Turbulent drag reduction by additives
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TURBULENT DRAG REDUCTION
BY RIGID POLYMERS

Abstract

Although the phenomenon of the drag reduction has been known for almost half a century, its precise mechanism is not fully understood and still continues to be a fascinating challenge. In recent theories of drag reduction in wall turbulence, it was assumed that the presence of the polymer leads to an effective viscosity that increases linearly with the distance from the wall. Such a linear viscosity profile reduces the Reynolds stress (i.e., the momentum flux to the wall) which in turn leads to drag reduction.

In this work, the turbulent drag reduction characteristics of the rod-like polysaccharide xanthan gum were investigated to understand the mechanism of the interaction of rigid polymers with turbulence using a horizontal closed-loop system. The use of rigid polymers leads to a shear thinning viscosity without any elastic effect, allowing to directly assess the effect of viscosity on drag reduction.
4.1 Introduction

Polymer drag reduction has found applications in many fields, primarily in pipe-flows, but also in marine and biomedical applications. The phenomenon of polymer drag reduction has shown that the drag reduction effect is achieved, using a minute amount of polymer in a turbulent fluid flow which results in a large reduction in the frictional drag in pipes and channels. Specifically, turbulent drag reduction by polymer additives has been extensively studied because of the significant potential benefits to many systems such as long-distance transportation of liquids, oil-well operations, transportation of suspensions and slurries, district heating and cooling, firefighting operations and irrigation. The use of polymer additives to enhance flow in petroleum pipelines has received the greatest attention due to its great commercial success [1, 2].

Despite there having been a large amount of experiments in addition to both theoretical and simulation approaches, the nature of the drag reduction phenomenon is incompletely understood and remains a subject of debate [3, 8]. The classical explanation of the drag reduction phenomena is based on the notion of an increased effective viscosity in the boundary layer. As suggested by Lumley [9, 10] the stretching of random coiled polymers would increase the effective viscosity through an elevated elongational viscosity [11]. The increase in effective viscosity suppresses turbulent fluctuations and leads to a reduction in wall friction through a thickening of the buffer layer. In more recent work, L’Vov et al. [12] and Benzi et al. [13] further developed a linear viscosity model for drag reduction. Recent direct numerical simulations (DNS) confirm that polymers change the properties of the flows by introducing an effective viscosity [14]. This leads to an effective viscosity that increases linearly with the distance from the wall. Such a linear viscosity profile reduces the Reynolds stress in the elastic sublayer, resulting in a reduction of momentum flux from bulk flow to the wall compared to that for Newtonian flow, more than it increases the viscous drag. This then leads to drag reduction. They stated that such a linear effective viscosity profile could originate from the polymer extension. However, the behaviour of a linear polymers is very non-linear [11] with a strong coupling between the flows and the polymers [15]. On the other hand, for rigid polymers, the flows only couples to the orientational degrees of the freedom, and not to the internal degrees of freedom of the polymer [16]. It is therefore interesting to study the drag reduction for rigid polymers.
Turbulent drag reduction with rigid polymer has perhaps obtained less attention than flexible polymers, because they are not considered to be as effective at reducing drag at a given concentration [17, 18]. However, rigid polymers are of great interest, since they are inexpensive, environment friendly products and show significant resistance to mechanical degradation compared to flexible polymers with similar molecular weights [19, 20]. Therefore these polymers have a great potential to be used in many engineering and industrial applications. The properties of rigid polymers differ from those of flexible polymers. The main difference between flexible and rodlike polymers is that flexible polymers require a minimal value of shear rate to stretch the molecules, while rigid polymers are already in a rodlike conformation. Another important difference in the rheology between rigid and flexible polymers is an elongational viscosity. It was found that the elongational viscosity of the rigid polymer solution is so low that filament dynamics are indistinguishable from pure water [21].

The aim of this work is to investigate a linear viscosity mechanism for drag reduction on the basis of experimental analysis. In this work, the turbulent drag reduction characteristics of the rod-like polysaccharide xanthan gum are presented.

4.2 Materials and Experimental Setup

4.2.1 Xanthan Gum

Xanthan Gum (XG) is a polysaccharide produced by the fermentation of the bacteria xanthomonas campestris. Being an environment friendly, high efficiency additive, xanthan is widely used in the food, cosmetic and pharmaceutical industries. In addition, due to their high viscosity of solutions and water solubility, these biopolymers are utilized for applications in the petroleum industry, such as for drilling fluids and in enhanced oil recovery processes. In all these areas, xanthan gum is extensively used as a stabilizer, thickener, and processing aid.

