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# Research Article

## Effects of Polymer Addition to a Newtonian Solvent in Horizontal Pipe Flow

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### Abstract

**Objective:** The understanding of the behaviour of drag reducing polymer additives or DRA is critical especially for the oil and gas industries. This study aims to discuss the flow characteristics with and without the addition of polymers in a 400 L flow loop facility. **Methodology:** A series of experiments were conducted in the 10 m long and 75 mm inner diameter test section of a flow loop to experimentally determine and investigate the entrance length of turbulent flow in the pipe of a Newtonian solvent. The experiments were conducted using a differential pressure transducer (PMD75) and a coriolis mass flow meter. The pressure drop measurements within the fully developed regime of the Newtonian solvent and two other shear thinning fluids are conducted. The rheological characteristics of the shear thinning fluids are measured using a TA instruments controlled stress rheometer, AR-G2, before and after the pressure drop assessment to monitor biological and mechanical degradation. **Results:** Comparative assessment shows that the shear thinning fluid exhibits drag reduction with xanthan gum showing greater mechanical degradation resistance, the retro-onset is observed for the xanthan gum solution. **Conclusion:** Xanthan gum exhibits drag reduction characteristics typical of type B drag reduction behaviour.

**Key words:** Drag reduction, entrance length, turbulent flow behaviour, drag reducing polymers, shear thinning fluid

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**Competing Interest:** The authors have declared that no competing interest exists.

**Data Availability:** All relevant data are within the paper and its supporting information files.

## **INTRODUCTION**

Drag reduction also known as "Tom's phenomenon" is a phenomenon first experimentally observed by Toms<sup>1</sup>, where addition of high molecular weight polymer or surfactants to a Newtonian solvent induces a large reduction of frictional drag in a turbulent flow. In his experiments small amounts of polymer were added in a simple flow apparatus and observed increased flow rates, while investigating the mechanical degradation of polymers in pipe flow. Among the many strategies for drag reduction in pipe flows, polymer additives are the most efficient, however, they are most complex to understand<sup>2</sup>. Several studies have been conducted to understand how the polymer interacts with the flow and how the interaction modifies the turbulent flow properties. Virk<sup>3</sup>, Dunlop and Cox<sup>4</sup>, Graham<sup>5</sup> and White and Mungal<sup>6</sup> have all attempted to explain the phenomenon. The most common mechanism proposed considers the stresses added by the individual polymer molecules in unravelling the flow and making changes in the flow configuration. Other approaches are based on the physical considerations and interpretations of low-order statistical velocity moments<sup>2</sup>. Further researches are being conducted using direct numerical simulations to enhance the understanding of how the polymer additives modify the turbulence and induce drag reduction. Iaccarino<sup>7</sup> have shown success using the Finite Extensibility Non-linear Elastic (FENE-P) dumbbell model. The model reproduced the level of drag reduction observed over a wide range of rheological parameters with good prediction accuracy for both the flow mean velocity and turbulence fluctuations. The approach was found to be computationally attractive because of its limited increase in computational cost in comparison with its Newtonian counterpart. However, the present implementation only considers the extension of the polymer chains and not their orientation. One most extensive study on drag reduction was published by Virk<sup>8</sup>. It addresses the drag reduction fundamentals of dilute solutions of linear, random-coiling macromolecules in turbulent pipe flow. This study covers broad areas of drag reduction studies including gross flow, mean velocity profile, turbulence structure and mechanisms of drag reduction. Virk<sup>3</sup> proposed the concept of maximum drag reduction asymptote and the drag reduction envelope. The proposed envelope was bounded by two universal asymptotes, the Prandtl-Karman law for Newtonian turbulent flow and the maximum drag reduction asymptote. Between these two limits is a polymeric regime, in which the observed friction factor relations are approximately linear on the Prandtl-Karman coordinates and are characterized by two main parameters the wall shear stress at the onset of drag

