Turbulent drag reduction by additives

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By Additives

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Cover photo shows a representation of a turbulent flow, designed by Kulmatova 2013.

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Abstract

The addition of a minute amount of polymer or surfactant additive to a turbulent fluid flow can result in a large reduction in the frictional drag in pipes and channels. Over the past decades numerous studies have been carried out on drag reducing additives (DRA). DRA have been successfully applied for potential benefits in various industrial processes, including oil well operations, heating and cooling water circuits, marine and biomedical systems. The use of additives to enhance flow in petroleum pipelines has received the greatest attention due to its great commercial success in reducing cost and energy consumption. Although this effect has been known for almost half a century, the detailed mechanisms of drag reduction have still not been clearly identified and is still a subject of ongoing controversy.

The aim of this thesis is to develop an understanding of the role of drag reducing agents and to explain the nature of the drag reduction mechanism. This could have an impact on the design of efficient pumping systems, the design of drag-reducing agents that are more stable over time, and the modelling of mixing processes that could be an important consideration in designing practical systems.

Het toevoegen van een kleine hoeveelheid polymeer aan een turbulente vloeistofstroom kan leiden tot een een enorme reductie van wrijving in pijpen en leidingen. In de afgelopen decennia zijn er talloze onderzoeken gedaan naar additieven die de weerstand verminderen. Deze additieven zijn succesvol toegepast voor potentiële voordelen in verschillende industriële processen, onder andere bij oliebronnen, verwarmings- en koelingswatercircuits en zee- en biomedische systemen. Het gebruik van additieven om de stroom in petroleumpijpleidingen te versterken heeft veel aandacht gekregen vanwege de reductie van kosten en energieconsumptie. Ondanks dat dit effect al bijna een halve eeuw bekend is, zijn de details van de weerstandsreductie nog altijd niet duidelijk in kaart gebracht en is het ook nog steeds een onderwerp van voortdurende controverse.

Het doel van dit proefschrift is om begrip te krijgen voor de rol van weerstandsverminderende additieven en het uitleggen van de aard van het weerstandsreductiemechanisme. Dit kan een grote impact hebben op het ontwerpen van efficiënte pompsoennet, het ontwerpen van weerstandsverminderende additieven die stabiel zijn en het modelleren van mix-processen die van belang kunnen zijn voor de ontwikkeling van praktische systemen.
INTRODUCTION

The transfer of solid, liquid and gaseous materials is very important to the world economy. To transfer liquids, pipeline technology is most often utilized. However, this process requires expensive upgrades and does not overcome the needs of a growing human population. In most practical applications the flow in pipes is turbulent. Turbulent flow results in a lot of energy loss due to the turbulent dissipation of energy. For this reason, doubling the energy invested will not double the flow rate. One possible way of improving the drag efficiency of turbulent flow could be the phenomenon that was discovered by Toms [1]. He was the first to publish drag reduction data on what would later become known as the “Toms effect”. Toms reported that very dilute solutions of polymethylmethacrylate in monochlorobenzene experienced a greatly reduced pressure drop, relative to a pure solvent at the same flow rate.

Most turbulent flows find their origin in the boundary layer near solid surfaces. As the flow velocity increases, so does the friction. The energy losses due to turbulence friction can be very high. These large losses are what make drag reduction research necessary. DR can be achieved by the introduction of minute concentrations of polymers, surfactants and fibres [2, 5]. One industrial application of this effect is crude oil transportation in the Trans-Alaskan pipeline. In 1979, 50-percent drag reduction was achieved in the Trans-Alaskan Pipeline (TAPS), thereby increasing capacity and eliminating the need for installing two pumping stations [6]. Drag reducing agents (DRAs) have been used in many petroleum product pipeline installations such as the Oseberg Field in the North Sea [7]. By 1994, the effectiveness of DRA was 14 times greater than it was during the 1980s.

Turbulent DR by additives has been extensively studied because the potential for industrial application is high, but despite over four decades of extensive DR research, there is no universally accepted model that explains how macromolecules reduce friction (Virk et al. [8], Armstrong et al. [9], Thirumalai et al. [10], Balkovsky et al. [11] and Groisman et al. [12]). Drag reduction involves many subjects of interest such as polymer science, fluid mechanics and mathematical
modelling. Many books have been published on simulations, experiments and mechanisms regarding the maximum attainable drag reduction in a turbulent channel flow. Many of these books and papers were multi-disciplinary, and they all demonstrate that DR methodologies can save energy. It is therefore quite helpful to industries, especially the oil servicing and transportation industries, to advance the research of DR for the purposes of designing the optimal operation of oil pipelines. Success on this front would have a tremendous impact on the economics of energy propulsion.

1.1 What is Drag Reduction?

Drag reduction is the phenomenon whereby minute amount of drag reducing additives are added to a turbulent flow, to achieve a large reduction in the frictional drag in pipes and channels (Truong [13]). Newtonian fluids exhibit two qualitatively different flows: laminar and turbulent. Laminar flow through a pipe is described by the well-known Hagen-Poiseuille equation and defined by a linear dependence of flow rate on driving pressure.

\[ Q = \frac{\Delta P \pi R^4}{8\eta L} \]  

(1)

Where \( Q \) is the volumetric flow rate, \( \Delta P \) is the pressure gradients along pipe, \( L \) is the length of pipe, \( R \) is the radius and \( \eta \) is the dynamic viscosity of fluid.

As the flow rate increases above a certain threshold, the pressure begins to increase faster than the flow rate does. At this point, the flow becomes turbulent. Turbulent flows are defined by strong mixing action that leads to momentum transfer between liquid layers in a spanwise direction. This means that the increase in pressure difference in the turbulent regime leads to smaller flow rate increase in comparison to the laminar flows. Turbulent flow was first described by Prandtl’s and Karman’s efforts. They have developed an expression of dependence of friction factor on Reynolds number for Newtonian turbulent flow in a smooth pipe [14].

\[ \frac{1}{f^{1/2}} = 4.0 \log_{10} \left( \text{Re} f^{1/2} \right) - 0.4 \]  

(2)

Drag reduction is accompanied by reduction the intensity of vortices in a turbulent flow and the turbulent kinetic energy in general (see Figure 1). In other words, the required pressure difference necessary to reach desired flow rate in a 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.
Research has revealed a large number of drag reduction effects, falling into both active and passive categories (Truong V.T [13]). Active drag reduction relies on the introduction of external agents such as drag reduction active polymers or air bubbles in order to decrease friction in turbulent flows, whereas passive techniques contain compliant coatings and riblets. Passive techniques involve modifications of the geometry of the surface to alter the flow characteristics. However, the level of drag reduction is not as effective as the active ones. (Choi K.S [15]). In the case of polymers, drag reduction can be achieved by the addition of a minute amount of polymer to a turbulent fluid flow. Polymer can reduce the pumping pressure by 80 percent, even when the concentration of the polymer is as low as a few parts per million. Alternatively, the flow rate can be increased by 40 percent at the same pumping pressure.

Figure 1: Planar Laser Induced Fluorescence A) image for water and B) for 100 wppm of polyethylene oxide with \( M_w = 4.5 \times 10^6 \) g/mol.

1.2 Goal of this thesis

The addition of minute amounts of drag reduction additives to a turbulent fluid flow can result in a large reduction in the frictional drag in pipes and channels. The nature of the drag reduction mechanism by which this occurs is not been clearly identified. The objective of this project is to develop an understanding of nature of the drag reduction mechanism. For this, we study the effect of the addition of the most common drag reducing agents (polymers and surfactants) on the characteristics of turbulent flows.
1.3 Outline

The dissertation is composed of the following chapters:

Chapter 2 covers a comprehensive survey of the literature review to give a brief outline of early and recent developments in the field of drag reduction of polymer and surfactant additives. Thereafter, the types of additives and applications have been reviewed. The fundamentals of turbulent flow characteristics are firstly covered, followed by the concepts of the drag reduction phenomenon.

Chapter 3 gives a detailed description of the apparatus and experimental procedures used in these studies. General information about the Rheologica StressTech rheometer is presented. A horizontal closed loop experimental set up and Particle Image Velocimetry (PIV) system used in the characterization of drag reduction are described in this chapter. The counter rotating disc apparatus and Laser Doppler Velocimetry (LDV) used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids, are also introduced in Chapter 3.

Chapter 4 examines the turbulent drag reduction characteristics of the rod-like polysaccharide xanthane. The experimental results are discussed in relation to a linear viscosity model. The mean velocity profiles, turbulence velocity fluctuations, Reynolds shear stress, cross-correlation coefficient, turbulent kinetic energy and effective viscosity of xanthane polymer solution have been investigated to understand the mechanism of the interaction of rigid polymers with turbulence and to shed light on the nature of the drag reduction mechanism. The experimental results support the notion that an effective viscosity could be an important factor in understanding the drag reduction phenomenon by rigid polymer additives.

Chapter 5 investigates the structure of turbulence in a drag reducing surfactant and polymer systems. The experimental results are discussed in relation to the recent investigations which showed modifications of the energy density spectrum and the second order structure function at scales near the dissipative range and beyond. In this chapter, we reexamine the issue of the modification of the structure of turbulence, using the diluted surfactant and polymer solutions as
the complex fluid, through the possible modifications of the scaling behaviour of the energy density spectrum and the velocity structure functions. The examination of turbulence properties of CTAB (a surfactant DR) and PEO (a polymer DR) were made using a two counter rotating baffled disk. By investigating the spectral properties and the structure function scalings, we found an important difference arise with respect to the reference case, water. The experimental results demonstrated that CTAB surfactant solutions showed a strong intermittency at small scales in relation to the pure water and PEO polymer solution. At the large scales this intermittency is either absent or very small. While this transition is observed in the structure function scalings, no sign of this transition is seen in the power spectrum of velocity fluctuations which shows a single scaling range. The strongly intermittent small scale region, despite the scaling of the power spectrum, exhibits properties reminiscent of the near dissipative range.

Chapter 6 provides a summary of the research of turbulent drag reduction characteristics of the rod-like polysaccharide xanthan gum and the structure of turbulence in a drag reducing surfactant and polymer systems presented in the earlier chapters.
2.1 Drag Reduction Additives

Drag reduction in turbulent flow can be achieved by several types of additives. These include surfactants, fibers, aluminum disoaps, and high polymers. These drag reducing additives can dramatically affect the turbulent structures of the flowing fluid, increase the flow rate and decrease the energy consumption. This section gives an overview of drag reduction and the commonly used DRA.

2.1.1. Drag reduction characterisation

The addition of a minute amount of drag reducing additives 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 amount of drag reduction is generally expressed as the pressure gradient differences between the solvent and the drag reducing solution. Savins [16] was the first in using the term “Drag Reduction” with the definition:

\[
\% DR = \left( 1 - \frac{\Delta P_{\text{Polymer}}}{\Delta P_{\text{Solvent}}} \right) \times 100
\] (3)

where \( \Delta P_{\text{Polymer}} \) and \( \Delta P_{\text{Solvent}} \) signify the pressure drops in friction in the presence and absence of drag reduction.

Drag reduction efficiency can also be expressed in terms of the friction factors of the solvent and the drag reducing fluids as:

\[
\% DR = \left( 1 - \frac{f_{\text{Polymer}}}{f_{\text{Solvent}}} \right) \times 100
\] (4)
The effect of drag reduction is also presented in the terms of wall shear stress \( \tau_w = \frac{D\Delta P}{4L} \), friction factor \( f = \frac{D}{2pU^2} \frac{\Delta P}{L} \) and Reynolds number \( \text{Re} = \frac{pUD}{\eta} = \frac{UD}{v} \).

Where \( \tau_w \) is the wall shear stress, \( d \) is the pipe diameter, \( U \) is the mean fluid velocity in the pipe and \( p, \eta \) and \( v \) are the dynamic viscosity and kinematic viscosity of the fluid respectively.

In order to analyze the drag reducing additive effectiveness, the best known method of representing the data in terms of these parameters is the classical \( f \) versus \( \text{Re} \) as shown in Figure 2. As illustrated in the Figure 6, with the drag reducing agent, above a particular Reynolds number, the friction factor falls below that for the case of pure solvent flow.

\[ \text{Figure 2: Methods of representing drag reduction data (Virk [8]).} \]
Prandtl–Karman coordinates \((f^{1/2} \text{ vs } Re \ f^{1/2})\) are normally used to illustrate drag reduction. The advantage of this representation is that the Newtonian turbulent flow forms a straight line.

\[
\frac{f^{1/2}}{u} = \frac{\sqrt{2}u_t}{u} \text{ as ordinate}
\]

\[
Re \ f^{1/2} = \sqrt{2} \frac{Du_t}{v} \text{ as abscissa}
\]

describe ratios of bulk to turbulent velocities and pipe to turbulent length scales respectively. According to Newtonian flow, the relationship between \(1/f^{1/2}\) and \(Re \ f^{1/2}\) are given by

\[
\frac{1}{f^{1/2}} = 4.0 \log_{10} \left(Re \ f^{1/2}\right) - 0.4 \quad \text{or} \quad f = \frac{16}{Re}
\]

In the case of the absence of drag reduction, the frictional factor can be expressed using the Prandtl–van Karman law for Newtonian turbulent pipe flow

\[
\frac{1}{f^{1/2}} = 4.0 \log_{10} \left(Re \ f^{1/2}\right) - 0.4
\]

2.1.2 Drag reduction by polymers

Polymer solutions are the most widely studied and most employed of drag reduction systems. The addition of a small amount of polymer to a turbulent fluid flow can greatly reduce the amount of drag a fluid creates on its vessel. Drag reduction can occur in water, but also in a range of organic solvents. The most important aspects of the polymers are that they possess a high molecular weight, chain flexibility, and long linear chain structure. It is also important that polymers are very soluble in the fluid (Morgan S.E. et al [17]).

Table 1 provides a list of the most common polymer drag reducers. Previous studies on polymer drag reduction indicate that the most polymers meeting parameters described above are able to reduce the drag in a turbulent flow.
Table 1: Most Widely Used Drag Reducing Polymer agents [15].