Xanthane is one of the most effective natural, water-soluble polymers with having a wide range of industrial applications, and provides effective drag reduction due to its chemical and mechanical stability [22].
Figure 1: Xanthane structure.

Xanthane, purchased from Sigma-Aldrich, was used without any further purification and tap water was used as a solvent. Xanthane is soluble in both cold and hot water. Similar to other hydrocolloids, xanthan gum needs to be slowly mixed upon introduction to an aqueous medium to avoid the formation of lumps. Xanthane is prepared by slow magnetic stirring, adding the required amount of polymer powder weighed using an electronic balance (BA 210S, Sartorius, Germany) in tap water, and allowing the time needed for the polymer to mix fully before adding more polymers in an effort to avoid lump formation at room temperature. During stirring, the top of the glass container is sealed with a stopper to prevent evaporation of the medium. Polymer solution is stirred until a homogeneous solution is obtained. Then the solution was diluted with additional tap water to a desired test concentration.

4.2.2 Characterization of experimental set up

Turbulent drag reduction characteristics of the rod-like polysaccharide xanthan gum were investigated using a horizontal closed loop system. This system consists of two long linear sections (22.5 mm diameter pipe). The first part is made from stainless steel equipped with a differential pressure transducer. This pressure transducer is connected to two pressure taps, 6.2 m
apart. The measurement range of pressure sensors is 0-350 bar. The second part is used to visualize the flow with PIV through a transparent glass tube, around 1.2 meters long with a diameter of 22.5 mm. The fluid flow is driven by a volumetric pump from a reservoir tank of 30 liters. To reduce the fluctuations of pressure in the closed system, a pressure damper is installed at the outlet of the pump. On the other side, a magnetic meter is placed to measure the flow rate. The volumetric pump and valve are used to adjust the flow rate. The pump used here can deliver up to 8 bar (for 0.95kW). The temperature is measured when entering and exiting the system. Temperature is controlled by a heat exchanger and measured by two sensors. All data, consisting of pressure gradient, temperature and flow rate, are then processed by a computer. The velocity profile experiment was performed with the PIV measurements at the concentration of 500 ppm of xanthan gum with tap water at Re=20000 and Re=30000. For a better quality of results, the velocity profiles of xanthan gum were carried out in the 22.5 mm diameter channel at a temperature of 20°C.

The particle image velocimetry experiment was performed by placing the glass test tube section in a rectangular Perspex box filled with index-matching liquid to minimize the effect of optical curvature. At the distance of Lb=70 cm, measurements were taken, where Lb is the distance from the glass pipe inlet to the test section. The flow is seeded with glass particles of 15 µm in diameter. An Nd-Yag type laser is used as a source of illumination and a CCD camera (of 1024x1280 pixels resolution) is used to record flow images. The velocity fields are measured by a particle image velocimetry method using the DaVis software (from La Vision). The average velocity field parameter is then calculated from several instantaneous fields.

### 4.3 Results and Discussions

#### 4.3.1 Xanthane rheology

The rheology of the xanthane solution is studied on the Rheologica StressTech rheometer. The viscosity of xanthane at different concentrations is determined as a function of shear rate. As will be seen, xanthane shows a pronounced shear-thinning behavior (i.e., viscosity decreases with increasing velocity gradients), without significant elastic effects [16].
4.3.2 Drag reduction of xanthane

The addition of tiny amounts of polymer to a turbulent fluid flow can cause a large reduction in the frictional drag relative to a pure solvent at the same flow rate. The coefficient of friction is defined as follows:

\[
f = \frac{2 \tau_w}{pU^2} = \frac{\Delta PD}{2pU^2L} = \frac{\Delta P \pi^2 D^5}{32pLQ^2}
\]

where \( f \) is the fanning friction factor and defined as the ratio of the viscous tangential force and inertial force. It depends on the density of the solution \( p \), bulk velocity \( U \) and \( \tau_w \) wall shear stress.

A fanning friction is experimentally calculated using the measurements of the flow rate \( Q \), the pressure drop \( \Delta P \) between two locations spaced at a distance of \( L \), and inner diameter \( D \) of the pipe.