reduction and the slope increment, by which the polymer solution slope exceeds Newtonian. Virk's envelope provides a useful method of evaluating drag reduction performance of polymer solutions. Virk<sup>9</sup> using the concept of drag reduction envelope, further discussed two extreme forms of drag reduction behaviour, types A and B, that are respectively associated with random-coiling and extended additive concentration, where type A drag reduction is exhibited by random-coiling macromolecules and depends on the Reynolds number and concentration, while type B is exhibited by a variety of additives including extended polyelectrolytes and fibres. Unlike type A, it is independent of the Reynolds number, depending only on the concentration. Several references that appear in petroleum literature indicate the importance and potential applications of drag reduction in the industry. Savins, amongst many others reported the results of pipe flow measurements on several synthetic and natural polymeric materials within three different tubing sizes and observed the diameter effect when compared to the Dodge-Metzner friction factor correlation<sup>10</sup>. This study aims to discuss the flow characteristics with and without the addition of polymers in a 400 L flow loop facility.

## **MATERIALS AND METHODS**

Two polymers have been used in this setup, Xanthan gum which is a "rigid" or "rod-like" polymer and Polyacrylamide, a flexible type polymer, both polymers that as a drag reducing agent. The experimental setup involves a flow loop that consists of a pump, a reservoir and a 10 m long straight pipe section. The straight pipe section has an average internal diameter of  $75 \pm 1$  mm and is made of Perspex<sup>11</sup>. This section is preceded and succeeded by 90° angle bends from the same material. The straight pipe section was equipped with 20 pressure tappings that are connected to the differential pressure transducer. Mass flow rate and density were measured by means of a Coriolis mass flow meter. Figure 1 shows a schematic of the 10 m long pipe-flow facility. A quantity of approximately 400 L of UTP tap water was used as a solvent for the test fluid within the pipe-flow facility. Prior to the addition of polymer, water was circulated within the facility to remove any dissolved air. Mixing of part of the solvent with the polymer powder was achieved by circulating the polymer solution within the mixing loop at a low pump speed for at least 5 h before the mixing loop was opened and the solution was circulated in the flow loop, allowing further mixing with the rest of the solvent in the pipe for at least another 5 h, until the solutions appeared to be visibly homogeneous.

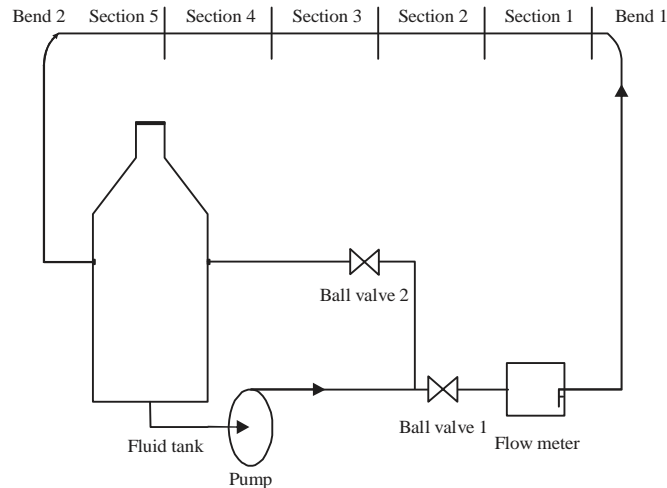


Fig. 1: Schematic of the flow loop

The homogeneity of the solution was confirmed by comparing the viscometric data obtained from a TA instrument controlled stress rheometer, using the 4 cm, 2° cone and plate geometry at a gap setting of 10 μm of a small sample (~500 mL) solution of the same concentration prepared separately. The polymer solution was then left to hydrate in the flow loop for at least 24 h prior to any measurements. Measurements of fluid rheology using the controlled stress rheometer for all the solutions were conducted prior to and after each series of pressure drop measurements to check for signs of mechanical and bacteriological degradation. A decrease of the shear viscosity by more than 5% from the initial state was taken as a sign of degradation.