<table>
<thead>
<tr>
<th>Water-soluble polymers</th>
<th>Hydrocarbon soluble polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene oxide (PEO)</td>
<td>Polyisobutylene (PIV)</td>
</tr>
<tr>
<td>Polyacrylamide (PAM)</td>
<td>Polystyrene (PS)</td>
</tr>
<tr>
<td>Guar gum (GGM)</td>
<td>Polymethylmethacrylate (PMMA)</td>
</tr>
<tr>
<td>Xanthan gum (XG)</td>
<td>Polydimethylsiloxane (PDMS)</td>
</tr>
<tr>
<td>Carboxymethyl cellulose (CMC)</td>
<td>Polycisisoprene (PCIP)</td>
</tr>
</tbody>
</table>

Polyethylene oxide (PEO) and polyacrylamide (PAM) have been much studied in fundamental research and industry because of their low cost and high rates of availability. PEO, with its linear and flexible molecular structure, has been widely studied for commercial applications, such as fire prevention and marine propulsion. On the other hand, its usefulness in most practical applications is limited because of its extreme sensitivity to shear degradation. Conversely, polymer mixtures and DRA additives, such as grafted PEO polymers and soap mixtures, and polymer/dye mixtures are quite effective and have shown different levels of drag reduction effectiveness [18, 19]. The search for shear-stable drag reducing polymers continues to be a challenging task.

Biopolymers, being environmental friendly, show great resistance to mechanical degradation. Biopolymers, such as high molecular weight polysaccharides, are made by living organisms and exhibit effective drag reduction [20]. For instance, polysaccharides of several fresh water and marine algae, fish slime, seawater slime and other fresh water biological growths are excellent drag reducers. Yet, due to their production of fouling substances, these biological additives can substantially reduce DRA efficiency. It has been found that industrial polysaccharides such as xanthan gum (XG) show significant resistance to mechanical degradation compared to flexible polymers with similar molecular weights. Xanthane is one of the most popular commercial drag reducing biopolymers. Taofeaq [21] has proven that XG polymer has greater shear stability compared to other drag-reducing additives. The following sequence: PAM>XG>PEO>GG demonstrates the decreasing factor of shear stability, and resistance to shear degradation of flexible and rigid polymers.
2.1.3. Drag reduction by surfactants

Surface-active molecules are known as surfactants, and some of them are effective DR agents. Early publications on drag reduction by additives deal with surfactant solutions, however these kinds of additives have recently obtained less attention than polymers. Studies of drag reduction have increased during the last twenty years to use surfactants as drag reducing additives. These compounds have a self-assembled structure, and after mechanical degradation they are assembled which permits them to be used in recirculation systems such as district heating and cooling systems [22]. Surfactants have been utilized as drag reducing agents in many research studies. Surfactant molecules have unique self-repairing ability that keeps the drag-reducing effect through mechanical shear stress. Drag reducing surfactant molecules form “aggregates,” called wormlike micelles. As fluid comes into a shear region, the micelles change their structure. Furthermore, surfactants are commercially available and, during operations, are easy to handle. Therefore, surfactants are more desirable than many types of polymers in certain commercial applications, such as in district heating or cooling systems [23].

2.1.4 Drag reduction by fibres

Fibres, which are stable both chemically and mechanically in aqueous surroundings, are also used as DRA for many practical applications, which has a significant practical importance to the papermaking industry, the food industry and in the production of fiber-reinforced plastics. Since the most fibrous materials are not affected by water chemistry, piping substances, and temperature, they can withstand a wide temperature range [24, 25]. Drag-reducing fibers are considered not to cause an envorimental pollution because they do not react with any material and do not produce toxic substances. Lee et al. [26] and Doulah et al. [27] believed that fiber drag reduction might be caused by suppression of turbulent eddies in the turbulent core areas. It was observed that a 95 percent drag reduction occurred due to mixtures of fiber systems and polymers [28, 29]. Compared to the drag reduction of polymers and fibers alone, this drag reduction level is greater. In this system, the actual polymer was also more resistant to degradation. However, it is difficult to use fibers in these surroundings because they can create plugging problems in pipelines as a result of the high concentration (as high as a few percent required for drag reduction).
2.1.5 DRA applications

Using polymer and surfactant additives provides benefit to various industries, such as long-distance transportation of liquids, district heating and cooling, fire-fighting operations, irrigation systems and the oil servicing and transportation industries for designing the optimal operation of oil pipelines. The use of drag reducing additives to enhance flow in petroleum pipelines has received the greatest attention due to its great commercial success in reducing cost and energy consumption.

The best known practical application is the use of polymers to enhance the crude oil flow in Trans-Alaska Pipeline system where 1 ppm of drag reducer increased the flow rate by 33 per cent. Burger et al. [30] reports that DRAs are used in petroleum product pipeline installations, like the Oseberg Field in the North Sea. Many other great benefits can be obtained by drag reduction in oil fields by increasing the water injection rate and hence the oil production rate, energy saving and reducing the level of corrosion [31]. The use of the drag reducing agents in sewerage pipes and storm-water drains to increase the flow rate can be much cheaper than constructing new larger pipes. Polymer additives can reduce the pumping power costs of transportsations of ash, coal, sediments, etc. by pipelines. This application is very important for the transport of high weight solids in many locations worldwide [32]. In military applications, the drag reduction phenomenon can be applied to operations, like increasing the speed of underwater bodies (e.g., torpedoes and submarines). Of great importance, a 20% drag reduction creates an increase in speed of 6.8% [33]. For the past forty years, drag reducing polymers have also been used in the biomedical industry. One such application of drag reducing polymers is the treatment of circulatory or cardiovascular diseases [34].

Surfactants have been widely used in district heating and cooling systems (DHC) for reducing pumping power or increasing flow rate as they are very stable and recover from degradation quickly compared to polymers. The use of drag reducing surfactant additives in large scale district heating systems has lowered pipe flow energy significantly. Saeki [35] has reported that cationic surfactants in aqueous systems have been maintained in over 130 buildings in Japan, and they have helped to decrease pumping energy by 20%-60%. In addition, surfactant DRA were also used to aid in the prevention of the agglomeration of ice slurries [36]. Due to their ice-dispersion ability and drag reduction effectiveness, the ice slurry systems showed improved performance in
advanced cold heat storage, transportation, and heat exchange systems [37]. As the drag reducing additives bear a close relationship to energy conservation, they will receive more attention and exhibit increased usage in the near future.

2.2 Drag Reduction Behavior of Polymers

The addition of a minute amount of polymer additives to a turbulent fluid flow can result in a large drag reduction. Many studies have confirmed that the effectiveness of polymer's drag reduction in a turbulent flow is strongly influenced by polymer degradation, molecular-weight, concentration, preparation of polymer solutions, solvent properties, solution temperature, turbulent intensity, flow rate, geometry and types of pumps used (Den Toonder et al. [38] and Lee et al. [39]).

2.2.1 Polymer Degradation

An important problem in the application and study of drag reduction by polymer additives is the degradation of the polymers. It is well known that the drag reducing capability of a polymer is limited by two types of degradation: chemical and mechanical (Den Toonder et al. [38]).

Chemical degradation occurs when a change in the polymer structure is caused by a chemical reaction. It can be caused by the presence of metals or free radical initiators where oxygen is present and a high level of salinity or calcium in the solvent may also cause chemical degradation (Choi et al. [40]). In comparison, mechanical degradation occurs due to mechanical energy acting on the polymers in the solution. In practical terms, this means passing the fluid through pumps or pipes or both. Den Toonder [38] suggested that this mechanical stress causes the polymer to break, thereby reducing the molecular weight of the polymer and thus its drag-reducing capability.

Mechanical degradation is linked to shear-flow, causing degradation of dilute polyethylene oxide solutions when present (Sellin et al. [41]). Bueche [42] showed evidence that the mechanical degradation of the polymer within elongated flows, which exist in some regions of turbulent pipe flow, is extremely severe. This is because a polymer molecule in a turbulent flow is subjected to stretching and rotation, due to interaction of the vortices. The practical use of polymers in a turbulent DR application is consequently mostly hindered by mechanical shear degradation.
There have been numerous investigations (Patterson et al. [43], Nakano and Minoura [44], Tabata et al. [45], Hunston and Zakin [46] and Moussa and Tiu [47]) regarding mechanical degradation of both dilute and concentrated polymer solutions. Yet these studies show conflicting results depending on a number of variables in the experiment, including laminar, turbulent flow and polymer concentration range.

Molecular chains in polymer may undergo scission due to a range of external actions. Polymer chains can be stretched due to weak extensional flows, and they can be broken in a strong extensional flow, according to Choi et al. [48]. This degradation decreases the polymer’s average molecular weight, causing the drag reducing properties of the polymer to become weaker and eventually vanish.

Several studies have been performed to determine the conditions that can affect a polymer’s ability to reduce turbulent drag. Fabula [49] found that an increase in turbulent flow and a drop in pressure occurred at a certain pipe diameter and attributed this effect to either molecular disentanglement and/or degradation. Nakano and Minoura [44] observed that a polymer degrades faster in a good solvent than in a poor solvent at a low concentration by noting that the interaction between polymer molecules weakens at low concentrations. Their results suggest that a decrease in concentration of polymer solution positively affects the scission of chains, implying that mechanical degradation is affected by the stretching of the polymeric chains (Yu et al. [50]).

Many experiments have illustrated mechanical shear degradation using turbulent flow conditions. Zakin and Hunston [51] evaluated DR efficiency in a capillary tube, which is very sensitive to changes in polymer molecular weight at extremely low concentrations. Culter et al. [52] showed that mechanical degradation in turbulent flow occurs at the entrance of capillary tubes. In an effort to reduce the entrance effect, Horn and Merrill [53] established that fitting a conical funnel at the entrance from the feed solution reservoir. Bueche [42] demonstrated that in shear flows, the polymer molecule rotates along the principal axis of strain much too quickly, causing the flow to stretch. In elongational-types of flows, vorticity is much lower relative to the stretching and aligning actions of the strain than in shear flows, in relation to the strain of stretching and aligning actions. In these elongational flows, stretching is generally expected and scission of polymer molecules may occur.
2.2.2 Effect of Molecular Weight of Polymer on Drag Reduction

It is important to determine which property is mainly responsible for a polymer's drag reduction efficiency. The most important property is often believed to be the molecular weight but other properties may contribute as well, including the polymer's chain length, radius of gyration or hydrodynamic volume. The effect of a polymer's molecular weight on drag reduction is shown in Figure 3. As the molecular weight of a polymer increases, the onset of drag reduction occurs at a lower Reynolds number, which in turn implies greater drag reduction. The high molecular weight fraction of polyethylene oxide contributes more to drag reduction for a mixture of highly fractionated polymers than any other trait, as illustrated in the work of Gampert et al. [54].

![Figure 3: Drag reduction data for PEO with various molecular weight (Virk [8]).](image)

Polymers with higher molecular weight fractions are believed to be able to interact with bigger vortices and are responsible for higher levels of drag reduction, as suggested by Hunston et al. [55]. The decrease in the overall turbulent dissipation of energy leads to higher values of drag reduction, according to Liberatore et al. [56], who systematically investigated the link between degradation and molecular weight distribution. Their results supported the notion that not only single molecules of the highest polymer molecular weight tail are responsible for drag reduction but polymer aggregates could also be important for drag reduction.
2.2.3 Effect of polymer concentration on drag reduction

Polymer concentrations of as low as 0.02 ppm can create polymer drag reduction (Oliver and Bakhtiyarov [57]). An increase in polymer concentration results in an increase in drag reduction. Kim et al. [58] studied the concentration of different chemical additives on drag reduction. Their result is illustrated in Figure 4.

![Figure 4: Effectiveness of synthetic polymers (PEO, PAM) and different polysaccharides in pipe flows, Kim et al. [58].](image)

Figure 4 shows that a small amount of a polymer is needed to reduce drag in a solution. The figure demonstrates a large drag reduction attainable with various concentrations of natural and synthetic polymers. Research shows that drag reduction is at a maximum at a certain concentration for a given Reynolds number. Increasing the polymer concentration further after the maximum does not lead to an increase in drag reduction.
Figure 5 provides another look on the effect of polymer concentrations on drag reduction (Bewersdorff et al. [59]). The figure 4 shows a decreasing Fanning friction factor with increasing polymer concentrations, indicating an increase in drag reduction. It is worth noting that the friction factor increases after a certain Reynolds number value, a phenomenon which can possibly be explained by polymer degradation.

![Figure 5: a) Xanthane (Rhodopol 23) concentration influence on friction factor as a function of Reynolds number in water in a 5.2 m pipe [59].](image)

Litte [60] investigated the influence of polymer concentration and molecular weight on drag reduction. He found a general relation between polymer concentration and drag reduction for a certain Reynolds number value. The relationship is defined by

$$\frac{C}{DR} = \frac{[C]}{DR_{\text{max}}} + \frac{C}{DR_{\text{max}}}$$

(9)

where $DR_{\text{max}}$ is the maximum level of drag reduction, C is the polymer concentration and $[C]$ is the intrinsic concentration (in wppm) defined by

$$[C] = \frac{DR_{\text{max}}}{\lim_{C \to 0} \left( \frac{DR}{C} \right)}$$

(10)
2.2.4 Effect of polymer degradation on drag reduction

Over the past few decades, extensive research on drag reduction has shown that there is no common model explaining the mechanisms corresponding to macromolecules that reduce polymer friction. Drag-reducing polymers are found to lose their effectiveness when subjected to an intense turbulent flow for sufficient amounts of time. These losses are due to the polymer degradation that is suspected to occur as a result of polymer chain and/or the breakdown of molecular aggregates. Some researchers observed polymer backbone scission (Rho et al. [61], and Choi et al. [62]) others the breakup of polymer aggregates (Cox R.H. et al. [63] and Malik et al. [64]). The different conclusions of various researchers could be explained by different shear rates in the testing apparatus. An experiment carried out under sufficiently low shear rates may reveal the presence only of aggregates while at high shear rates both aggregates and molecules may manifest themselves in reducing drag. The same polymer solution may therefore have quite different characteristics in experiments performed under different shear rates. Gadd [65] established the aging effect of polyethylene oxide (PEO) solutions on friction reduction was small at high concentrations. The results were obtained when the concentration fell to 10 ppm suggesting that large molecular aggregates were initially present but were broken because of aging. Elias [66] observed the aggregation of polymer molecules in solution. They showed that the degradation process is caused by breaking of polymer aggregates based on a free energy calculation. The result that was obtained in the experiments can not be reconciled with the breaking of chemical bonds and the degradation hypothesis, but it is in accord with disaggregation hypothesis.