Drag reduction occurs if the pressure drop is reduced at the same flow rate or if the flow rate is increased at the same pressure drop. The percentage of DR at a constant flow rate is defined based on the friction factor of the polymer solution and water.
\[ DR\% = \left( \frac{f_s - f_{DR}}{f_s} \right) \cdot 100 \]  

(2)

where \( f_s \) and \( f_{DR} \) are respectively the friction coefficient of the solvent and drag reducing solutions.

Drag reduction result for 500 ppm Xanthane:

At \( Re=20000 \), the drag reduction is about 35%.
At \( Re=30000 \), the drag reduction is about 40%.

As can be seen from the data obtained, drag-reduction increases with increasing the Reynolds number [23] and the addition of a minute amount of xanthane polymer to a turbulent fluid flow can result in a large reduction of the frictional drag in channel flow by 40%.

4.3.3 The mean velocity profiles of water and xanthane

Drag reduction is accompanied by changes in the strength of turbulent fluctuations and velocity profiles. The measurement of velocity profiles and velocity fluctuations gives insights into the nature of the maximum drag reduction phenomenon. The velocity profiles are usually represented by non-dimensional semilogarithmic coordinates of the fluid velocity \( U^+ \) versus distance from the wall \( y^+ \) defined as follows:

\[ U^+ = \frac{u}{u_s} \]  
\[ y^+ = \frac{yu_s}{v} \]  

(3)  
(4)

where \( u \) is the local velocity at the distance \( y \) from the wall, \( v \) is the kinematic viscosity of the fluid and

\[ u_s = \sqrt{\frac{\tau_w}{\rho}} \]  

(5)

designates a wall friction velocity, \( \tau_w \) and \( \rho \) being the wall shear stress and the density of the fluid. The velocity profiles show changes between a drag reducing rigid polymer solution and a pure solvent. The measured mean velocity profiles for both xanthane and water flows are presented in figure 3(a). The velocity gradient for water flow shows a good agreement with the theory. As can be seen in figure 3(a), the highest velocity gradient close to the wall is observed for water. For the drag reducing flow, the addition of polymer has only a small impact on the core region while it...
decreases the velocity gradient near the wall significantly. As can be seen, the mean velocity gradient near the wall is lower than the one for the solvent. As shown in figure 3(a), the velocity gradient near the wall compared to that found for water decreases with the increasing drag reduction but in the bulk region, it can be seen that, with increase of DR, the distribution of mean velocity in the drag reduced flow becomes further away from that of turbulent water flow with a flattening in the center. It is well known that the momentum transfer between the wall and flow is directly linked to this velocity gradient. Hence lower velocity gradient in the case of flow with polymer gives rise to a lower wall shear stress and drag. Lumley point out that the difference in the boundary layer turbulence structure between the Newtonian case and the drag reducing flows is that polymer molecules are expanded in the flow outside the viscous sublayer due to possible stretching of the polymer molecule. This produces an increase effective viscosity and in turn damps dissipative eddies. However, the precise mechanism of the higher viscosity in relation to the polymer dynamics remained unclear; this is why we use here a linear rod-like polymer that shows a shear thinning but no strong elasticity. For our case, we observe an increase in effective viscosity and a thickening of the viscous layer, leading to a decrease in the velocity gradient at the wall. The observed decrease in the velocity gradient for the xanthane in Figure 3(a) also indicates the thickening of the viscous sublayer.

Figure 3: (a) The average velocity and (b) the mean velocity profiles of water and xanthane at Re=20000 and Re=30000, C=500 ppm in the diameter of 22.5 mm channel.
Drag reduction is greatly linked to the changes in the velocity profile. This change can clearly be seen in figure 3(b). In the velocity profile, the solvent viscosity was used to calculate the length scale \((y^+)\). The turbulent velocity law of the wall for Newtonian flow is given by

\[ U^+ = 2.5 \ln y^+ + 5.5 \]  

and Virks’ maximum velocity profile in the polymer drag reducing flow [24] are also presented in the figure.

\[ U^+ = 11.7 \ln y^+ - 17.0 \]

From figure 3(b), it can be seen that the measured velocity profile for water is in close agreement with the turbulent velocity law of the wall profile in the logarithmic region. For the xanthane, the mean velocity profiles as a function of the dimensionless wall distance are upshifted in the log-law layer with a larger gradient compared with that of water. This might be due to a change in the structure of turbulence or due to viscosity varying with the wall distance (which would also influence the structure of turbulence). The difference between velocity profiles of the xanthane solution and water flows in the logarithmic region increases with DR level due to thickening of the buffer layer. The velocity profiles show that interaction between polymer molecules and the turbulent structures takes place in the buffer layer. Further away from the wall the velocity of xanthane solution increases compared to water, which is consistent with the observed drag reduction. The result of the velocity profile measurement clearly demonstrates thickening of the buffer layer and an increase in the slope of the logarithmic profile in the wall region.