Mechanical and bacteriological degradation in polymer solutions results in a decrease of the drag-reduction effectiveness<sup>12</sup>. Mechanical degradation is due to the high deformation experienced, especially when the fluid goes through the pump or any contraction section, resulting in molecular breakage. The mechanical degradation has been reported to be in inverse proportion to concentration<sup>13,14</sup> and also a function of structural chain rigidity. Rigid polymer solutions have been discovered to exhibit better degradation resistance compared to flexible polymer solutions<sup>12,15</sup>. Bacteriological degradation, on the other hand, occurs due to the organic nature of the polymer solutions but can be minimized by addition of a suitable amount of biocide. As the fluids utilized throughout this study were circulated for long periods of time, it was critical for the chosen fluid to have a good degree of resistance to mechanical degradation. To obtain accurate and repeatable results, only a minimal temperature difference (within ±1 °C) was allowed during the measurements. The pressure drop of the pipe sections was

measured from the pressure tapings by means of a differential pressure transducer. One millimeter diameter pressure taps in the pipe flanges were surface polished to avoid disturbing the flow, which could generate further uncertainties in the readings. The pressure taps were connected to the transducer via clear vinyl tubing filled with the fluid under study to eliminate corrections due to different specific gravities. The entrance length of the pipe section was first determined by measuring and plotting the pressure drop over a distance from the entrance of the test section. Figure 2 shows that the velocity profile ceases to change and stabilizes by the end of the entrance length. Due to the relation in Eq. 1, it is possible to conclude that the stabilization of the velocity profile is partly contributed by the pressure drop. The fully developed region is then assumed when the pressure drop per unit length is no longer changing with the distance from the pipe entrance:

$$\Delta p = \Delta p (D, L, \bar{V}, \rho, \mu) \quad (1)$$

The pressure-drop measurements for the assessment of the effects of polymer addition in turbulent flow were conducted at a location of 105  $D_H$  downstream of the inlet to the pipe test section over a distance of 20  $D_H$ . These measurement locations are sufficient for the Newtonian and non-Newtonian flows to reach fully-developed conditions as they are longer than that of the laminar development length proposed by Durst<sup>16</sup> for Newtonian fluid and by Poole and Ridley<sup>17</sup> for power-law non-Newtonian fluids. The development length is defined as the axial distance required for the centreline velocity to reach 99% of its fully-developed value. For example, a development length of 112  $D_H$  is

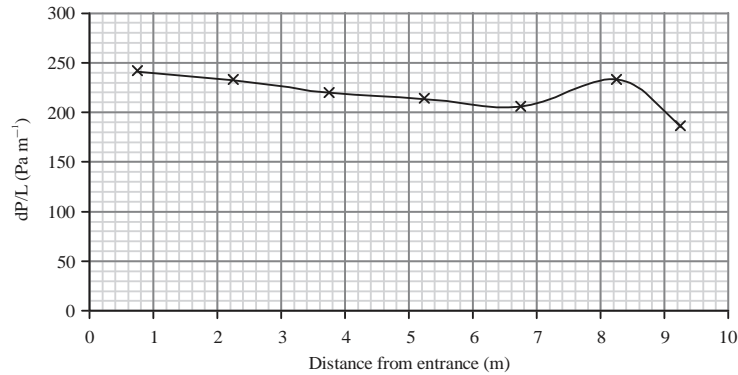


Fig. 2: Pressure drop gradient per unit length of pipe at 300 kg min<sup>-1</sup>

required for a laminar, Newtonian fluid flow at  $Re = 2000$ , while the same length is required for a laminar, non-Newtonian fluid flow with a power law index  $n$  of 0.4 at the same Reynolds number<sup>18</sup>:

$$\left( Re_{MR} \equiv 8(\rho U_B^{2-n} / k)(n / (6n + 2)) \right)^n$$

to be fully developed. The development length required for laminar flow has been established to be greater than the development length required for turbulent flow at the same Reynolds number<sup>19,20</sup>.