Kowalski and Brundrett [67] developed macromolecular entanglement hypothesis based on measurements of the turbulent energy spectrum collectively with and without polymer solutions. Major changes in the dissipative scales correspond to much larger molecules than were nominally present but could correspond to large intertwined chains which entrap large amounts of the solvent. A large amount of evidence has been obtained for molecular aggregates (Dunlop et al. [68], Warholic et al. [69], Liberatore et al. [56] and Khan et al. [70]). Dunlop observed PEO and PAM samples at different MW and concentrations in rotating-disk apparatus. Their results showed that transient existence of aggregates was more effective than drag reducers in comparisons to individual polymer molecules. Virk [8] provided the results of a drag reducing solution of polyethylene oxide. He observed that the individual polymer molecules are involved at lower
volume fraction than entanglement aggregates. It is estimated that the volume fraction occupied by polymer coils is 0.1. This suggests that individual polymer molecules are involved at lower volume fraction than the entanglement concentration $C^*$. 

Warholic et al. [69] studied turbulent flow in a channel with heterogeneous polymer systems. They found different levels of DR at varied concentrations of injected polymer at constant mixed polymer concentration and Re. They suggest that aggregates form before injection, and that these aggregates have a positive effect on drag reduction.

Liberatore and his coworkers [56] observed a link between degradation and molecular weight distribution. Their experimental results also suggest the existence of aggregates of molecules. This could be important in understanding polymer drag reduction; the action of shear might be break up these aggregates rather than breaking up the constituent molecules.

Khan et al. [70] used light scattering to study aggregation. He found that aggregation occurred in low molecular weight samples; however, in higher molecular weight samples little evidence for aggregation both in water and methanol. Kim et al. [71] suggested that above concentrations of 3000 ppm, macromolecular aggregates should be present. This showed that when macromolecular aggregates are present, the drag reduction roughly doubles. They also found that onset Re is slightly higher for unstructured polymer solutions than for solutions containing aggregates.

Although some researchers have observed the polymer backbone scission others polymer aggregates break up (Den Toonder et al. [72] and Vanapalli et al. [73]). The various conclusions of researchers could be explained by different shear rates in the testing apparatuses. Kalashnikov [74] was capable of demonstrating the complex process of degradation, which depends on variables such as hydrodynamic variables, which describes the polymeric fluid in support of a single homogeneous continuum without consideration of the micro-domain structure. The hydrodynamic variables are in consideration of dimensionless parameters, the Reynolds number

$$\text{Re} = \frac{\omega r^2}{v},$$

the Weissenberg number ($We = \theta \omega$) and the relative amplitude of the shear-thinning viscosity

$$\Delta = \frac{\eta_0 - \eta_\infty}{\eta_\infty}.$$ 

Where $\omega$ is the angular velocity of the rotor, $v$ is the solvent kinematic viscosity of the fluid respectively, $r$ is the radius of the cylindrical surface of the rotor, $\theta$ is the natural time of the
polymer solution and $\eta_0$ and $\eta_\infty$ are the limiting viscosities at zero and infinite shear rates respectively.

In demonstration, Kalashnikov discovered in his earlier work [75] that the decisive role of these parameters for describing initial drag reduction was unchanged due to degradation in the flows when considering polymeric liquid. The study showed that degradation is determined by the characteristics of network structures of the solution although these characteristics have no direct impact on the initial drag reduction there was not observed a direct dependence on the individual properties of macromolecules.

Polymer degradation can usually be expressed using an exponential expression. Brostow [76] introduced an empirical model. He assumed a midpoint polymer chain scission in turbulent flow. Brostow model was adopted by many research groups [77, 78]. Brostow’s model is given as:

$$\frac{DR(t)}{DR(0)} = \frac{1}{1 + W(1 - e^{-h})}$$

(11)

Where $DR(t)$ stands for level of drag reduction in time $t$ and $DR(0)$ for initial drag reduction. Parameter $h$ is the decay constant and a large value of $h$ is in relation to the rapid degradation, and a larger value of $W$ indicates lower shear stability. The Brostow model was an empirical model over the past few decades for the polymer degradation or chain scission phenomenon. However, there has been no development in formulating a clear understanding of this. Recent evidence suggests that aggregates of molecules existed, but polymer degradation is suspected to occur through polymer chain scission and/or the breakdown of molecular aggregates, although this is also unclear.

2.3 Drag Reduction Behavior of Surfactants.

Drag-reducing surfactants have been successfully applied in industrial applications. Surfactants have an advantage over polymers due to their quick self-repairing ability after mechanical degradation and they can consequently keep the drag-reducing effect for a long time. This self-repairing ability of surfactants has great potential in district heating and cooling systems (DHC) for reducing pumping power.
2.3.1 Surfactant drag reducing additives

Drag reduction with surfactant additives was first studied by Mysels [79]. These kinds of additives have received less attention than other drag reducing additives, especially polymers. During the past years this has changed due to their self-repairing advantages and their ability to keep the drag-reducing effect over long periods of time. Many authors have reported that the surfactant molecules come together, forming rod-like micelles that are necessary for drag reduction. The drag reducing surfactant solutions are described with the presence of cylindrical micelles, which form above a critical micellar concentration. They are mainly effective within a certain range of temperatures and concentrations. The drag reduction correlates to the alignment of cylindrical micelles in the flow direction (Bewersdorff and Gyr [80]). To improve drag reducing power, it is possible to mix counterions with surfactants. Lin et al. [81] described that, by adding sodium salicylate (NaSal) to cetyltrimethyl ammonium bromide surfactant (CTAB) provided significant the drag reduction qualities. However, this solution lost solubility in an effective temperature range. When fluid temperature returns to the effective range, the drag reducing ability can easily be recovered.

![Figure 6: The chemical structure of CTAB and NaSal.](image)

2.3.2 Aggregation of surfactants

Surface-active agents or “surfactants” are molecule, having one hydrophobic group (nonpolar end) and one hydrophilic group (polar end). The nonpolar tail is generally made up of a long carbon chain. This unique structure makes it easy to modify physical properties. Having this particular chemical nature (hydrophilic and hydrophobic) in the same molecule causes the self-aggregation of the surfactant molecules when dissolved in water at concentrations above the CMC. These
aggregates are known as micelles [82]. The micelles are formed by the balance of two opposing forces: the attractive, tail–tail, hydrophobic interaction creates the aggregation of the surfactant molecules. Conversely, the electrostatic repulsion among the polar head groups decreases the size of the micelle. The environment of aggregates is found to be tuned by controlling solution conditions, such as temperature, concentration, and ionic strength. Many types of aggregates are formed, having a variety of shapes and sizes, such as spherical or ellipsoidal, cylindrical or thread-like micelle, disk-like micelle, membrane, and vesicles [83, 85]. It is worth studying the formation of these different structures because surfactant solutions are often used in various industrial and research applications [86]. The behavior of surfactants in aqueous solutions depends on concentration and temperature. Ekwall et al. [87] found that ionic surfactants generally form spherical micelles in dilute solutions. In solution with low concentrations, the molecules are present in the liquid in the shape of monomers. Once the concentration goes just above the first critical concentration "CMC_1," surfactant monomers associate forming spherical micelles. When the concentration is further increased, the number of surfactant molecules per micelle will increase and surfactants form rodlike micelles. The concentration at which surfactants form rodlike micelles is called CMC_II [88]. As is shown in the figure 7, the critical micelle concentration (CMC_1) is almost independent of temperature, while temperature goes up, the value of the CMC_II increases.

![Figure 7: Critical micelle concentrations CMC_1 and CMC_II [88].](image)
2.3.3 Main classes of surfactants in drag reduction

The classification of surfactants depends on the chemical nature of the hydrophilic polar group. There are four distinguishable groups of surfactants:

- **Anionic**
- **Cationic**
- **Zwitterionic**
- **Nonionic**

These surfactants have been used as drag as drag reducing agents in many industrial and research studies. Savins [89] investigated drag reduction of anionic surfactants in aqueous media and obtained a reduction of more than 80%. However, anionic surfactants have limited applications because of their precipitation after the salt formation with the calcium and magnesium ions (Zakin and Jacques [90]) that are present in water. In addition, due to their tendency to form foams, anionic surfactants also cause some problems when exposed to air. This can cause complications in some systems that cannot handle the formation of foam. Thus they are not thought to be as good candidates as drag reducing agents. The drag reduction effect by anionic surfactants can be achieved at very high concentrations (about a few thousands ppm) [91, 92]. This situation creates high costs and severe environmental problems.

Cationic surfactants, unlike anionic surfactants, possess a positive charge in aqueous solutions. As opposed to anionic surfactants, these surfactants are not affected by metal ions found in tap water. Also, cationic surfactants have superior drag reduction results over a wide temperature range and therefore have larger potential for industrial applications. Other positive characteristics of cationic surfactants include relatively stability and self-reparability. Their major disadvantage is that they are not readily biodegradable, and this creates problems when leaks or spills occur [93].

Because cationic surfactants are not easily biodegradable, many researches focused on testing other types of surfactants that are more biodegradable with the intention of finding more environmental friendly surfactants with equal drag reducing ability. Zwitterionic surfactant and combinations of zwitterionic with anionic surfactants have been studied as drag reducers by many
researchers [94, 96]. Zwitterionic surfactants have both negative and positive charges on the molecule’s head group. As these surfactants have both charges, the surfactant molecule is sensitive to the presence of ions in water or solutions. This situation can reduce the stability of these surfactants. Beneficial characteristic of zwitterionic surfactants are biodegradability and low toxicity. Due to their environmentally friendly nature, if leaks or spills happen in the system, these additives can not represent an environmental risk.

Unlike the three, aforementioned surfactants, nonionic surfactants do not have charged head groups. These stable surfactants can self-repair quickly after degradation due to high shear. Zakin [90] noticed that nonionic surfactants, having straight chain alkyl groups were very effective. Moreover, mixtures of nonionic surfactants at 1% concentration effectively reduced drag at temperatures around the cloud point, which is the temperature where the phase separation of mixture starts to occur, thus becoming cloudy. Lu et al. [97] demonstrated that these kinds of surfactants are not toxic, and easily degradable. Like zwitterionic surfactants, nonionic surfactants have low toxicity and rapid biodegradability. A large number of studies have shown that the effectiveness of drag reduction depends strongly on surfactant type and temperature range. The investigations demonstrate that the surfactants’ unique structure makes them widely used in district heating and cooling systems and research applications.

2.3.4 Heat transfer reduction of surfactant drag reducing flow

Along with drag reduction, the heat transfer ability of surfactant solutions is also significantly reduced from 10 to 65% of heat transfer. The nature of the heat transfer reduction of drag reducing surfactant solutions is still not clearly understood. Many research studies that compared to Newtonian fluids, the viscous sublayer of drag reducing solutions is extended. Sellin et al. [94] suggested that the extended viscous sublayer increases the thermal resistance between the wall and bulk fluid. Therefore, the heat transfer effectiveness of the solution decreases. Moreover, the velocity fluctuations of drag reducing surfactant solutions in turbulent flow along radial and tangential directions are suppressed compared with Newtonian fluids [98, 100]. Authors have explained that the velocity fluctuations in the radial direction are strongly associated with a fluid’s heat transfer ability. Therefore, in the radial direction, the heat transfer is significantly decreased due to a reduction in the radial velocity fluctuations.
2.3.5 Rheologic behavior of surfactant drag reducing solutions

The knowledge of rheological properties of non-Newtonian materials is a key factor in understanding the nature of surfactants in solution. The drag reducing surfactant solutions have an unusual rheological behavior because of the presence of the micelles. Surfactant solutions with micellar structure present complex rheological properties such as shear thinning, shear thickening, viscoelastic and elongational characteristics [101].

Figure 8: (a) Viscosity of the surfactant solution measured in a Couette cell: two concentric cylinders spaced by 1 mm or 3 mm. Inset: visualization in the gap between crossed polarizers; the fluid becomes birefringent at the viscosity increase. b) The elongational viscosity [101].
The structure of surfactant solutions changes, when they self repair upon removal from high shear. When studying a solution’s behavior, it is necessary to look at its rheological properties. It is generally believed that the surfactant solution flows have viscoelastic characteristics and the drag reduction by surfactant additives is due to interaction between viscoelasticity and turbulence in the flow. Lu et al. [97] found that the certain surfactant solutions do not exhibit any viscoelastic character. Gyr and Bewersdorff [102] declare that elongational viscosity has a minor effect on the drag reduction. Furthermore, local shear-thickening is not a characteristic of pressure loss in drag reducing surfactants. Despite many studies on surfactant drag reducing flow, the precise nature of complex rheological features of surfactant systems is not fully understood and it still continues to be a challenging subject of controversy.

2.3.6 Shear induced structure (SIS)

Many research studies have been devoted to a solutions’ rheology of surfactants [103, 107]. The behavior of surfactant solutions changes as a result shear effects. The change in the rheological properties is explained by the formation of the micelles structure in the surfactant solution. It was observed that at high concentration, with quite long surfactants chains, the micelles can form complicated structures with three-dimensional forms. These superstructures are formed under the action of shear stress, and therefore the condition at which this happens, we call this shear-induced structure (SIS) phase a “gel” [105]. The precise nature of shear-induced structure is not clearly understood. It was examined that the rheological characteristics of this kind of solutions have an enormous industrial importance. Yunying Qi [108] explained this with a change in the structure of the micelles at a critical shear rate causing formation of a “shear induced structure”. A particular complex rheological behavior may occur for some surfactant solutions at a critical shear rate at which the shear viscosity and elasticity have a sudden increase. This phenomenon is known as shear induced structure (SIS). It has been observed that the sizes of these structures may be roughly twice the size of a surfactant molecule and a length that can be thousands of times the molecular size resulting in a large increase in viscosity [109]. The results show that with increasing shear rate, shear induced structure becomes unstable and viscosity begins to decreases with shear rate. Hu et al. [110] observed that the micelles are completely aligned in the direction of flow at the viscosity peak by the birefringence [111] and scattering methods, such a light
scattering (LS) or small-angle-neutron scattering (SANS) [112, 113]. From rheological behavior studies, it was noted that the critical shear rate for SIS is dependent on surfactant concentration, chemical structure, counterion, temperature, and geometry of the rheological measuring devices [108]. Several studies have been performed to determine the nature of shear induced structure. According to several authors, SIS of surfactants may relate to the drag reduction phenomenon in turbulent flow [114, 117]. They concluded that SIS is not a phase transition caused by the micellar alignment or elongation, but rather a shear induced inhomogeneity and phase separation.

