K\frac{v^2}{2g}$ (2)

iii) For Sudden Expansion : $h = K\left(\frac{Vs^2 - Vl^2}{2g}\right)$ (3)

iv) For Sudden Contraction : $h = K\left(\frac{Vs^2}{2g}\right)$ (4)

2. EXPERIMENTAL SECTION

2.1. Materials Used

Three polymers namely, PAM (Polyacrylamide, MW=5x10^6), PEO (Polyethylene Oxide, MW=6000) and HPMC (Hydroxypropyl Methylcellulose, MW=22000), all supplied by SIGMA ALDRICH, were used with the solvent, water (density=1kg/L) at room temperature and pressure.

2.2. Polymer Solution Preparation

The polymeric DRAs were made *in-situ* by adding known weight of polymer to 100ml of water in a beaker with continuous stirring using a magnetic bead. The solution was kept for stirring at room temperature, till homogeneity was obtained. It was then allowed to settle for 24 hours to attain steady state before being used in the Fluid Friction Apparatus (Subbarao *et al.*, 2008). Solutions of concentration 20ppm, 40ppm and 60ppm were prepared for all three polymers.

3. EXPERIMENTAL PROCEDURE

The Fluid Friction Apparatus (FFA) shown in Fig. 3 below was employed for this work. The apparatus consisted of numerous pipes, valves and fittings that include,

- 45 degree elbow of diameter 16.00 mm

Fig. 3. Fluid Friction Apparatus.

- 90 degree miter of diameter 16.00 mm
- Sudden expansion with smaller diameter = 7.50 mm and larger diameter = 16.00 mm
- Sudden contraction with smaller diameter = 7.50 mm and larger diameter = 16.00 mm
- A by-pass valve for controlling the flow rate.

The prepared polymer solution was added to 30L of water in the sump tank and the motor was turned on. The solution was allowed to flow through all the pipes and fittings for 5 minutes. After that, only the valve corresponding to the fitting under experimentation was kept open and rest all were closed. Pressure sensors were employed across the fitting to determine the pressure drop. The flow rate of solution flowing through that particular fitting was measured using a measuring tank and a stop watch. Using this experimental set-up, DR studies could be conducted at various pressure drops (210mm Hg, 362mm Hg and 538mm Hg) and concentrations of DRAs for each pipe fitting. The same procedure was carried out for pure water as well without polymer. The drag reduction is calculated as mentioned in Eq. (5)

$$\%DR = (1 - \frac{K_L^P}{K_L^W}) \times 100 \tag{5}$$

4. RESULTS and DISCUSSION

The three different polymers viz., PAM, PEO and HPMC have been chosen for our drag reduction studies for the flow of water through four different fittings to understand the influence of nature polymer, their molecular weight and hence their degradation resistance besides polymer-fluid interactions. These polymers have been found to be reasonably high %DR for flow of water through straight pipes in our earlier studies (Sreedhar *et al.*, 2014)

4.1. Results for PAM

Experiments have been carried out using PAM as DRA for flow of water through various fittings to understand the influence of its concentration and pressure gradient. The drag reduction results using PAM in water for various fittings are shown in the figures below (Figs. 4-7). From the results, it's clear that the concept of Virk's Asymptote (Kenis, 1971; Ptasinski, Nieuwstadt, Van Den Brule, and Hulsen, 2001; Virk *et al.*, 1967; Wang, Yu, Zakin, and Shi, 2015), i.e. the optimum concentration of the polymer for maximum drag reduction is clearly evident, though the values differed for different fittings. The maximum drag reductions achieved are 10% at 40ppm for 45 degree elbow, 12% at 40ppm for 90 miter, 22% at 20ppm for sudden expansion and 5% at 20ppm for sudden contraction. From the results, it is clear that there is an optimum concentration of PAM to give maximum %DR and also the pressure gradient which are found to be specific to be nature of fitting. As concentration of the PAM increases, the DR increased due to enhanced dampening of eddies responsible for the drag upto certain value beyond which the increase in solution viscosity would offset the increase in %DR.