### RESULTS AND DISCUSSION

**Entrance length for Newtonian flow:** The Pressure drop data across the pipe sections were acquired at different flow rates. Beginning with the maximum mass flow rate possible for the flow loop, 300 kg min<sup>-1</sup>, the values were acquired for every 1.5 m of the straight section starting from the inlet. Other mass flow rates utilized were 200 and 50 kg min<sup>-1</sup>, within a sufficient Reynolds number range attainable within the flow loop; i.e. from Reynolds number of 15000-94000, all within the turbulent flow regime. The data were summarized by plotting the average pressure drop per unit length against the distance from entrance of the straight section for all the flow rates as shown in Fig. 2-4. Data shows that the fully developed region can be assumed to be achieved beyond 4 m downstream of the inlet, i.e., 50  $D_H$ . A slight pressure drop spike at the 8th meter mark is consistent for all the flow rates studied and is believed to be due to the imperfection within the test section. However, the effect is assumed negligible. Subsequently the pressure drop data within the fully developed region were measured to “validate” the experimental setup. The fanning friction factor from the

pressure drop is then plotted against the Reynolds number on a logarithmic scale and compared to existing correlations for a Newtonian fluid available in the literature. For a Newtonian fluid the Fanning friction factor,  $f$  and the Reynolds number,  $Re (\equiv \rho U_B D / \eta)$  relationship is given by Poiseuille’s law<sup>21</sup> as Eq. 2:

$$f \cdot Re = 16 \tag{2}$$

The Fanning friction factor, which represents the non-dimensional wall shear stress can be calculated from the wall shear stress,  $\tau_w$  via Eq. 3:

$$f = 2\tau_w / \rho U_B^2 \tag{3}$$

The  $f$ - $Re$  empirical relationship for the turbulent pipe flow of Newtonian fluid, known as the Blasius approximation is as Eq. 4:

$$f = 0.0791 Re^{-1/4} \tag{4}$$

Equation 4 is valid up to a Reynolds number of 100,000<sup>22</sup>. The Fanning friction factor,  $f$  is plotted against Reynolds number,  $Re$  for UTP tap water and is shown in Fig. 5. Due to the low viscosity of water, laminar flow conditions were not attainable within the operating range of the flow loop. The majority of pressure-drop measurements taken were therefore, limited to the turbulent regime and little information could be gleaned regarding transitional Reynolds numbers, etc. The behaviour of water, which was the solvent for the polymer solutions, in the turbulent regime follows the empirical relationship given by Eq. 2 and hence, “validate” the experimental setup and instrumentations utilized.

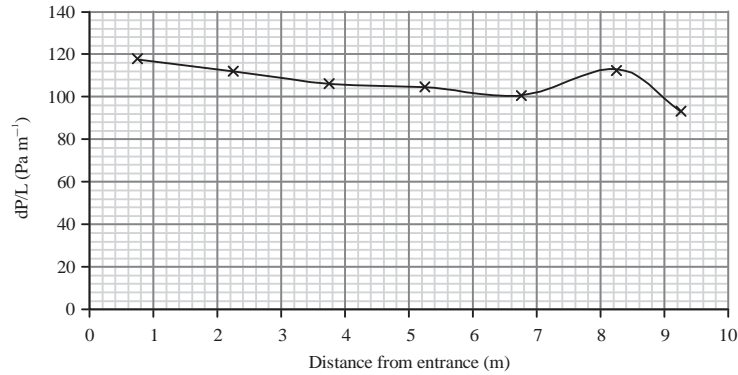


Fig. 3: Pressure drop gradient per unit length of pipe at 200 kg min<sup>-1</sup>