Despite numerous studies, the complex nature of SIS is not clearly understood. The relationship between SIS and drag reduction still continues to be controversial and needs to be further investigated.

2.4 Flow Properties of Drag Reduction Additives

2.4.1 Maximum drag reduction asymptote

One of the most significant characteristics of the data for polymer drag reduction is that there is a maximum drag reduction asymptote (MDA). The effectiveness of drag reduction by polymers is limited by the “maximum drag reduction asymptote”. Virk et al. [118] described the empirical laws in which all diluted polymer systems demonstrate asymptotic behavior. They found that the maximum drag reduction obtainable using DRA in turbulent pipe flow is limited due to the “maximum drag reduction” asymptote, which is a function of Reynolds number. The magnitude of DR increases with the DRA concentration in the system, until the MDR asymptote is reached. Subsequent addition of DRA to the system has not further effect on the frictional drag. Virk et al formulated the following correlation to data for the MDR friction factor. He described that the equation is the formula, which gives the maximum possible drag reduction asymptote, where the drag reduction is unaffected by polymer properties.

\[
\frac{1}{\sqrt{f}} = 19 \log_{10} \left( \text{Re} \sqrt{f} \right) - 32.4 \quad \text{or} \quad f = 0.58 \text{Re}^{-0.58}
\]  \hspace{1cm} (12)
However, the surfactant drag reducer differs from the polymeric reducer, in several aspects particularly having a greater level of drag reduction that crosses the Virk’s maximum drag reduction asymptote. Zakin et al. [119] offered an alternative drag reduction asymptote for surfactant systems, demonstrating that this assumption probably does not always hold in its full generality.

\[ C_f = 0.32 \text{Re}^{-0.55} \]  

(13)

Thus, it shows that the effect is more complicated because different additives behave differently. It is still open to conjecture whether or not certain additives have their own MDA asymptotes.

2.4.2 Mean velocity profiles and turbulence structures

Drag reduction is accompanied by changes in the strength of the turbulent fluctuations and in the velocity profiles. Mean velocity profiles exhibit changes between a drag reducing polymer solution and a pure solvent. The velocity profiles are generally expressed in non-dimensional semilogaritmic coordinates of the fluid velocity \( U^+ \) versus distance from the wall \( y^+ \) defined as follows.
where $U$ is the average local velocity at a distance $y$ from the wall and $u_r$ stands for the friction velocity. Figure 10 illustrates a typical representation of mean velocity profiles in flows with a drag reducing agent.

**Figure 10: Non-dimensional velocity profiles for a system with drag reduction (Virk [118]).**

The average local velocity alters with distance from the wall. As a result, the mean velocity profile for a Newtonian fluid can be divided into 3 regions:

- **Viscous sublayer:** $u^+ = y^+$, $y^+ \leq 5$
- **Buffer layer:** $u^+ = y^+$, $y^+ \leq 30$
- **Logarithmic region:** $U^+ = 2.5 \ln y^+ + 5.5$, $y^+ > 30$  \[ (16) \]

The area between the viscous sublayer and the Newtonian plug is called the elastic sublayer. When maximum drag reduction occurs, the elastic area extends into the pipe’s center and the Newtonian region disappears. Virk’s maximum drag reduction asymptote is given by

$$ U^+ = 11.7 \ln y^+ - 17.0 $$  \[ (17) \]
It is possible to compare the velocity profile of a drag reducing fluid to the model and to a Newtonian fluid at any Reynolds number. The ultimate profile for maximum drag reduction by polymers is also represented in a similar way. Based on the asymptote found for polymers, Virk proposed a model to describe the mean velocity profiles of drag reducing fluids in the turbulent region, analogous to those of Newtonian fluids.

Viscous sublayer: \( u^+ = y^+ \)
\[ y^+ < 11.6 \]
Transition zone: \( U^+ = 11.7 \ln y^+ - 17.0 \)
\[ 11.6 > y^+ < y_e^+ \] \hspace{1cm} (18)
Turbulent core: \( u^+ = 2.5 \ln (y^+) - 5.5 + \Delta B \)
\[ y^+ > y_e^+ \] \hspace{1cm} (19)
\( \Delta B \) is the difference between the core and the profile for a Newtonian fluid and \( y_e^+ \) is the joint point of the elastic sublayer and the transition zone.

For the case of surfactants, Chara [120] proposed a model to describe the average profile of velocities in the limiting case of maximum drag reduction. The model consists of three different layers (Fig.11).

Viscous sublayer: \( u^+ = y^+ \)
\[ y^+ < 15 \]
Transition zone: \( u^+ = 5 \ln (y^+) - 3.05 \)
\[ 15 > y^+ < y_e^+ \] \hspace{1cm} (20)
Turbulent core: \( u^+ = 23.41 \ln (y^+) - 65 \)
\[ y^+ > y_e^+ \] \hspace{1cm} (21)

![Figure 11: Velocity profiles in wall coordinates for a flow with a Newtonian fluid and Non-Newtonian flow: polymers (Virk) and surfactants (Chara [120]).](image)
Many authors have measured a turbulent velocity field when using additives. They investigated the turbulence in the flow using by Laser Doppler Velocimetry (LDV) (Hibberd et al. [121], Harder and Tiederman [122], Ptasinski et al. [123], and Kim and Sirbiente [124]). Measurements using Particle Image Velocimetry (PIV) are reported by Warholic et al. [125] and by White et al. [126]. The overall conclusion of PIV and LDV measurements is that, the addition of DRA gives rise to a decrease in the spanwise velocity fluctuations and a rise in streamwise fluctuations. This is illustrated by two examples in Figure 12. The figure clearly demonstrates that the addition of DRAs to a solvent increases the intensity of the streamwise fluctuation $\text{rms}(u_z^+)$ but on the other hand suppresses the spanwise turbulence fluctuation $\text{rms}(u_r^+)$. 

![Figure 12 Results for streamwise and spanwise velocity fluctuations showing influence of polymer addition (Ptasinski et al. [123]).](image)

*Figure 12 Results for streamwise and spanwise velocity fluctuations showing influence of polymer addition (Ptasinski et al. [123]).*
2.4.3 Drag reduction in other geometries

Most of the drag reduction studies reported are concerned with straight channel flows. However, other systems have also been studied to understand the nature of the drag reduction mechanism.

**Rotating disc cells.** As shown in Figure 10, turbulent flows can be created by two counter-rotating discs (either with baffles or without baffles). Tests for this kind of apparatus are reported by Bonn et al. [127], Cadot et al. [128] and Sohn et al. [129]. They found that polymers hinder the formation of coherent-vorticity filaments while slowing the rate of formation of large eddies, for which high-vorticity filaments provide nuclei. Cadot et al. [128] discovered drag reduction for the smooth discs; however, they found no drag reduction for the baffled discs (see Figure 13). They concluded that the drag reduction effect happens in the viscous boundary layers. If there is no boundary layer (b), there is no DR. In this case, the dissipation of energy does not change even when the turbulent flow structure in the bulk is altered using polymers.

*Figure 13: Schematic of counter-rotating cell apparatus with smooth discs (a) and with discs with baffles (b) (Cadot et al. [128]).*
Grid turbulence. Using PIV with DRA solutions, Van Doom et al. [130] examined the turbulence decay behind a towed grid. Unlike pure water, the turbulent energy components demonstrate marked anisotropy and decay very slowly.

Coiled tubing (CT) has been used in the oil and gas industry because of various advantages. Zhou and Shah [131] have provided measurements of drag reduction in terms of coiled tubing. When compared with straight tubing, coiled tubing caused a delay in the onset of turbulence and drag reduction. Also, the effect of polymer concentration on drag reduction was small.

2.5 Mechanism of Polymer and Surfactant Drag Reduction

2.5.1 Theoretical studies of drag reduction

In the last 50 years, many papers have illustrated the experimental, numerical and theoretical aspects of drag reduction of turbulent flows by polymer additives. The explanation for drag reduction can generally be divided into two classes based on the proposed effects of polymer stretching on the flow. The first class focuses on viscous effects (Lumley [132], L’vov et al. [133] and Ryskin [134]), whereas the second class focuses on elastic effects (Tabor & de Gennes [135]). A review of drag reduction by additives is available in Lumley’s work. Lumley stated that stretching random coiled polymers would increase the effective viscosity. The increase of viscosity suppresses turbulent fluctuation and therefore it leads to reduce a wall friction and a thickening of the buffer layer separating the viscous layer. For given pressure gradient, this leads to increased flow, i.e., drag reduction. Little et al. [136] examined alternative mechanisms and supported the idea of elongational viscosity as suggested by Lumley. However, Bermann [137] studied many molecular models and concluded that the stretching of individual molecules to full length was not relevant. With the aid of scaling arguments and a model polymer, Ryskin [134] formulated an expression for effective viscosity increase as a result of polymer stretching in a turbulent flow. According to the derived expression, the effective viscosity is a function of polymer concentration and the largest extensibility of a polymer. Lumley and Ryskin therefore both state that drag reduction is due to an increase in the local effective viscosity of flow during hydrodynamic interaction between polymer chains and flow.
Subsequently, Tabor & de Gennes [135] proposed a new hypothesis, however, arguing that drag reduction is caused by a polymer’s elastic properties, rather than its viscosity. This was illustrated by experiments in which polymers were active at the centre of the pipe, where viscous forces do not play a meaningful role [138]. Tabor & de Gennes assert that the elastic energy stored by the partially stretched polymers is an important variable for DR and the increase in the effective viscosity is small and inconsequential. The elastic theory postulates that the onset DR takes place once when the cumulative elastic energy stored by the partially stretched polymers becomes comparable with the kinetic energy in the buffer layer at some turbulent length scale. Experiments [138] and numerical simulations [139, 140] have demonstrated that the elastic theory is effective in terms of being useful in the prediction of DR. According to the scaling arguments and experimental data, the time criterion requires that for DR to occur. It is important that polymer possess a longer relaxation time than a representative time scale of the near-wall turbulence $T_z$. The relaxation time, $T_z$, is defined as the average time it takes for a stretched polymer to reach its initial coiled configuration. Sreenivasan and White [138] used the following this relationship for relaxation time:

$$\frac{1}{T_z} = \frac{kT}{\eta_0 R_G^3}$$

(22)

Where $\eta_0$ is the viscosity of the solution, $k$ is the Boltzman constant, $T$ is the solution temperature and $R_G$ is the radius of gyration.

For flexible linear molecules, the radius of gyration is represented by:

$$R_G \approx N^{3/5} a$$

(23)

where $N$ is the number of repeating monomers in the molecule, and $a$ is the length of a single monomer. Sreenivasan and White declare that there is a turbulent length scale $r^*$ whose time scale $\tau_*$ matches $T_z$. The length scale is defined as:

$$r^* = u_r T_z$$

(24)

where $u_r$ is the velocity scale, given by Kolmogorov [141] as:

$$u_r = \left( r^* \langle \epsilon \rangle \right)^{1/3}$$

(25)
where $\langle \varepsilon \rangle$ is the average dissipation rate of the turbulence kinetic energy. Given a certain scale range $r^{**} < r < r^*$, elastic theory proposes that the polymers are stretched a little amount; therefore, they do not produce a reciprocal effect on the flow. Sreenivasan and White developed this concept to explain the phenomenological process of drag reduction in terms of the elastic model.

In more recent work, L’Vov et al. [142] and Benzi et al. [143] rationalized these concepts by constructing a model for drag reduction according to Reynolds averaged momentum and energy equations. The effect of the drag reducing polymers is closely related to the effective viscosity, which was shown to be negligible at the wall and increases with wall-distance. The drag reduction of polymer is therefore the result of the suppression of the Reynolds stress in the elastic sublayer. Numerical simulations [144] have shown that a space dependent viscosity model that varies linearly from the wall indeed produces drag reduction.

In fact, the paper by Cadot et al. [128] shows that the Tabor & de Gennes theory must be wrong, since they could assess that DR in a boundary layer effect.

Although, the first publications on drag reduction by additives dealt with on surfactant solutions, these kinds of additives have obtained less attention than polymers. Mysel [79] investigated the drag reduction in turbulent pipe flow using surfactant. He studied the effect of aluminum disoaps on gasoline flow. Savins [89] found 80% drag reduction could be obtained using a 0.2% Sodium Oleate aqueous solution with KCl as the counterion.

It was long believed that the mechanism of turbulent drag reduction by surfactants should be similar to that of polymers, implying that the phenomenon is due to a high elongational viscosity. Some investigations on drag-reducing surfactants stated that there is a strong correlation of high extensional viscosity with the drag reduction [145]; however, others report that its importance is negligible. A large number of researchers have proposed that viscoelastic effects of surfactant solution could be responsible for turbulent drag reduction. However, some drag reducing solutions, like surfactant ones, are neither viscoelastic fluids nor present an elevated elongational viscosity (Zakin [103], Lu et al. [97] and Lin et al. [146]). According to Gyr and Bewersdorf’s investigation [102], the shear induced structure can be responsible for drag reduction. Therefore, other hypotheses have been examined, such as local shear thickening (Guillou and Makhlooufi [147]) or wall slip (Drappeir et al. [148]). Bewersdorff & Ohlendorf [93] illustrated that the micro and integral scale of turbulence axial velocity fluctuations can increase when compared to Newtonian solvent. They demonstrated that this increase in the size of eddies could be due to an
increase in local viscosity resulting from the formation of the shear induced structures. During drag reduction, when the critical shear gradient is exceeded in surfactants, the formation of the shear induced state causes suddenly increase of the shear viscosity and elasticity. At the high viscosity peak, micelles are fully aligned in the direction of flow. This is confirmed by birefringence experiments [111] and a small-angle-neutron scattering (SANS) [112]. Accordingly, in the SIS, micelles must build up larger, super-order structures. The critical shear rate for SIS takes place at the onset of drag reduction [107]. It follows that drag-reducing surfactant solutions show increased shear viscosity at the buffer zone of a turbulent velocity profile.