From the results, it could be understood that maximum total drag reduction was achieved in sudden expansion at a DRA concentration of 20ppm and a pressure of 362mm Hg while the minimum was observed in sudden contraction. From these results, we understand that polymeric influence as DRA is evident for those cases when in total drag, skin drag is dominating over form drag. Thus the polymer induced drag reduction is not strong in form drag vis. a vis. skin drag. Even the effect of pressure drop which normally has positive influence on drag reduction (Kim, Kim, Lim, Chen, and Chun, 2009; Virk, 1975, White, 1966), is found to have an optimum value for those cases where form drag is dominating skin drag. This is due to a possible trade-off between higher flow rate and hence turbulence and higher polymer degradation that happens at higher pressures (Kenis, 1971; Ptasinski *et al.*, 2001; Sreedhar, Jain, Srinivas, and Reddy, 2014; Virk *et al.*, 1967; Wang *et al.*, 2015). The detailed analysis could be done if polymer degradation and rheometric studies are conducted.

4.2 Results for PEO

Experiments have been conducted using PEO as DRA for the flow of water to compare its performance vis a vis PAM in terms of concentration and pressure gradient for the same set

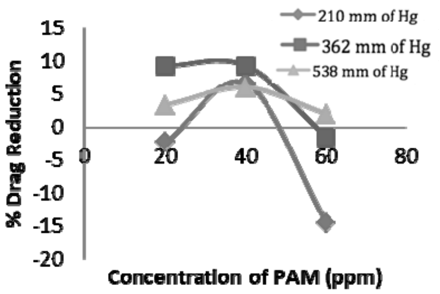

Fig. 4. %DR vs. concentration of PAM for 45º elbow.

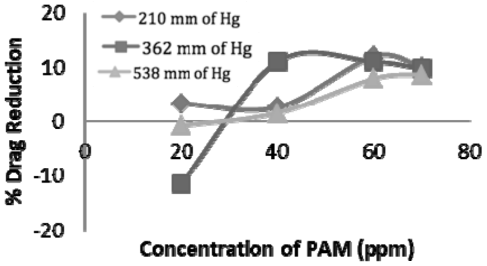

Fig. 5. %DR vs. concentration of PAM for 90º miter.

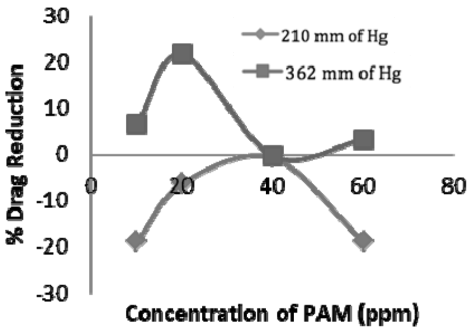

Fig. 6. %DR vs concentration of PAM for sudden expansion.

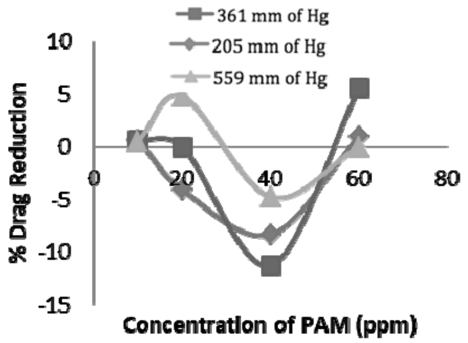

Fig. 7. %DR vs concentration of PAM for sudden contraction.

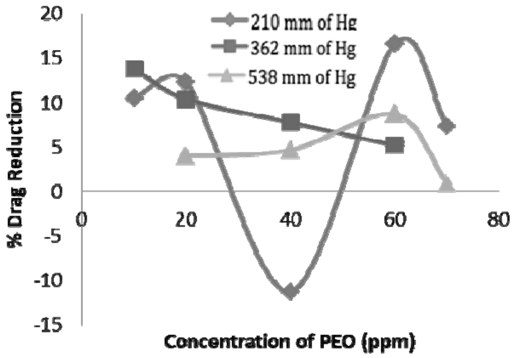

Fig. 8. %DR vs. concentration of PEO for 45º elbow.

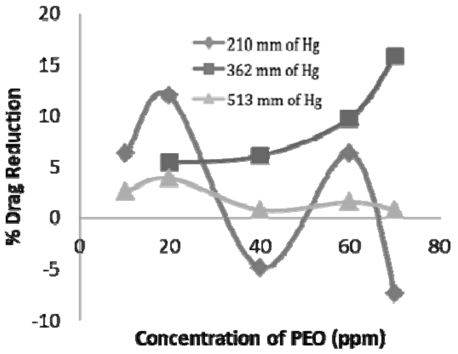

Fig. 9. %DR vs. concentration of PEO for 90 degree miter.