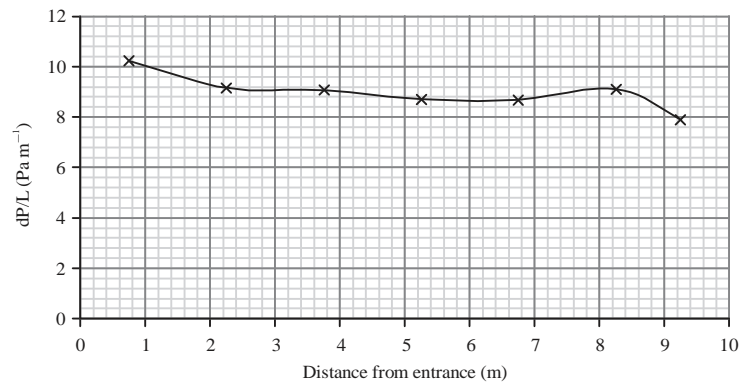


Fig. 4: Pressure drop gradient per unit length of pipe at 50 kg min<sup>-1</sup>

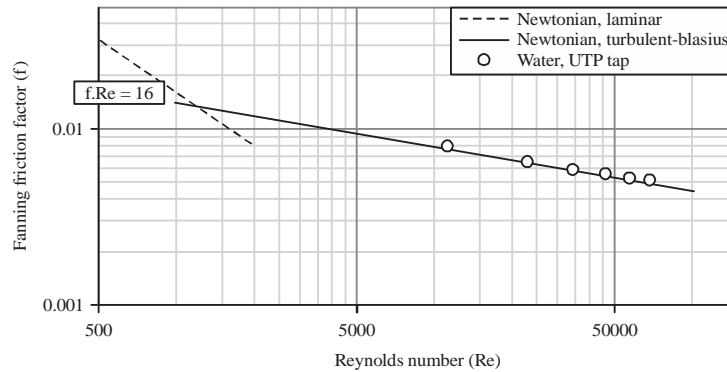


Fig. 5: f-Re data for water

**Non-newtonian flow (Xanthan gum):** Xanthan gum, a polysaccharide secreted by the bacterium *xanthomonas campestris*<sup>23</sup> is a “rigid” or “rod-like” polymer that acts as a drag reducing agent. It received little attention partially due to their weaker effectiveness at drag reducing compared to flexible polymer solutions. For this study, the polymer is tested at a concentration of 0.1% (w/w) with water as the solvent. The flow rate of the solution was varied from

10 and 300 kg min<sup>-1</sup> to produce a flow with Reynolds numbers between 800 up to 35000. The drag reduction exhibited by the 0.1% (w/w) xanthan gum was observed to be up to 55%. The drag-reduction value quoted is calculated based on the friction factor of the polymer solution and the friction factor for water calculated at the same wall Reynolds number based on the Blasius approximation i.e., in Eq. 5:

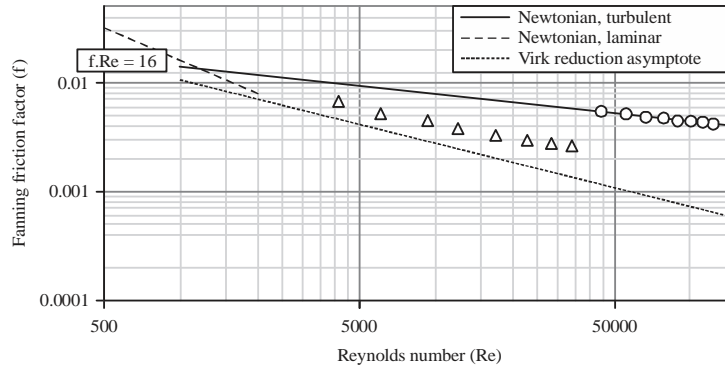


Fig. 6: f-Re data for XG: Xanthan gum (0.1% w/w)