In spite of the large amount of research into the drag reduction with additives, the nature of the drag reduction mechanism by which this occurs is not fully understood and it still continues to be challenging subject of controversy.
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CHARACTERIZATION TECHNIQUES

This section presents general information about techniques used in the experiment. The rheological measurements were made with a Reologica StressTech rheometer and the drag reduction measurements were realized using a horizontal closed-loop system. The counter rotating disks were used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids. This chapter presents a detailed characterization of the rheometer, the horizontal closed-loop system, Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and the counter rotating baffled discs techniques.
3.1 Reologica StressTech Rheometer

Knowledge of viscosity is a key factor in understanding the rheological behavior of DR agents. The viscosity was measured using the Reologica StressTech rheometer, which is optimized for stress-controlled rheology measurements. It is equipped with a wide selection of modular cone plates, plate-plates, and coaxial cylinder measurement systems. Different geometries can be used, depending on the fluid being tested.

![Reologica StressTech rheometer](image)

*Figure 1: Reologica StressTech rheometer.*

3.1.1 Parallel plate geometry

A parallel plate geometry consists of a fluid placed between two parallel plates. The bottom plate is fixed, while the top plate moves freely under an applied force. This geometry works for fluids that are viscous enough to prevent them from flowing out of the sides of the plate. The shear rate varies from zero (at the center) to $R \omega / D$ (at the edge of the plate), where $R$ is the plate radius [m], $D$ the gap [m], and $\omega$ the rotation rate [rad/s]. A schematic of parallel plate geometry is given in Figure 2, below.
Shear rate (sec$^{-1}$): $\dot{\gamma} = \frac{R \omega}{D}$  \hfill (1)

Shear stress (Pa): $\tau = \frac{2}{2 \pi r^3}$ \hfill (2)

Viscosity (Pa·s): $\eta = \frac{\tau}{\dot{\gamma}}$  \hfill (3)

### 3.1.2 Cone and plate geometry

A cone and plate system involves placing the sample between a lower fixed circular disk and a rotating angled cone. The plate is rotated and the corresponding torque on the cone is measured. Since the angle is a very small, the shear rate can be considered to be constant. Cone and plate geometry only requires a very small amount of sample. The determining parameters include the disk radius $R$ [m], the rotational rate $\omega$ [rad/s], the angle between cone and plate $\theta$ [rad], and the torque $M$ [N·m]. A schematic of cone and plate geometry is shown in Figure 3.
Figure 3: Cone and plate geometry.

Shear rate (sec\(^{-1}\)): \[ \dot{\gamma} = \frac{\omega}{\sin \theta} \] (4)

Shear stress (Pa): \[ \tau = \frac{3M}{2\pi r^3} \] (5)

Viscosity (Pa·s): \[ \eta = \frac{\tau}{\dot{\gamma}} \] (6)

3.1.3 Bob and cup (Couette) geometry

Bob and cup geometry (or “couette geometry”, after inventor Maurice Couette) was the first rotating device to measure viscosity [1]. For this type of geometry, the resistance to flow is assumed to be in a small gap. The input parameters include the rotational speed [rad/s], the torque M [N·m], the bob radius \( R_b \) [m], the bob height L [m], and the internal radius of the cup \( R_c \) [m]. A schematic of bob and cup geometry is given in Figure 4.
Shear rate (sec$^{-1}$): $\dot{\gamma} = \left( \frac{2R_z}{R_c^2 - R_b^2} \right) \omega$

(7)

Shear stress (Pa): $\tau = \frac{M}{2\pi R_c^2 L}$

(8)

Viscosity (Pa·s): $\eta = \frac{\tau}{\dot{\gamma}}$

(9)
3.2 Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) is the most effective and progressive measurement tool for the quantification of the velocity field in fluid mechanics and aerodynamics. PIV technique is widely used to study turbulence properties of fluids. Measurements using Particle Image Velocimetry are described by Hibberd et al. [2], Warholic et al. [3] and White et al. [4].

Particle Image Velocimetry is an optical method of visualization to measure instantaneous velocity. The PIV system gains information on the particle displacements in the fluid over a known interval of time. The velocity is calculated by dividing the particle displacement by the time:

\[ u = \frac{\Delta X}{\Delta t} \]  \hspace{1cm} (10)

(where \( \Delta X \) is the average displacement of particles in the fluid over interval of time \( \Delta t = t_2 - t_1 \)).

Typically, the PIV system consists of double-pulse (Nd-Yag type) lasers, a CCD camera (a digital camera with a high resolution), a laser plane (pulse) for illumination of the flow, a particle seeding mechanism, and a computer with image-processing software (DaVis) for data storage and analysis. In the PIV method, the flow is seeded with sufficiently small tracer particles that perfectly follow the molecules of the fluid and scatter enough light from the incident laser beam. In this case, the flow was seeded with glass particles 15 µm in diameter. The density of the glass particles is close to the density of water (between 9 and 11 microns). The flow visualization was performed using Nd-Yag lasers, which each have an output of 45 mJ/pulse and a wavelength of 532 nm. Two laser pulses illuminated the particles, with a short time difference. The time interval between the two laser pulses (\( \Delta t \)) or the duration between two successive illuminations determines the movement of the particles (\( \Delta X \)) between two successive images.

The light scattered by the seeds is collected by an optimized CCD camera sensor. The CCD camera is a key element in the study and in our measurement, we used a high-resolution digital camera (1024x1280 pixels). The image acquisition is based on scanning several pairs of successive images over an interval of time, which are then transferred to the computer for processing. The computer calculates the instantaneous velocity fields by means of algorithm cross-correlation. Finally, the PIV technique yields the mean velocity field and turbulence quantities of
the flow by statistical treatment of the instantaneous data sets. The statistical treatment of turbulent flow requires the calculation of different averages from a set of sufficient instant fields vectors, in order to have a convergence of the statistical properties of the flow (mean, variance, standard deviation, correlation coefficient). The number of instant fields needed for calculation of the average field depends on the experimental conditions, and can be estimated with statistical methods.

Fig 5: Working principle of particle image velocimetry (www.lavision.de).
3.3 Characterization of Horizontal Closed-Loop System

The drag reduction measurements were realized using a horizontal closed-loop system (shown schematically in Figure 6 and Figure 7). This set up was developed at Caen University. The system consists of two main parts: The first part is made from a stainless steel tube equipped with a deferential pressure transducer (DRUCK, PDCR 2111) to measure the pressure drop. This pressure transducer is connected to two pressure taps, 6.2 m apart. The pressure taps are controlled by two sensor arranged along the channel to measure the pressure loss and calculate the pressure drop. The measurement range of the pressure sensors is 0-350 bar. The second part is used to visualize the flow of PIV through a transparent glass tube, around 1.2 meters long with a diameter of 22.5 mm. This tube is made from a borosilicate pipe glass, manufactured by the company PRECIVER. The fluid flow is driven by a volumetric pump (PCM, MR13I10) 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 flow meter is placed after a bend of 180° (400 mm radius of curvature) to measure the flow rate. The temperature is measured when entering and exiting the system. Temperature is controlled by a heat exchanger and measured by two sensors (ANALOG DEVICES, AD592CN). A 1.5 m heat exchanger tube is introduced into the loop before the tank. This part of the heat exchange is supplied with a coolant by a large capacity cryostat. 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) and the range of flow rate covered is up to 676 [L/min]. This flow rate can be adjusted by changing the frequencies (between 20 to 60 Hz) and opening the valve installed on the outlet of the pump. The reference frequency of the drive can be entered manually or via a computer connected to the driver. A filter on the driver reduces the noise generated. The valve, placed at the outlet of the pump, is used to regulate the flow circulating in the loop system and maintain normal operation of the pump (to avoid operation of the pump at low speeds of rotation, in the case of low flow rates). All data, consisting of pressure gradient, temperature and flow rate, are then processed by computer. Our experiment used a PC with an acquisition system (delivered by LAVISION), with DaVis processing software.
Figure 6: Installation of the camera on the PIV experimental test loop.

Figure 7: Schematic design of the experimental setup.
3.4 Characterization of Counter Rotating Baffled Disks.

The counter rotating disk is an apparatus broadly used in the determination of the turbulent properties of a fluid. Such a set up has been widely used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids. Studies on this type of apparatus are reported by Bonn et al. [5], Cadot et al. [6] and Sohn et al. [7]. Cadot et al have found that drag reduction occurs with smooth discs but not with baffled discs. Turbulent flows can be generated between two counter-rotating discs (either with baffles or without baffles). In the present study, we used two counter rotating baffled disks. The experimental set up is also described in more detail in chapter 5. Here, what we examine is the modification of the turbulence properties in the bulk of the solution. The turbulence is generated in the cylindrical cells between two counter-rotating disks at a constant angular velocity, $\Omega$. The counter rotating disc used for the determinations of turbulence properties was equipped with four baffles having a height of 4 cm. These disks are driven by two separate motors which can rotate at different frequencies controlled by two current supplies. Then cylindrical cell was filled with approximately 2.5 litres of the desired solution. The cells have a radius of 7 cm and a height of 20 cm. The design of the measurement cell is shown in Figure 8.

![Diagram of counter-rotating cell apparatus with baffles](image)

*Figure 8: Schematic of counter-rotating cell apparatus with baffles.*
3.5 Laser Doppler Velocimetry (LDV)

Laser Doppler Velocimetry (LDV) produces temporal traces of the velocity of micron sized seed particles in solution and is measured at a fixed location in the cell. The LDV probe was positioned slightly below the centre of the cell so as to have a nonzero mean flow velocity. Visualization is realized by seeding the experimental fluids with glass particles which are 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. In our experiment, the reference state is water and the complex fluid used is a dilute aqueous solution. The Reynolds numbers examined are defined as

\[ Re = \frac{\Omega R^2}{v} \]

and range from 5000 to 100000, where \( R \) is the radius of the discs, \( \Omega \) is the angular rotation, and \( v \) the kinematic viscosity of the fluid.

3.6 Taylor’s Frozen Turbulence Hypothesis

In this experiment, we have recast the frequency into a wave number by using the Taylor’s frozen turbulence hypothesis, when representing the power spectra of the velocity fluctuations. Taylor [8] proposed an assumption in which he could deduce the spatial structure of a turbulent velocity field from a single point measurement of its temporal fluctuation. Taylor’s frozen turbulence assumption is often used in laboratory experiments to investigate the large-scale turbulent structures. The Taylor hypothesis for frozen turbulence basically assumes that the velocity of turbulence is insignificant compared to its advection velocity. To examine turbulence from a continuous record of measurements from a single point, the turbulence is assumed to be frozen. This means that the fundamental properties of the eddies remain unchanged, or frozen over a point. The Taylor hypothesis is very valuable since according to this, the frozen turbulence assumption may be used to convert the frequency spectra to wave-number spectra. Such approximation of wave number is given by

\[ k_x = \frac{2\pi f}{U_0} \]

Where \( f \) is the frequency of the fluctuations \( U_0 \) is the relative flow speed, and \( k_x \) is the wavenumber.
Bibliography


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].
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:

\[
f = \frac{2\tau_w}{\rho U^2} = \frac{\Delta P D}{2\rho U^2 L} = \frac{\Delta P \pi^2 D^5}{32\rho L Q^2}
\]

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 \( \rho \), 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.
\[ DR\% = \left( \frac{f_s - f_{DR}}{f_s} \right) \cdot 100 \]  \hspace{1cm} (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:

\[ U^+ = \frac{u}{u_*} \]  \hspace{1cm} (3)
\[ y^+ = \frac{y u_*}{\nu} \]  \hspace{1cm} (4)

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

\[ u_* = \sqrt{\frac{\tau_w}{\rho}} \]  \hspace{1cm} (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

$$U^+ = 2.5 \ln y^+ + 5.5$$  \hspace{1cm} (6)

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

$$U^+ = 11.7 \ln y^+ - 17.0$$  \hspace{1cm} (7)

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.

$$u'_{rms} = \frac{\langle uu \rangle}{u_r}$$  \hspace{1cm} (8)

$$v'_{rms} = \frac{\langle vv \rangle}{u_r}$$  \hspace{1cm} (9)
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 ($u_\tau$).

$$UV^+ = \frac{uv}{u_\tau^2}$$

(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 demonstrates the cross-correlation coefficient for water and xanthane solution. This coefficient is defined as follows:

\[
R_{uv} = \frac{\overline{uv}}{u'_{rms} v'_{rms}} \tag{11}
\]

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 \( u'_{\text{rms}} \) and \( v'_{\text{rms}} \) 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 \( u'_{\text{rms}} \) and \( v'_{\text{rms}} \) 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

\[
TKE = \frac{1}{2}(u'^2 + v'^2)
\]  

(12)

where \( u'^2 \) and \( v'^2 \) 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 ($y+$)

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

$$\eta = \frac{\nu_{\text{eff}}}{\nu_0}$$

(14)

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

$$-\frac{u'v'}{u'_r} = 1 - \frac{y}{R} - \frac{\nu_{\text{eff}}}{\nu_0} \frac{dU^+}{dy^+}$$

(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


Abstract

We here examine the structure of turbulence in the case of a complex fluid made up of water and surfactants. This fluid has the particular property of shear thickening when driven at shear rates above a certain threshold. Through a study of the spectral properties and the structure function scalings, important differences arise with respect to the reference case, i.e., water. The surfactant solution shows strong intermittency at small scales. The large scales are on the other hand free of intermittency. While this transition is observed in the structure function scalings, no sign of this transition is seen in the power spectrum of velocity fluctuations which shows a single scaling range. The strongly intermittent small scale region, despite the scaling of the power spectrum, exhibits properties reminiscent of the near dissipative range.
5.1 Introduction

Turbulence in fluids is widespread in both natural and industrial settings. Since the early works of Richardson and Kolmogorov, many features of turbulent flows in simple fluids are known even if some are not fully understood [1, 2]. That 3D turbulence in simple fluids is governed by a direct cascade of energy from the large scales to the small scales giving rise to a well defined energy density spectrum across the scales is now fully accepted. That a closer look at finer details of such a state through the so called structure functions of the velocity field yields anomalies is another known fact. Such anomalies can be phenomenologically explained starting with the work of Kolmogorov himself [2]. Nonetheless this anomalous behavior is believed to be at the heart of a full understanding of this ubiquitous state. In natural and industrial settings however, the fluids or liquids are far from simple: rivers transport particles and sediment, oceans are host to a variety of mesoscopic and microscopic entities, and industrial fluids are usually mixtures of complicated molecules. It has been known for a long time now that some properties of turbulence, at least at the macroscopic scale, can be influenced by the addition of minute amounts of polymers, fibers or surfactants for that matter [3, 4]. Despite the large interest in such modifications and their possible use for drag reduction in pipes, the structure of the turbulence is still unclear. Recent work (and less recent work) did show modifications of the energy density spectrum [5] and the second order structure function [6] at scales near the dissipative range and beyond raising additional questions as to how such modifications may occur and what their role may be.