4.3.4. The turbulent statistics of water and xanthane

The drag reduction effect is accompanied by the modification of the turbulent structure. The measurements of the turbulence in the flow can lead to much better understanding of the mechanism of the interaction of the xanthane polymer with the turbulence. The turbulence intensity of the streamwise and wall normal velocity fluctuation for water and xanthan gum solution are presented in figure 4. Nondimensionalization of the streamwise and wall normal velocity fluctuations were made by a friction velocity.

\[ U_{rms} = \frac{\sqrt{\langle uu \rangle}}{u_r} \]  

\[ V_{rms} = \frac{\sqrt{\langle vv \rangle}}{u_r} \]
Figure 4: Dimensionless a) streamwise and b) wall-normal velocity fluctuations of water and xanthane at Re=20000 and Re=30000, C=500 ppm in the diameter of 22.5 mm channel.

Figure 4 (a) shows that the location of the maximum value of streamwise fluctuations for water is very close to the wall and these velocity fluctuations monotonously decrease from the near-wall to the center of the channel. In drag reducing flows, in the vicinity of the wall, the turbulence intensity for xanthane is damped in comparison to water, whereas in the buffer layer an increase of the streamwise turbulence intensity occurs. As can be seen, the peak levels of the streamwise velocity fluctuation for xanthane shift further away from the wall by a few millimeters and the most characteristic changes occur in the near-wall buffer zone. The normalized turbulence intensity in the streamwise direction in the drag reducing flow shows a shift of the maximum fluctuations towards larger wall distances and the peak itself was broader than for water. On the other hand, the streamwise velocity fluctuations monotonously decreased toward the center of the channel. This behaviour of the streamwise intensity is similar to that found in drag reducing dilute flexible polymers by Berman [25].

However, along the transverse axis, the dimensionless wall normal fluctuation of water is higher by about 1/3 compared with those found for the solutions of xanthane. In the drag reducing flows, the transverse turbulent intensity profiles $v'_{rms}/u_\tau$ normalized with a friction velocity ($u_\tau$) decreased drastically as result of polymer addition compared to the water at a similar Reynolds number. As can be seen in figure 4, the decreasing the level of the wall normal fluctuation is much higher than the increasing the level of the streamwise velocity fluctuations. This fact indicates that the turbulent kinetic energy transport between the different directional fluctuations is suppressed
by the effect of xanthane. Thus, the fluctuations become anisotropic in the drag reducing flow. The measured turbulence intensity results showed that the streamwise velocity fluctuations increase towards higher wall distances while the wall-normal velocity fluctuations decrease significantly compared to the water. The main conclusion of the velocity fluctuation measurements is that drag reduction leads to modification of turbulent structures and energy particularly in the buffer layer.

4.3.5 The Reynolds shear stress of water and xanthane

It is widely believed that polymer drag reduction is the combined effect of a dampening of the Reynolds stress without generating additional resistance in the viscous sub-layer. This leads to a thickening of the viscous sub-layer with the net effect of a reduced friction factor (Lumley [8]). Many studies have confirmed both experimentally and theoretically that the Reynolds shear stresses which characterize the turbulent momentum transport are drastically reduced in the drag reducing polymer solution compared to water [26, 28]. Figure 7 presents the Reynolds shear stress profile for the water and aqueous xanthan gum solution. The Reynolds shear stress profile normalized with a friction velocity ($u_f$).

$$UV^+ = \frac{\overline{uv}}{u_f}$$  \hspace{1cm} (10)

Figure 5: The Profiles of Reynolds shear stress of water and xanthane at $Re=20000$ and $Re=30000$, $C=500$ ppm in the diameter of 22.5 mm channel.
As revealed by the plot, the measured Reynolds stress for water is in close agreement with the theory. For the xanthane, it shows that the addition of the polymer results in a decrease of the Reynolds stress. The profiles of the Reynolds shear stress clearly demonstrate that the Reynolds shear stresses which characterize the turbulent momentum transport are drastically reduced in the drag reducing polymer solution compared to water. As can be seen, the Reynolds stresses are found to be almost zero. This indicates that the momentum transport mechanism of the drag-reducing flow is quite different from that of the Newtonian fluid flow. This is similar to the observations of Warholic et al. [28, 29] who found the Reynolds stress to be very close to zero for both polymer and surfactant drag reducing solutions.