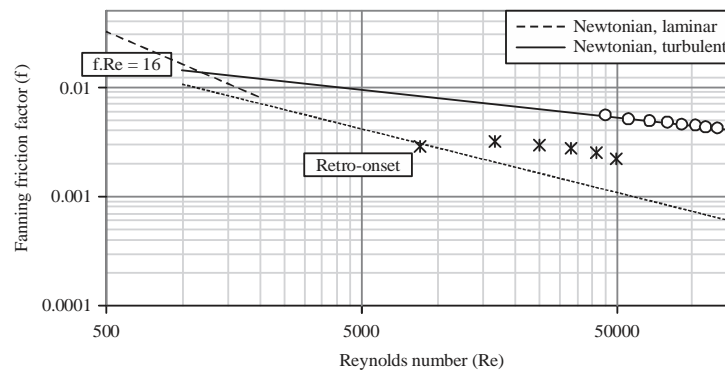


Fig. 7: f-Re data for PAM: Polyacrylamide (0.05% w/w)

$$DR (\%) = \left[ \frac{f_n - f_p}{f_n} \right] \times 100 \quad (5)$$

where, the subscripts n and p are the Newtonian fluid and the polymer solution, respectively. The Fanning friction factor is plotted against the Reynolds number in logarithmic scale and compared to that for water data as in Fig. 6. The Reynolds number is defined based on the mean flow velocity, pipe diameter D and the shear viscosity,  $\mu$  at the wall, acquired using the viscosity profile obtained using the controlled stress rheometer at the respective wall shear stress  $\tau_w$ . The wall shear stress is determined from the pressure drop measurements via Eq. 6:

$$\tau_w = \frac{\Delta p D}{L 4} \quad (6)$$

Shown together on the figure is the empirical relation proposed by Virk<sup>3</sup>, also known as Virk’s maximum drag reduction asymptote. The data also shows that the addition

of xanthan gum reduced the maximum Reynolds number in the pipe by 61% which allows the flow to achieve laminar region in Eq. 7:

$$f = 0.58 Re^{-0.58} \quad (7)$$

**Non-Newtonian flow (Polyacrylamide):** Polyacrylamide is a polymer formed from acrylamide subunits. This study describes the results achieved using non-ionic polyacrylamide (PAM), which is less prone to aggregation than hydrolyzed polyacrylamide (HPAM). However, PAM degrades more easily as it has a smaller average molecular weight<sup>24</sup>. A polyacrylamide solution with a concentration of 0.05% (w/w) with water as the solvent was utilized. The flow rate of the solution was varied from 35-300 kg min<sup>-1</sup> to produce a flow with a Reynolds number range between 5500 and 50000. For Reynolds numbers below 5500, pressure drop data showed no significant difference as they lie beyond the precision of the pressure transducer and hence were discarded.

The drag reduction was observed to be up to 65% at the highest Reynolds number attained. The Fanning friction factor

is plotted against the Reynolds number in logarithmic scale and compared to that for water data as shown in Fig. 7. The Reynolds number for the PAM solution is calculated similar to that for xanthan gum solution. Data shows that the addition of PAM reduced the maximum Reynolds number in the pipe by 61%. The friction factor data lies parallel but is down shifted from that of the Newtonian flow. However, the data at lower Reynolds number commences on the maximum drag reduction asymptote, exhibiting a "Retro-onset". Virk<sup>9</sup> discussed a similar phenomenon of retro-onset for type B drag reduction typical for rigid polymer molecules.

### CONCLUSION

From the data obtained and presented, the flow within the pipe-flow facility for a Newtonian fluid with a low viscosity, such as water can reach fully developed condition in the turbulent regime. The  $f$ - $Re$  data for the Newtonian solvent agrees with the Blasius approximation for Newtonian flow "validating" the experimental setup. The data presented for the rigid polymer xanthan gum and the flexible polyacrylamide confirms that they are both effective drag reducing agents at all stages of the flow and depend significantly on the Reynolds number. "Retro-onset" is confirmed for the sigia xanthan gum solution.

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