We here reexamine the issue of the modification of the structure of turbulence, using a dilute surfactant solution as the complex fluid, through the possible modifications of the scaling behavior of the energy density spectrum and the velocity structure functions. We use the so called Von Karman cell in which the turbulence is generated in a large cylindrical tank by two counterrotating discs. As the disks are equipped with baffles, the energy dissipation is independent of the viscosity, which is a prerequisite for having inertial turbulence [7]. At the same time, if drag reducing agents are added to such a flow, no drag reduction is observed since the latter is due to boundary-layer effects that are suppressed by using the baffles [8]. This puts us in a comfortable situation to investigate the effect of complex fluids on the structure of the turbulence itself. Because the overall dissipation does not change upon addition of surfactants, one can compare flows with and without the complex fluid at the same energy dissipation. Perhaps our most
important result is the presence of strong intermittency at small scales for the surfactant solution but practically no intermittency at large scales indicating that the structure of the fluid itself maybe playing a strong role. This difference between the small scale and the large scale properties is however absent in the energy density spectrum which shows the same scaling law for the two ranges. We argue that the nature of the fluid plays a role in setting the anomalies with respect to the pure Kolmogorov case opening the possibility of probing these anomalies through the fine tuning of the fluid properties.

5.2 Materials and Experimental Setup

5.2.1 Cetyltrimethyl ammonium bromide (CTAB)

Cetyltrimethyl ammonium bromide (CTAB) is one of the most effective water-soluble cationic group of surfactants; it is worth noting that this surfactant is not affected by metal ions found in tap water. The CTAB surfactant can be mixed with counterions to improve the performance of a cationic surfactant over single counterions. NaSal counterion is added to cationic surfactant solutions for aiding the formation of rodlike micelles which is considered to be a cause of drag reduction. The chemical structure of CTAB and NaSal are given below in Figure 1.

![Figure 1: The chemical structure of CTAC and NaSal.](image-url)
CTAB can be used in a very wide range of temperatures. Other positive characteristics of CTAB surfactant include relatively stability and self-reparability and therefore they have superior drag reduction results over a wide temperature range and have a great potential for industrial applications such as district heating and cooling systems and provide significant energy savings. CTAB was purchased from Sigma Aldrich. Sodium salicylate (NaSal) is added to provide counterions. The surfactant solution we used for this experiment is made with 0.5 wt% of CTAB and 0.1 wt% of NaSal purchased from Sigma Aldrich in tap water. Approximately 2.5 L of solution was prepared for the experiment. The required amount of CTAB and NaSal powder was weighed on an electronic balance (BA 210S, Sartorius, Germany) and was dissolved in tap water by stirring slowly by magnetic stirring until a homogeneous solution is obtained. Then the solution was diluted with additional tap water to the desired test concentration.

**5.2.2 Polyethylene oxide (PEO)**

Polyethylene oxide (PEO) is a synthetic polymer obtained by the interaction of ethylene oxide with water, ethylene glycol, or ethylene glycol oligomers. PEO is one of the most effective water-soluble synthetic polymers with a wide range of industrial applications such as pharmaceuticals, cosmetics, textile, mining, paper and cleaning products. Polyethylene oxide is one of the most popular commercial drag reducing polymers and provides an effective drag reduction due to its chemical and mechanical stability. The use of polyethylene oxide polymer to enhance flow in petroleum pipelines has received the greatest attention due to its great commercial success in reducing cost and energy consumption.

![Figure 2: The chemical structure of PEO polymer.](image)

Polyethylene oxide ($M_w=4 \times 10^6$) was purchased by from Sigma-Aldrich and used without any further purification. PEO needs to be slowly mixed upon introduction to an aqueous medium to avoid the formation of lumps. The required amount of PEO powder was weighed on an electronic
balance (BA 210S, Sartorius, Germany) and was gradually dissolved in tap water by stirring slowly with a magnetic stirrer and allowing the polymer to mix fully before any further polymer was added to avoid aggregate formation at room temperature. The solution was stirred until a homogeneous solution was obtained. Then the solution was diluted with additional tap water to the desired test concentration.

5.2.3 Characterization of experimental set up

We use an experimental apparatus allowing for a turbulent flow between two counter rotating baffled disks. Such a set up has been extensively used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids [9, 7, 8, 10]. This apparatus and due to the manner in which the turbulence is created (i.e., the baffles instead of a flat and smooth surface) does not present drag reduction. What we examine is therefore the modification of the turbulence properties in the bulk of the solution. We use Laser Doppler Velocimetry (LDV), which produces temporal traces of the velocity of micron sized seed particles in solution and measured at a fixed location in the cell. Our reference state is water and the complex fluid used is a dilute aqueous solution. The Reynolds numbers examined are defined as $R^2 \Omega / \nu$ and range from 5000 to 100000 (R is the radius of the disk, $\Omega$ is the angular rotation, and $\nu$ is the kinematic viscosity of the fluids used). The dimensions of the cell are a radius of 7 cm and a height of 20 cm.

For the measurements to be presented here, estimates of the Taylor microscale yield values near 0.5 mm with associated Reynolds number taking values near 200. The standard deviation of the velocity fluctuation can be as high as 50 cm/s yielding high turbulent intensities that can reach 50%. The standard deviation takes smaller values for the surfactant solution with values near 20 cm/s. The two disks are equipped with four baffles of height 4 cm. The two disks are mounted on two separate motors that can rotate at different rotation frequencies controlled by two current supplies. Measurements of the power injection versus the rotation frequency indicate that this power increases as the third power of the rotation frequency as expected and is independent of the fluid used and therefore of the viscosity confirming previous observations [8]. The cell was then filled with approximately 2.5 L of the desired solution. We have used surfactant solutions of 0.5% CTAB and 0.1% NaSal (by weight). In this concentration range, the solution is composed of wormlike micelles in the dilute regime [10].
5.3 Results and Discussions

5.3.1 The rheological properties of CTAB and PEO

The rheological characterization of the CTAB and PEO solutions was carried out using the Rheologica StressTech Rheometer. This surfactant solution is shear thickening as has been shown before [10]. The viscosity of the solution is near that of water for shear rates below a threshold value (which varies between 20 and 100 s\(^{-1}\)). Above this shear rate, the viscosity increases abruptly by over a factor 5 and then decreases slightly as the shear rate increases. The rheological properties of this complex fluid are therefore very different from the often used polymer solutions which generally shown shear thinning behavior. For comparison, we have also carried out experiments using a long chain polymer solution, PEO of \(4 \times 10^6\) molecular weight at 50 ppm by weight.

5.3.2 The energy density spectrum of Water, PEO and CTAB

We now turn to the description of the turbulence properties. The first feature we have examined is the energy density spectrum obtained from the time series of the longitudinal velocity fluctuations. The LDV probe was positioned slightly below the center the cell so as to have a nonzero mean flow velocity. The probe can be positioned at different distances from the wall and we chose to do our measurements between 5 and 10 mm from the wall. These considerations are for practical reasons: in order to increase the count rate of the LDV, a sufficient amount of particles has to be dispersed in solution. At such concentrations, measurements deep into the solution become complicated due to multiple scattering by the particles in the bulk fluid. While we checked that variations of this distance between a few mm from the wall and at least 1 cm from the wall did not change the major features of the results, we cannot confirm that wall effects are totally absent. However, an estimate of the viscous sublayer width gives 0.5 mm leading us to conclude that our measurements are at least outside of this layer. Other considerations arise: in a recent paper, flow reversals were observed [13]. We do not know how these flow reversals affect the results but runs with practically no reversals were also analyzed with no major changes on the main results. In figure 3, we show the energy density spectra obtained for the reference solution and for the
polymer solution. At this level, the difference between the polymer solution and the reference solution seem absent. We have recast the frequency into a wave number by using the frozen turbulence assumption when representing the power spectra of the velocity fluctuations. The reference solution (water for a rotation frequency of 5Hz) shows a range in scales where a power law decrease is observed (figure 3a). Recall that these are one dimensional energy density spectra obtained from a time series of the velocity along the flow direction. The exponent extracted from this power law decrease is near -1.46. In the case where the frozen turbulence assumption is valid, we expect an exponent of -5/3 which is characteristic of Kolmogorov scaling for 3D fluid turbulence. While the value we obtain seems close to the expected value it is smaller nonetheless. Previous work in a similar cell also measured exponents smaller than -5/3 [9]. Such a feature is probably due to the proximity of the wall and possibly to a failure of the Taylor hypothesis when the intensity of the turbulence is strong, which is the case here. Nonetheless, the spectrum shows scaling and the exponent is not far from the expected one. In addition to this scaling regime, the power spectrum seems to decrease more steeply for scales below about 0.3 cm (as marked by an arrow in figure 3a). The arrows in the plot indicate the approximate transition scale to a steeper spectrum. The polymer solution, figure 3b, shows a similar behavior: a scaling regime with a roughly similar exponent as water along with a steeper decrease at smaller scales below 0.5 cm (arrow in figure 3b). There are no marked differences between the polymer solution and water.

Figure 3: The energy density spectra: a) Water and b) PEO solution at a rotation frequency of 5Hz.
The surfactant solution also shows power law scaling for the energy density spectrum with a higher exponent near -1.7 as seen in figure 4a and 4b which seems consistent with a Kolmogorov scaling. Apart from differences in the exponents measured, another feature comes out of these spectra: while the water spectrum and the polymer solution spectrum show a steeper decrease at small scales below 0.3 cm and 0.5 cm respectively, no such decrease is observed for the surfactant solution up to scales of 0.01 cm. While for the water and the polymer cases, a signature of a near dissipative range (the dissipative scale is estimated to be 100 microns) is a probable cause for the steepening of the spectrum at small scales, no such signature appears in the spectra of the surfactant solution. This is true for both frequencies examined as shown in figure 4a and 4b.

![Figure 4: The energy density spectra a) CTAB solution at a rotation frequency of 4Hz and b) CTAB solution at a rotation frequency of 5Hz.](image)

Note that the peak in the spectrum of the surfactant solution corresponds to 4 times the driving frequency and is indicative of the passage of the baffles; this peak is also present in water and polymer spectra but its amplitude is smaller due to the higher turbulent intensity in these fluids as compared to the surfactant solution. The exact significance of this peak and its relation to the scale of energy injection is unclear to us as the distance between two baffles in the outer periphery of the disk is nearly 10 cm while the position of the peak using the Taylor hypothesis varies from run to run.
5.3.3 The velocity structure function of Water, PEO and CTAB

Let us now take a look at the structure functions of the velocity using the LDV scheme and the obtained time traces. These functions are defined as $S_n(\tau) = \delta u^n(\tau) = \langle (u(t+\tau) - u(t))^n \rangle$ where $u$ is the fluctuating part of the longitudinal velocity in the mean flow direction. Again, the use of the frozen turbulence assumption allows to convert time scales to length scales. For water and the polymer solution, these functions are shown in figure 5a and 5b. About a decade of power law scaling is observed, corresponding to the scaling range of the power spectrum: the scaling range for the water case is between roughly 0.3 and 4 cm in good agreement with the scaling of the energy density spectrum which shows scaling for scales larger than 0.3 cm. The scaling range for the polymer solution is also in agreement with that of the power spectrum and extends roughly between 0.5 cm and 7 cm. A quantity of interest is the exponent of these power laws and its variation with the order $n$ of the moment. Indeed, and for three dimensional turbulence, the exponents $\xi_n$ characterizing the scaling law for each order $n$ is predicted to be $n/3$. This rule is displayed by several experiments up to $n=4$ beyond which the exponents vary more slowly [2]. This anomaly is attributed to intermittency of the fluctuations leading to changes in the functional form of the probability density functions of velocity differences as the scale changes. Our results for water and the polymer solution show good agreement with the expected result: a roughly linear increase of $\xi_n$ (see inset of figure 5a and 5b).

For higher moments, the exponent deviates, as it is smaller than expected. This behavior is now well established for 3D turbulent systems and our results reproduce such a phenomenology despite the fact that our spectral exponent is not exactly $-5/3$. In fact, the increase of the structure function exponents can be mimicked using $0.23n$ instead of $n/3$ in agreement with the smaller value of the exponent of the velocity power spectrum. The exponent for the second order structure function is related to the spectral exponent through $\xi_2 = \alpha - 1$ where alpha is the spectral exponent. This leads to $\xi_n = n\xi_2 / 2 = n(\alpha - 1) / 2$. For $\alpha = 1.46$, $\xi_n = 0.23n$ in good agreement with our results. At scales smaller than 0.3 cm for water and 0.5 cm for the polymer solution, the structure functions seem to decrease more steeply in agreement with the steeper decrease of the power spectrum. Here again, the differences between the polymer solution and the water case are very minor: the amplitude of the structure functions for the polymer case at small scales are however smaller than for water as noted in previous work [6].
Figure 5: The velocity structure function a) Water and b) PEO solution at a rotation frequency of 5Hz. The structure functions were shifted vertically for better visibility.