of fittings. The results of total drag reduction of PEO in water are shown in the figures below [Figs.8-11]. From the figures, it is clear that maximum total drag reduction achieved are 17% at 60ppm for 45 degree elbow, 15% at 60ppm for 90 degree miter, 31% at 60ppm for sudden expansion and 17% at 70ppm for sudden contraction. Then results are similar qualitatively that there is an optimum concentration of PEO and the pressure gradient to get maximum %DR specific to each fitting. Quantitatively, these results indicate that slightly higher total drag reduction has been achieved by PEO vis. a vis. PAM but at relatively higher concentrations. As discussed earlier, the polymeric influence as DRA is more prominent on such fittings where skin drag is dominant over form drag and the presence of optimum pressure drop due to the trade-off between turbulence and polymer degradation at higher values is also observed (Kenis, 1971; Ptasinski *et al.*, 2001; Sreedhar *et al.*, 2014; Virk *et al.*, 1967; Wang *et al.*, 2015).

4.3 Results for HPMC

The third polymer, HPMC has been employed as DRA after PAM and PEO to understand the influence of its concentration and pressure gradient to give highest %DR for each of the four fittings. From these studies, comparison could be drawn on the influence of the nature of polymer on %DR by

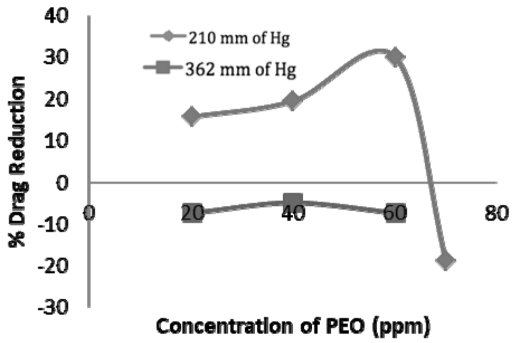

Fig. 10. %DR vs. concentration of PEO for sudden expansion.

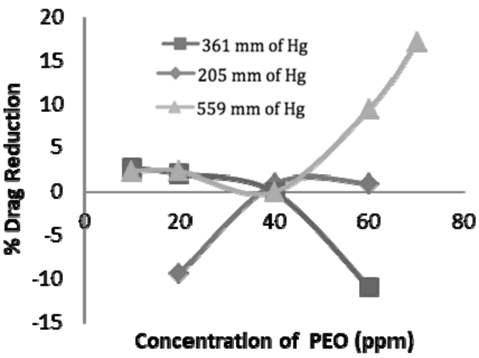

Fig. 11. %DR vs. concentration of PEO for sudden contraction.

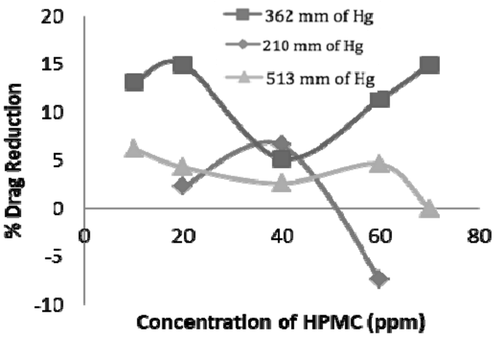

Fig. 12. %DR vs. concentration of HPMC for 45° elbow

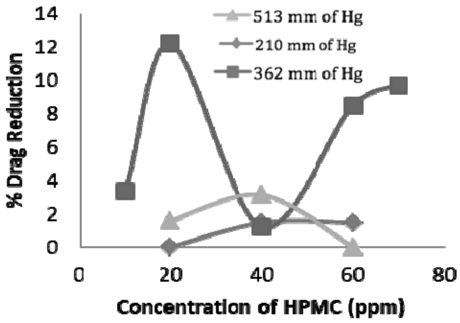

Fig. 13. %DR vs. concentration of HPMC for 90° miter.

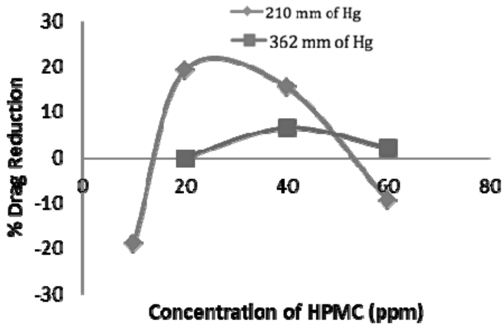

Fig. 14. %DR vs. concentration of HPMC for sudden expansion.