The decrease of the Reynolds stress could be explained by a decoupling of the streamwise $u'_{rms}$ and the wall normal $v'_{rms}$ fluctuations. Figure 6 demostrates the cross-correlation coefficient for water and xanthane solution. This coefficient is defined as follows:

$$ R_{uv} = \frac{\overline{u'v'}}{u'_{rms}v'_{rms}} $$

(11)

where $u'_{rms}$ and $v'_{rms}$ are the velocity fluctuations in the streamwise and wall-normal directions and $\overline{u'v'}$ is the Reynolds shear stress coefficient.

Figure 6. The cross-correlation coefficient between $u'_{rms}$ and $v'_{rms}$ velocity fluctuations at $Re=20000$ and $Re=30000$, $C=500$ ppm in the diameter of 22.5 mm channel.
As can be seen from Figure 6, the cross-correlation coefficients between the streamwise and wall normal fluctuations are drastically reduced compared to those found for water flow. The experimental results obtained for xanthane solutions show that a complete damping of the Reynolds stress does not directly result in a decrease of turbulence fluctuations but in rather in a decorrelation of $u'_{rms}$ and $v'_{rms}$ fluctuations. The loss of correlation between the streamwise and wall normal velocity components, consequently the decrease of the Reynolds stress, is suggested to be responsible for DR. The results obtained show that the reduction in Reynolds stress arises from a decorrelation between $u'_{rms}$ and $v'_{rms}$ velocity fluctuations, consistent with the descriptions in the literature by Hoyer and Gyr [30].

4.3.6 The turbulent kinetic energy of water and xanthane

Ptasinski et al. [27] considered the various terms in the mean energy budget and found that a large amount of the mean flow kinetic energy is transferred directly to the polymers instead of the turbulence. This corresponds to a direct suppression of the turbulent kinetic energy. It is also of interest to consider flow turbulent kinetic energy profile to understand the energy exchanges between the polymer and turbulence. The turbulent kinetic energy (TKE) is defined as

$$TKE = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} \right)$$

where $\overline{u'^2}$ and $\overline{v'^2}$ are the mean square values of the velocity fluctuations in the streamwise and wall-normal directions.

Figure 7 presents a turbulent kinetic energy for the water and aqueous xanthan gum solution. In the water flow, the highest kinetic energy is observed. In the case of a drag reducing flow, near the wall, the kinetic energy dissipated is lower compared than those found for water under the same experimental conditions. As can be seen in figure 6, the production of kinetic energy is reduced in the drag reducing xanthane solution flows due to the depression of the Reynolds shear stress. At the same time, a peak in the kinetic energy profile moves away from the wall with increase of DR level. The turbulent kinetic energy profiles show that drag reduction leads to modification of energy particularly in the buffer layer. These results obtained are again in good agreement with those obtained by other researches [31, 32].
4.3.7 The effective viscosity profile of xanthane

Knowledge of the role of the effective viscosity in the mechanism of drag reduction by rigid polymer additives is one of the most important in understanding the nature of the drag reduction phenomenon. In a recent theory of drag reduction in wall turbulence, it was suggested that presence of the polymer leads to an effective viscosity which increases linearly with the distance from the wall. Such a viscosity profile could suppress the Reynolds stress in the elastic sublayer, resulting in a reduction of the momentum flux to the wall more than it increases the viscous drag which in turn leads to drag reduction. The Reynolds stress deficit occurs in flows of drag reducing polymer solutions where solvent shear viscosity is employed in the calculation of the distance from the wall (y+)

\[
-\frac{\bar{u} \bar{v}}{u'^2} = 1 - \frac{y}{R} \frac{dU'^+}{dy'^+} - G
\]  

(13)
Where $G$ is the Reynolds stress deficit termed elastic stresses by the original authors [33]. Giving $G$ the name elastic stress implies that deficit is due to elastic properties resulting from rheological effects. Another way of expressing this would be to say that turbulent flow structures are altered so that they can be dominated by viscosity up to higher distances from the wall. The quantity $G$ could be interpreted by a wall distance dependent, effective viscosity, $\eta$.