Note that the insets in a and b show the variation of the structure function exponents versus order. The lines indicate the expected Kolmogorov scaling (n/3) and the variation found here for the low order moments.
For the surfactant solution, power law scaling is also observed (see figure 6a and 6b), but two different ranges seem to exist contrary to the power spectrum where no particular feature was observed as the scaling range seemed to extend down to the smallest scales examined. The first scaling range for the surfactant solution is observed for scales between 0.8 cm and 8 cm for the 4Hz rotation speed and between 0.2 cm and 2 cm for the 5Hz rotation speed. The second scaling range occurs at scales below 0.8 cm and below 0.2 cm for the two rotation speeds respectively. The exponents extracted from the large scale end are shown in the insets of fig. 6a and 6b. The variation of the exponents versus n follows a straight line up to order 6. This line is in excellent agreement with the Kolmogorov prediction n/3 with no noticeable deviation and is therefore consistent with the measured value of the spectral exponent $\alpha$ for the surfactant solution which is very close to 5/3. The absence of a deviation from the n/3 law seems to indicate an absence of intermittency for this range of scales. This is the first surprising result as it shows that despite the complexity of the fluid used, a major feature of turbulence phenomenology, i.e., intermittency, is basically absent. On the other hand, the exponents extracted from the small scale range increase at first but beyond n=3, they no longer vary; they even show a tendency towards a saturation or a slight decrease (see insets of fig. 5b). This behavior, as far as we know, has not been reported before and seems at odds with the variation of the power spectrum which shows no distinction between the small scale range and the large scale range (delimited by an arrow in figure 4a through 4b). This variation of the exponents versus order would indicate that the phenomenon of intermittency for the velocity fluctuations at these scales is here at its maximum and at odds with the large scales which show none. Few cases show a saturation of the exponents: One dimensional compressible turbulence [14], granular turbulence [15], and thermal convection [16], have been shown to display such saturation. In all these cases, the presence of strong structures (shocks in the first case and in the second case and well defined thermal plumes in the third case) introduce large velocity gradients or large temperature gradients respectively giving rise to a flattening of the exponents of the structure functions. For the surfactant solution this may also be the case. Note that the arrows indicate the scale at which the structure functions show a transition to a more intermittent scaling range. The spectrum in the surfactant case shows no particular transition at this scale. The structure functions were shifted vertically for better visibility: the downward shift is by factors of 1.25, 2, 4, 8, and 20 for the second to the sixth order, respectively. The insets in 6a and 6b shows the variation of the structure function exponents (for the two regimes) versus order.
Figure 6: The velocity structure a) CTAB solution at a frequency of 4Hz and b) CTAB solution at a frequency of 5Hz. The structure functions were shifted vertically for better visibility: the downward shift is by factors of 1.25, 2, 4, 8, and 20 for the second to the sixth order, respectively. The insets in 6a and 6b shows the variation of the structure function exponents (for the two regimes) versus order.
It has been shown before that this solution may show the formation of gel like patches, i.e., very viscous patches, within the solution in regions subjected to strong shear [10]. We speculate that since the turbulence engenders large shears and large shear fluctuations, the solution may actually form such patches in different places and of different sizes. If such a patch is formed, relative velocities within the patch would be very small while the patch itself would move freely in solution. Under such conditions, the velocity gradients may be very large at the frontier between the patch and the fluid around it. We noted for example that the small scale end starts at 0.8 cm for the lower rotation speed while it starts at 0.2 cm for the higher rotation speed perhaps indicating that larger rotations give rise to smaller patches. If we estimate the deformation rate at these scales using \( S_1(r)/r \) we find 25 and 85 s\(^{-1}\) which is close to the shear rates for which shear thickening occurs [10]. Since at scales below the transition, the deformation rates are higher, it is plausible that the viscosity at these small scales is much enhanced. If this is indeed the case, the enhancement of the viscosity will also lead to an increase of dissipative scale which would be close to 600 microns. It is then possible that the small scale range is also influenced by the dissipation within the gel patches at small scales. The possibility that the viscosity increases with the decrease in scale may also lead to modifications of how energy is transferred and dissipated.

### 5.3.4 Probability density functions (pdfs) of Water and CTAB

In order to further probe the transition between the large scales, which show no intermittency, and the small scales, which show strong intermittency, we have examined the probability density functions (pdfs) of velocity differences across the scales, shown in figure 7a and 7b for water and the surfactant solution respectively. These pdfs are presented in a normalized representation: The horizontal axis has been normalized by the variance of the distribution, and the pdf normalized in such a way that the integral of the function is 1. In such a representation, and for the case where intermittency is absent, the pdfs for the different scales should collapse onto a single curve. This is not the case for neither water nor the surfactant solution at small scales whose pdfs display exponential like tails and therefore large deviations with respect to the mean. Moreover, differences arise between the two different systems.
Figure 7: Pdfs of velocity differences at different scales: a) Water and b) CTAB solution.
For the range of scales where the structure functions show Kolmogorov scaling, the collapse of the different curves seems to work better for the surfactant solution than for water despite the fact that the pdfs for the surfactant solution are not Gaussian. In addition, and for this large scale range, the pdfs for water seem to asymptote towards a Gaussian shape at large scales as expected from previous experiments while those for the surfactant solution seem to remain non Gaussian. These observations are in line with the less intermittent character of the fluctuations for the surfactant solution: the pdfs for water seem to change gradually towards a Gaussian shape while the surfactant pdfs remain non Gaussian with little change as the scale varies. The non collapse of the pdfs for the surfactant solution is manifest for the small scale range only. Despite the fact that the scales examined are well in the scaling region of the energy spectrum, the non collapse of the pdfs and their wide tails seems to indicate near dissipative range like behavior. In this respect, our data show that such a behavior is pronounced for water but only at scales near or below the range where the energy density spectrum shows a steeper decrease, i.e., in the near dissipative range. Note however that for comparable scales, the pdfs for the surfactant solution show even more important tails than those for water. This behavior suggests that scales below the transition between the two ranges, despite the scaling of the spectrum, reside in a near dissipative like range whose signature is absent in the energy spectrum. Is the inertial range of surfactant turbulence contaminated by large fluctuations in the dissipative scale, due to enhanced viscosity at different scales and different places, giving rise to a region where strong intermittency is observed? Our observations raise a number of questions as to how dissipation occurs in complex fluid turbulence, where viscosity variations may occur at different scales, and what role the scales in the near dissipative range play. In addition and since the proximity of the near dissipative range is thought to play a strong role in the intermittency properties of fluid turbulence [17, 18] the existence of such a range and its role in complex fluid turbulence may shed new light on the phenomenology of intermittency as it is strongly inhibited at the large scale end in our case.

5.4 Conclusion

In this work, turbulence properties of PEO and CTAB solutions were investigated using counter-rotating cell apparatus with discs with baffles. The CTAB surfactant solution showed strong intermittency at small scales with respect to the pure water case and with respect to PEO polymer
solution. This intermittency is then absent or very small for the larger scales. The origin of the strong intermittency at small scales has been traced to the highly non Gaussian statistics of the velocity fluctuations which may be due to the intrinsic properties of the solution and notably to its shear thickening character leading to the presence of very viscous parcels in the fluid. These parcels may enhance the local dissipation and therefore influence the turbulence properties at the scale of the parcel and beyond. Since another complex fluid, a polymer solution shows very similar phenomenology as the water case, we speculate that the fine tuning of fluid properties may shed new light on how intermittency occurs in fluid turbulence.


CONCLUSIONS

Drag reduction involves many subjects of interest such as polymer science, fluid mechanics and applied mathematics. The use of additives to enhance flow in petroleum pipelines has received the greatest attention due to a significant commercial success. In this study, we study the effect of the addition of the most common drag reducing agents (polymers and surfactants) on the characteristics of turbulent flows.

The conclusions drawn from Chapter 1 – 5 can be summarized as follows:

Chapter 1-2 reviewed early and recent developments in the field of polymer and surfactant drag reduction. A wide range of applications of polymer and surfactant additives in drag reduction brings potential benefits to many systems, such as long-distance transportation of liquids, oil well operations, transportation of suspensions and slurries, district heating and cooling systems, firefighting operations, and irrigation. Many efforts have consequently been made in the field of turbulent drag reduction by additives. Although much research has been carried out in the area of drag reduction, the detailed mechanism is not fully understood and it still continues to be a subject of controversy.

Chapter 3 presents the experimental techniques used for the characterization of drag reduction. This chapter describes the experimental setup including the experimental procedures and PIV system used to study the drag reduction by a rigid polymer. The rheology of drag reducing additives is studied using the Rheologica StressTech rheometer. The counter rotating turbulence cell and Laser Doppler Velocimetry system that were used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids are also introduced in this chapter. This chapter also presents a detailed characterization of the rheometer, the horizontal closed-loop system, Particle Image Velocimetry, Laser Doppler Velocimetry and the counter rotating baffled discs techniques.
Chapter 4 examines the turbulent drag reduction characteristics of the rod-like polysaccharide xanthan gum dissolved in water. The drag reduction measurements were made using a horizontal closed loop system. The amount of drag reduction was determined through pressure drop measurements. The results show that the addition of a minute amount of xanthan gum polymer to a turbulent fluid flow reduced the frictional drag in the channel flow by 40% in the turbulent regime. The mean velocity, turbulence velocity fluctuation, Reynolds shear stress, cross-correlation coefficient, kinetic energy and effective viscosity profiles of xanthan polymer solution flow were investigated to understand the mechanism of the interaction of rigid polymers with turbulence and to find the precise nature of the drag reduction mechanism. The result of the velocity profile measurements clearly demonstrate thickening of the buffer layer and an increase in the slope of the logarithmic profile in the wall region. The velocity profile analysis demonstrates that the interaction between polymer molecules and the turbulent structures takes place in the buffer layer and further away from the wall the velocity of the polymeric flow increases compared to the Newtonian case, which is consistent with drag reduction. For the drag reducing flow, it was found that the velocity gradient near the wall decreased compared with that found for water. The observed decrease in the velocity gradient also indicates the thickening of the viscous sublayer. Apart from velocity profile measurements, measurements of the turbulence intensities and turbulent kinetic energy are needed in order to understand the mechanism of the interaction of polymer additives with turbulence. The turbulence intensity and turbulent kinetic energy results showed that the drag reduction leads to modification of turbulent structures and energy, particularly in the buffer layer. The Reynolds stress is useful as a measure of the momentum transport due to the turbulent flow. Therefore, one possible way of explaining the drag reduction mechanism is by studies through the influence of polymers on the Reynolds stress. The Reynolds shear stress results show a significant reduction in the drag reducing polymer solution compared with water. The cross–correlation results showed that the reduction in Reynolds stress arises from a decorrelation between $u'_{re}$ and $v'_{re}$ velocity fluctuations. The loss of correlation between the streamwise and wall normal velocity components, and consequently the decrease of the Reynolds stress, directly leads to a decrease of the turbulent energy production and hence a reduction of a frictional drag. Knowledge of the role of the effective viscosity of the polymer solution as a function of the distance from the wall is one of the most important factors for understanding the drag reduction phenomenon. The effective viscosity profile demonstrates that there is a linear increase in effective viscosity with the distance from the wall with the addition of
xanthane. Based on the analyses, the drag reduction can be interpreted as an increase in the local effective viscosity with wall distance in the buffer zone. This result is in agreement with recent theory. The effective viscosity result demonstrates that an increase in the effective viscosity of the solution leads to a significant decrease of the Reynolds stresses (i.e., the momentum flux to the wall) compared to that for Newtonian flow. This in turn leads to drag reduction. Based on the experimental results obtained, it could be stated that the results support the notion that an effective viscosity profile could be an important factor in understanding drag reduction for rigid polymers.

Chapter 5 examines turbulence properties in a drag reducing surfactant and in polymer systems. The examination of the turbulence properties of surfactant solutions was made in a closed cell with baffled disks. In the latter geometry, due to the presence of the baffles, drag reduction is suppressed completely, since it is a boundary layer effect. Our experiments then probe how the turbulent structure itself is modified by the presence of DR agents. For comparison we also carried out experiments using a polymer solution. The results obtained clearly demonstrate that CTAB surfactant solutions showed a strong intermittency at small scales relative to the pure water case and PEO polymer solutions. This intermittency is absent or very small for the larger scales. The origin of the strong intermittency at small scales has been traced to the highly non-Gaussian statistics of the velocity fluctuations, which may be due to the intrinsic properties of the solution and notably to its shear thickening character leading to the presence of very viscous parcels in the fluid. We believe that the formation of the small gel parcels in the fluid may enhance the local dissipation and therefore influences the turbulence properties at the scale of the parcel and beyond. In fact, a polymer solution showed very similar characteristics as water. We consider that the fine tuning of fluid properties may shed new light on how intermittency occurs in fluid turbulence.
CONCLUSIES

Weerstandsvermindering omvat vele onderwerpen van belang, zoals polymeer wetenschap, stromingsleer en toegepaste wiskunde. Het gebruik van additieven voor het verbeteren van de doorstroming van petroleum door pijpleidingen heeft de grootste aandacht ontvangen door zijn significant commerciële succes. In deze studie bestuderen we het effect van de toevoeging van de meest voorkomende weerstandsverminderings middelen (polymeren en tensiden) op de kenmerken van turbulente stromingen.

De conclusies uit hoofdstuk 1-5 kunnen als volgt worden samengevat:

Hoofdstuk 1-2 beoordeeld vroege en recente ontwikkelingen op het gebied van polymeer en oppervlakteactieve weerstandsvermindering. Een breed scala van toepassingen van polymeer en oppervlakteactieve additieven voor vermindering van de weerstand geeft potentiële voordelen voor veel systemen, zoals de lange afstands-transport van vloeistoffen, oliebron operaties, transport van suspensies en mengsels, stadsverwarming en koelsystemen, brandbestrijding, en irrigatie. Vele inspanningen hebben dan ook vooruitgang geboekt op het gebied van turbulente weerstandsvermindering door de toevoeging van additieven. Hoewel veel onderzoek is uitgevoerd op het gebied van de vermindering van de weerstand, worden de bijzonderheden van het mechanisme niet volledig begrepen en het blijft het onderwerp nog steeds controversieel.