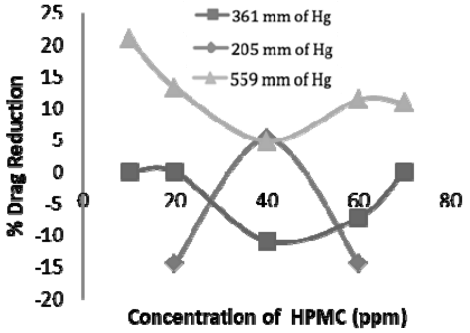

Fig. 15. %DR vs. concentration of HPMC for sudden contraction

comparing the results of PAM, PEO and HPMC. Figures 12-15 below show the results of HPMC in water. The maximum %TDR achieved is 15% at 20ppm for 45 degree elbow, 12% at 20ppm for 90 degree miter, 20% at 20ppm for sudden expansion and 20% at 20ppm for sudden contraction. From the results we understand that HPMC gave relatively higher TDR vis. a vis. PAM and PEO for 45 degree elbow and sudden contraction while lower values for the other fittings. Here too sudden expansion gave maximum TDR at an optimum pressure drop as observed earlier.

4.4 Comparison of Results

To have the comparison of the results shown by the three DRAs viz., PAM, PEO and HPMC for the flow of water through four different fittings i.e 45 degree and 90 degree elbows and sudden expansion and sudden contraction, results are shown at a glance in Fig. 16 below. Figure 16 shows the summary of the best results in terms of maximum total drag reduction achieved by various polymers in various fittings. It is clear from the results shown in the figure that maximum value of TDR is observed in sudden expansion by all the three polymers followed by sudden contraction (except PAM) and then by 90° miter and 45° elbow. From this we understand that polymer induced drag reduction is more prominent in cases where skin drag is major contributor to the total drag. The total drag reduction in all cases is found to be maximum at an optimum pressure drop.

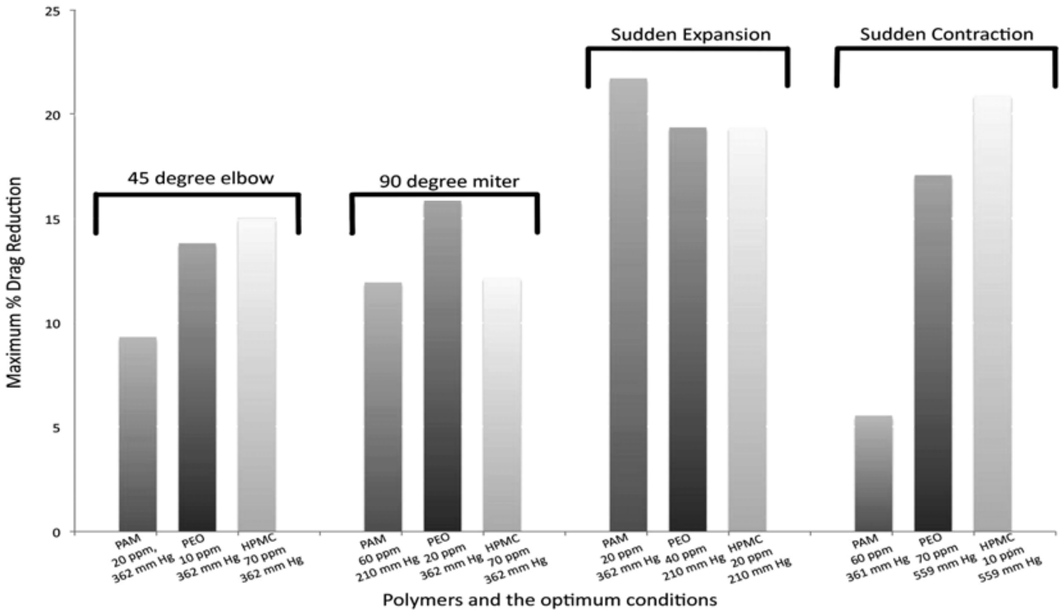

Fig. 16. Comparison of results.

5. CONCLUSION

In this work, the complex nature of polymer induced drag reduction in non-straight configuration is clearly evident. Not many studies have been reported on these flow configurations. Though the Virk's asymptote of optimum concentration for maximum drag reduction is visible in these cases too like straight pipes, but the influence of pressure drop on drag reduction is different. While in straight pipes, drag reduction is found to increase with pressure drop due to higher Reynolds number and thereby higher turbulence achieved, in case of fittings, there is an optimum pressure drop at which total drag reduction (skin, form) is achieved due to trade-off between higher turbulence and possibly higher polymer degradation observed at higher pressure drop.

These studies need to be further investigated employing appropriate analytical tools on visco- and rheometry and polymer degradation to understand the phenomenon better.

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