Turbulent drag reduction by additives

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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].

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

(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.

![Image of Planar Laser Induced Fluorescence](image.png)

*Figure 1: Planar Laser Induced Fluorescence A) image for water and B) for 100 wppm of polyethylene oxide with Mw = 4.5x10^6 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.