Hoofdstuk 3 presenteert de experimentele technieken die worden gebruikt voor de karakterisering van de vermindering van de weerstand. Dit hoofdstuk beschrijft de experimentele opstelling, waaronder de experimentele procedures en PIV-systeem dat wordt gebruikt om de vermindering van de weerstand door een stijf te bestuderen. De reologie van weerstandsverminderende additieven wordt bestudeerd met behulp van de Rheologica Stress-Tech reometer. De tegendraaiende turbulentie cel en Laser Doppler Velocimetry systeem dat werd gebruikt voor het onderzoek van turbulentie eigenschappen van eenvoudige vloeistoffen, alsmede bij weerstandsvermindering van complexe vloeistoffen worden ook in dit hoofdstuk behandeld. Dit hoofdstuk bevat ook een gedetailleerde karakterisering van de reometer, de horizontale closed-loop systeem, stromings-visualisatie, Laser Doppler Velocimetry en de tegendraaiende impeller technieken.
Hoofdstuk 4 gaat in op de turbulentie verminderende kenmerken van het staafvormige polysaccharide xanthaangom opgelost in water. De metingen voor weerstandsvermindering werden gemaakt met behulp van een horizontaal gesloten lus systeem. De weerstandsvermindering werd bepaald door drukval metingen. De resultaten tonen aan dat de toevoeging van een kleine hoeveelheid xanthaangom polymeer aan een turbulente vloeistof een reductie van 40% opleverde voor wat betreft de kanaalstroming in het turbulente regime. De gemiddelde snelheid, de snelheid turbulentie schommelingen, Reynolds schuifspanning, kruiscorrelatie coëfficiënt, kinetische energie en effectieve viscositeit profiel van xanthaangom polymeer-oplossingsstroom onderzocht om het mechanisme van de interactie van starre polymeren met turbulentie en de precieze aard te van het weerstandsvertragingsmechanisme te begrijpen. Het resultaat van het snelheidsprofiel metingen tonen duidelijke verdikking van de bufferlaag en een toename van de helling van de logaritmische profiel in het wandgebied. De analyse van het snelheidsprofiel toont aan dat de interactie tussen polyemeermoleculen en de turbulentie structuren plaatsvindt in de bufferlaag, en verder van de wand de snelheid van de polymeer stroom stijgt in vergelijking met de Newtonse vloeistof, wat overeenkomstig is met weerstandsvermindering. Voor de weerstandsverminderende doorstroming, bleek dat de snelheidsgradiënt nabij de wand vermindere vergeleken met die gevonden voor water. De waargenomen afname van de snelheidsgradiënt geeft ook de verdikking van de viskeuze sublaag. Naast snelheidsprofiel metingen, zijn de metingen van de turbulentie intensiteiten en turbulente kinetische energie nodig om het mechanisme van de interactie van polymere additieven met turbulentie begrijpen. De turbulentie-intensiteit en turbulente kinetische energie resultaten toonden aan dat de vermindering van de weerstand leidt tot een wijziging van turbulentie structuren en energie, met name in de bufferlaag. De Reynolds spanning is nuttig als een maat voor de hoeveelheid van beweging door de turbulente stroming. Daarom is een mogelijke manier van het uitleggen van de weerstandsvermindering door het bestuderen van de invloed van polymeren op de Reynolds stresstest. The Reynolds schuifspanning resultaten tonen een significante vermindering aan van de weerstandsverminderde polymeeroplossing vergeleken met water. De kruiscorrelatie resultaten tonen aan dat de vermindering van Reynolds spanning voort komt uit een decorrelatie tussen $u'_{rms}$ en $v'_{rms}$ snelheids fluctuaties. Het verlies van correlatie tussen de stroming en de wand normale snelheid componenten en dientengevolge de van het Reynolds spanning, direct leidt tot een vermindering van de turbulente energieproductie en derhalve een vermindering van een wrijvingsweerstand. Kennis van de taak van de effectieve viscositeit van de polymeer oplossing als functie van de afstand tot de wand, is een van de
belangrijkste factoren voor het begrijpen van het weerstandsverminderende fenomeen. Het effectieve viscositeitsprofiel demonstreert dat er een lineaire toename is in de effectieve viscositeit met de afstand van de muur wanneer xanthaan toegevoegd wordt. Gebaseerd op de analyses, kan de vermindering van de weerstand geïnterpreteerd worden als een vergroting in de lokale effectieve viscositeit met de afstand van de wand in de bufferzone. Het effectieve resultaat van de viscositeit toont aan dat een verhouding in de effectieve viscositeit van de oplossing leidt tot een aanzienlijke vermindering in de Reynolds spanningen (de impulsflux naar de wand) in vergelijking met die van Newtoniaanse vloeieigenschappen. Dit leidt weer tot weerstandsvermindering. Op basis van de experimentele resultaten kan worden vastgesteld dat de resultaten de stelling ondersteunen dat een effectief viscositeitsprofiel een belangrijke factor speelt in het begrijpen van weerstandsvermindering voor stugge polymeren.

Hoofdstuk 5 onderzoekt de turbulentie eigenschappen van een weerstand verminderd oppervlakteactieve stof en polymeer systemen. Het onderzoek van de turbulentie eigenschappen van oppervlakteactieve oplossingen werd gemaakt in een afgesloten cel met impeller schotten. In deze geometrie, door de aanwezigheid van de schotten, wordt weerstandsvermindering volledig onderdrukt, aangezien het een grenslaag-effect is. Onze experimenten meten dan hoe de turbulente structuur zelf wordt gemodificeerd door de aanwezigheid van DR agenten. Ter vergelijking hebben we ook experimenten uitgevoerd met behulp van een polymeer-oplossing. De verkregen resultaten tonen duidelijk aan dat CTAB oppervlakteactieve oplossingen een sterke onregelmatigheid vertoond op kleine schaal in verhouding tot het zuivere water geval en PEO polymeer oplossingen. Deze onregelmatigheid is afwezig of erg klein voor de grotere schalen. De oorsprong van de sterke onregelmatigheid op kleine schaal is terug te voeren op de zeer niet-Gaussische statistieken van de snelheidsschommelingen die het gevolg zijn van de intrinsieke eigenschappen van de oplossing en met name haar verschuivings-verdikkende karakter leidt tot de aanwezigheid van zeer viskeuze delen in de vloeistof. Wij geloven dat de vorming van de kleine gel delen in de vloeistof de lokale dissipatie kunnen versterken en daardoor turbulentie eigenschappen beïnvloed bij de omvang van het vloeistof-deel en daarbuiten. Daarbij vertoonde een polymeeroplossing vrijwel dezelfde kenmerken als water. Wij zijn van mening dat de fijnafstelling van vloeistofegenschappen nieuw licht kunnen werpen op hoe onregelmatigheid optreedt in vloeistof turbulentie.
### NOMENCLATURE & SYMBOLS

<table>
<thead>
<tr>
<th><strong>Angular rotation</strong></th>
<th>( \omega, \Omega )</th>
<th>rad/s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average displacement of particle</strong></td>
<td>( \Delta X )</td>
<td>m</td>
</tr>
<tr>
<td><strong>Average dissipation rate of turbulent kinetic</strong></td>
<td>( \langle \varepsilon \rangle )</td>
<td>( m^2/s^3 )</td>
</tr>
<tr>
<td><strong>Cross-correlation coefficient</strong></td>
<td>( R_{uv} )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Drag reduction</strong></td>
<td>DR</td>
<td>%</td>
</tr>
<tr>
<td><strong>Diameter of the pipe</strong></td>
<td>D</td>
<td>m</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>( \rho )</td>
<td>( Kg/m^3 )</td>
</tr>
<tr>
<td><strong>Dimensionless average velocity</strong></td>
<td>( U^+ )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Dynamic viscosity</strong></td>
<td>( \eta )</td>
<td>( Pa.s )</td>
</tr>
<tr>
<td><strong>Distance from tube axis</strong></td>
<td>r</td>
<td>m</td>
</tr>
<tr>
<td><strong>Distance from wall</strong></td>
<td>y</td>
<td>m</td>
</tr>
<tr>
<td><strong>Dimensionless extension tensor of polymer in yy plane</strong></td>
<td>( R_{yy} )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Dimensionless local velocity</strong></td>
<td>( U^+ )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Dimensionless distance from the wall</strong></td>
<td>( y^+ )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Dimensionless turbulent (Reynolds) stress</strong></td>
<td>( \tau_r^+ )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Elongational viscosity</strong></td>
<td>( \eta_e )</td>
<td>( Pa.s )</td>
</tr>
<tr>
<td><strong>Effective viscosity</strong></td>
<td>( v_{eff} )</td>
<td>( m^2/s )</td>
</tr>
<tr>
<td><strong>Exponent characterizing the scaling law</strong></td>
<td>( \xi_n )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Flow rate</strong></td>
<td>Q</td>
<td>( m^3/s )</td>
</tr>
<tr>
<td><strong>Friction velocity</strong></td>
<td>( U_\tau )</td>
<td>m/s</td>
</tr>
<tr>
<td><strong>Fanning friction factor</strong></td>
<td>f</td>
<td>---</td>
</tr>
<tr>
<td><strong>Friction coefficient of the solvent</strong></td>
<td>( f_s )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Friction coefficient of drag reducing solutions</strong></td>
<td>( f_{DR} )</td>
<td>---</td>
</tr>
<tr>
<td><strong>Fluctuating components of axial velocity</strong></td>
<td>( u_x' )</td>
<td>m/s</td>
</tr>
<tr>
<td><strong>Fluctuating components of radial velocity</strong></td>
<td>( u_r' )</td>
<td>m/s</td>
</tr>
<tr>
<td><strong>Intrinsic concentration</strong></td>
<td>([C])</td>
<td>wppm</td>
</tr>
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### NOMENCLATURE & SYMBOLS

- **Kinematic viscosity** \( v_0 \) \( \text{m}^2/\text{s} \)
- **Length of tube** \( L \) \( \text{m} \)
- **Lower limit of length scale over which polymer** \( r^{**} \) \( \text{m} \)
- **Mean fluid velocity** \( U \) \( \text{m/s} \)
- **Monomer length** \( a \) \( \text{m} \)
- **Maximum level of drag** \( D R_{\text{max}} \) \( \% \)
- **Number of rods per volume** \( n \) ---
- **Pressure** \( P \) \( \text{Pa} \)
- **Pressure difference** \( \Delta P \) \( \text{Pa} \)
- **Pressure drop in absence of drag reducing agent** \( \Delta P_{\text{Solvent}} \) \( \text{Pa} \)
- **Pressure drop in presence of drag reducing agent** \( \Delta P_{\text{Polymer}} \) \( \text{Pa} \)
- **Pi** \( \pi \) ---
- **Radius of the pipe** \( R \) \( \text{m} \)
- **Reynolds number** \( \text{Re} \) ---
- **Radius of gyration of molecule** \( R_G \) \( \text{m} \)
- **Relaxation time** \( T_z \) \( \text{s} \)
- **Reynolds shear stress** \( U V^+ \) ---
- **Reynolds stress deficit** \( G \) ---
- **RMS velocity fluctuations in the streamwise direction** \( \overline{u'^2} \) \( \text{m/s} \)
- **RMS velocity fluctuations in the wall normal direction** \( \overline{v'^2} \) \( \text{m/s} \)
- **Shear rate** \( \dot{\gamma} \) \( \text{sec}^{-1} \)
- **Shear stress** \( \tau \) \( \text{Pa} \)
- **Shear viscosity** \( \eta_v \) \( \text{Pa.s} \)
- **Shear viscosity at the critical micelle concentration** \( \eta_{\text{CMC}} \) \( \text{Pa.s} \)
- **Shift in dimensionless velocity profile** \( \Delta B \) ---
- **Time** \( t \) \( \text{s} \)
<table>
<thead>
<tr>
<th>NOMENCLATURE &amp; SYMBOLS</th>
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<tbody>
<tr>
<td>Temperature</td>
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<tr>
<td>Torque</td>
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<tr>
<td>Turbulent length scale</td>
</tr>
<tr>
<td>Time interval</td>
</tr>
<tr>
<td>Viscosity at the wall</td>
</tr>
<tr>
<td>Velocity scale</td>
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<tr>
<td>Wall shear stress</td>
</tr>
<tr>
<td>Weissenberg number</td>
</tr>
<tr>
<td>Zero Shear viscosity</td>
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### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>Cetyl Trimethyl Ammonium Bromide</td>
<td>CTAB</td>
</tr>
<tr>
<td>Cetyl Trimethyl Ammonium Chloride</td>
<td>CTAC</td>
</tr>
<tr>
<td>Coiled Tubing</td>
<td>CT</td>
</tr>
<tr>
<td>Direct Numerical Simulation</td>
<td>DNS</td>
</tr>
<tr>
<td>Drag Reducing Agents</td>
<td>DRAs</td>
</tr>
<tr>
<td>Drag Reducing Additives</td>
<td>DRA</td>
</tr>
<tr>
<td>District Heating and Cooling Systems</td>
<td>DHC</td>
</tr>
<tr>
<td>Finitely Extensible Non-Linear Elastic</td>
<td>FENE</td>
</tr>
<tr>
<td>Finitely Extensible Nonlinear Elastic with Peterlin Approximation</td>
<td>FENE-P</td>
</tr>
<tr>
<td>First Critical Concentration</td>
<td>CMCI</td>
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<tr>
<td>Laser Doppler Anemometry</td>
<td>LDA</td>
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<tr>
<td>Laser Doppler Velocimetry</td>
<td>LDV</td>
</tr>
<tr>
<td>Light Scattering</td>
<td>LS</td>
</tr>
<tr>
<td>Maximum Drag Reduction Asymptote</td>
<td>MDA</td>
</tr>
<tr>
<td>Particle Image Velocimetry</td>
<td>PIV</td>
</tr>
<tr>
<td>Polyethylene Oxide</td>
<td>PEO</td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>PAM</td>
</tr>
<tr>
<td>Probability Density Function</td>
<td>PDF</td>
</tr>
<tr>
<td>Sodium Salicylate</td>
<td>NaSAL</td>
</tr>
<tr>
<td>Shear Induced Structure</td>
<td>SIS</td>
</tr>
<tr>
<td>Second Critical Concentration</td>
<td>CM</td>
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<tr>
<td>Small-Angle-Neutron Scattering</td>
<td>SANS</td>
</tr>
<tr>
<td>Trans-Alaskan Pipeline</td>
<td>TAPS</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>TKE</td>
</tr>
<tr>
<td>Xanthan Gum</td>
<td>XG</td>
</tr>
</tbody>
</table>
High reynolds number turbulence in complex fluids

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