$$\eta = \frac{\nu_{\text{eff}}}{\nu_0}$$  \hspace{1cm} (14)

Giesekus [34] early suggested that such elastic stresses can be attributed to an increase in the local viscosity and eq. (13) becomes

$$-\frac{\overline{u'v'}}{u_r^2} = 1 - \frac{y}{R} - \frac{\nu_{\text{eff}}}{\nu_0} \frac{dU^+}{dy^+}$$  \hspace{1cm} (15)

where $R$ is the radius of the pipe, $\nu_{\text{eff}}$ is the effective viscosity and $\nu_0$ is the kinematic viscosity of the solvent.

Figure 8: The effective viscosity of xanthane at $Re=30000$
$C=500$ ppm in the diameter of 22.5 mm channel.

In figure 8, the effect of the effective viscosity profile is presented as a function of the dimensionless wall distance. The effective viscosity profile clearly demonstrates that there is an increase in effective viscosity with wall-distance with addition of xanthane. As can be seen in
figure 8, an effective viscosity grows approximately linearly with the wall distance (y+). This clearly shows that the effective viscosity increases almost linearly up to $y^+ \sim 30$ from the wall. However, outside the buffer layer, the effective viscosity becomes constant, as a function of the dimensionless wall distance. Based on the experimental results obtained, the drag reduction by rigid polymer can be interpreted as an increase in the local effective viscosity that is negligible at the wall and increases almost linearly with the wall distance in buffer zone which is in agreement with recent theory. This elevated effective viscosity could be an important factor in understanding the drag reduction phenomenon by rigid polymer additives.

4.4 Conclusion

In this work, the turbulent drag reduction characteristics of the rod-like polysaccharide xanthane were investigated. We performed the drag reduction measurements using a horizontal closed loop system. DR reduction characteristics of 500 ppm xanthane solution were studied at a temperature of 20°C at two different Reynolds numbers. The mean velocity profiles were investigated to understand the nature of the drag reduction phenomenon by xanthane polymer. The analysis of velocity profiles demonstrated that the highest velocity gradient is observed for water flow near the wall. For the drag reducing flow, the velocity gradient near the wall decreased compared to that found for water. The decrease in the velocity gradient for xanthane indicates the thickening of the viscous sublayer. The mean velocity profiles measured clearly show that interaction between polymer molecules and the turbulent structures takes place in the buffer layer, and further away from the wall, the velocity of the xanthane flow increases compared to the Newtonian case, which is consistent with drag reduction.

In addition to the velocity profile measurements, the turbulent intensity and the Reynolds stress measurements are needed in order to understand the mechanism of the interaction of the xanthane polymer with turbulences. The velocity fluctuation measurements show that the drag reduction leads to modification of turbulent structures and energy particularly in the buffer layer. In addition, the Reynolds shear stress profile clearly demonstrates a drastic depression of the Reynolds stress in the drag reducing polymer solution compared to water which directly results in a decrease of turbulence production and reduction of wall friction. Hence, this leads to DR. The cross-correlation results obtained confirm that the reduction in the Reynolds stress arises from a
decorrelation between the streamwise ($u_{rms}$) and wall normal ($v_{rms}$) velocity fluctuations. It is also of interest to consider flow kinetic energy to understand the drag reduction phenomenon. It was found that the production of kinetic energy is reduced in the drag reducing xanthane solution due to the depression of Reynolds shear stress.

A keyword in many attempts of explaining the mechanism of drag reduction by rigid polymer is an effective viscosity. The effective viscosity profile shows that the addition of the rodlike polymer in the Newtonian fluid leads to an increase in effective viscosity from the wall. The increase of effective viscosity with wall distance in xanthane polymer demonstrates drag-reducing properties. This elevated effective viscosity profile could strongly reduce turbulent fluctuations, lead to decrease of kinetic energy, drastically reduce the Reynolds shear stress (i.e., the momentum flux to the wall) compared to that for Newtonian flow, and which in turn leads to drag reduction. Based on the experimental results obtained, the drag reduction of rigid polymers can be interpreted as an increase in the local effective viscosity with the wall distance in the buffer zone, which is in agreement with recent theory. Such a linear viscosity profile that demonstrated the drag-reducing properties could be a very important factor in understanding the nature of the drag reduction phenomenon by rigid polymers.
Bibliography


