

## CHAPTER I

### INTRODUCTION

It is well known that the energy loss due to skin friction in a turbulent flow is substantially lowered when a small amount of polymer is added to the flowing solvent. This phenomenon is called drag reduction and it has been extensively researched over the past four decades due to its potential benefit in many systems such as long distance transport of crude oil, sewage, fire-fighting operations and irrigation. A review of the literature can be found in articles by Lumley (1969), Virk (1975), Berman (1978) and McCormick, et al. (1990). Despite the abundance of theoretical, experimental studies of the phenomenon reported, many unanswered questions remain, and no universally accepted model exists that explains physically the effect of polymer molecules on turbulent flows.

It is thought that extended macromolecules are involved in polymeric drag reduction. Polymer molecules are thought to be elongated by shear forces in the turbulent flow regime. There is a controversy, however, whether an increased elongational viscosity or elastic behavior of polymer molecules causes the friction reduction.

Although the mechanism producing drag reduction is not yet settled upon, a large number of polymer characteristics making for good drag reducers have been determined. A long-chain backbone and flexibility are important characteristics of drag reducing agents. However, it is still uncertain whether the parameters providing the best correlation are molecular weight, chain length or hydrodynamic volume ( $R_h$  or  $[\eta]$ ).

## 1.1 Background

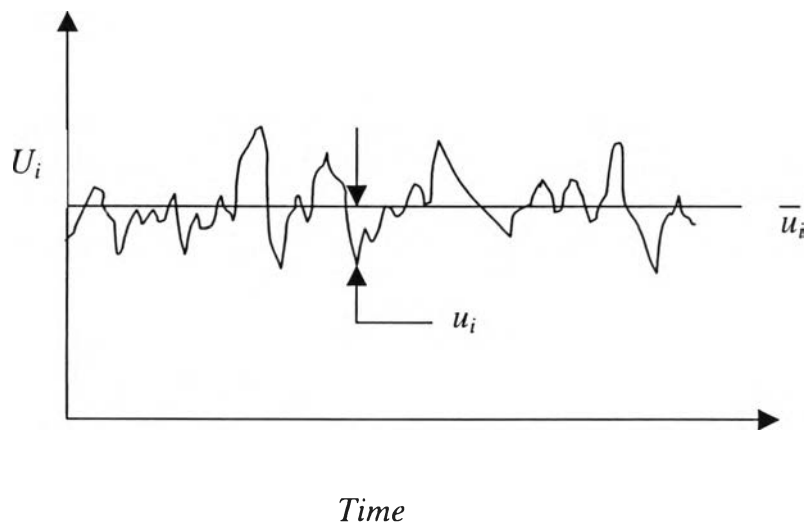
*Historical.* – Toms (1948) was the first to publish drag reduction data in 1948. He observed that the reduction of tens of parts per million (by weight) of poly (methyl methacrylate) to high Reynolds number turbulent pipe flow of monochlorobenzene reduced the pressure drop below that of solvent alone at the same flow rate. So sometime this phenomenon is called '*Toms phenomenon*'.

*Types of drag reduction additives.* - Drag reduction has been reported for several solvent/additives systems, including diluted solution of high molecular weight soluble polymers, surfactants and micellar systems (Shenoy, 1984), suspensions of fibers such as wood pulp, nylon and asbestos. Dust and sand particles in suspension in both air and water were reported to reduce friction. To date, polymer solutions are the most widely studied and most often employed drag reducing systems. A partial listing of polymeric drag reducing fluids is tabulated in Table 1.1 (Morgan and McCormick, 1990).

**Table 1.1** Drag reducing polymeric fluids.

<i>Water-soluble (and brine-solution) polymers</i>
Poly(ethylene oxide)
Polyacrylamide and hydrolyzed polyacrylamide
Guar gum
Carboxymethyl cellulose
Hydroxyethyl cellulose
<i>Hydrocarbon-soluble polymers</i>
Polyisobutylene
Poystyrene
Poly(methyl methacrylate)
Poly(cis-isoprene)

*Turbulent flow.* - The flow is broadly classified in terms of the fluid Reynolds number into laminar or turbulent flow. Laminar flow is the flow with smooth velocity profile, generally, occurring when viscous force is greater than inertial force. The turbulent flow is the flow in which medium processes velocity fluctuations in both space and time (Tennekes and Lumley, 1972). The fluctuating velocity field (see Figure 1.1) has various length scales therefore it consists of eddies of various sizes. The primary characteristic of turbulence is that the kinematic and dynamic variables are random fluctuating function of time. These fluctuations, as in the case of any time-varying signal, have a steady state mean value, if the flow rate,  $Q$ , is sufficiently long in comparison to some characteristic timescale of the fluctuations in the flow.



**Figure 1.1** Instantaneous values of measured characteristic of turbulent flow.

Typical drag reduction phenomenon does not occur in steady laminar flow but has been observed in pulsating laminar flows (Hansen, 1973). Existing results seem to indicate that the polymer molecules are active when large changes occur in the flow.

*Applications.* - Since drag reducing polymers provide a significant reduction in energy requirements, their use is economically attractive for a variety of commercial applications. The first industrial application is in

pumping gasoline. The most success of polymer drag reducers has been the used of oil-soluble polymers in the trans-Alaska pipeline (TAPS), where flow has been increased by ca 32,000 m<sup>3</sup>/d (Hoyt, 1986). Another major applications for friction reducing polymers are in turbulent flows of water. Tests and permanent polymer dosing systems have been implemented for sewers, drainage and irrigation systems, fire-fighting equipment and hydro-power systems. Significant efforts by the Navy and the marine industry have targeted utilization of drag reducers for ships or submersibles.

## **1.2 Literature Survey**

This section is based on a literature survey carried out by the author. The section includes a summary of the major effects of polymer on the structure of turbulent flow and experimental results and related physical explanations provided by different research workers.

### **1.2.1 Proposed Mechanisms**

Lumley (1969) considered that the extended macromolecules due to the fluctuating strain rate did not occur in the laminar sublayer; polymer coils were not greatly deformed and viscosity did not increase appreciably above that for the solvent alone. In the turbulent region, macromolecular expansion yielded a dramatically increased viscosity, which damped small dissipative eddies and reduced momentum transport from the buffer zone. Suppression of eddies in the buffer layer resulted in a thickening of the sublayer and a reduction of the drag.

Virk (1971) proposed the elastic sublayer model which is characteristic of the drag reduction phenomenon. The elastic sublayer

originated at onset, it then grew with increasing drag reduction and eventually occupied the entire pipe cross section at maximum drag reduction.

Virk (1975) defined four flow regimes for drag reducing polymer solutions in pipe flow as the laminar regime, where polymer solution flowed the same curve as solvent; the Newtonian regime, which was turbulent with no drag reduction; the polymeric regime, where drag reduction was dependent upon polymer solution properties such as concentration, solvation, and molecular weight, and the maximum drag reduction regime where changed in polymer solution parameters would no longer enhance drag reduction. He introduced the difference between solution and solvent slope of a plot between  $l/\sqrt{f}$  and  $Re\sqrt{f}$  called the slope increment,  $\delta$  and defined an intrinsic slope increment,  $\Pi$ . He related the intrinsic slope increment to the degree of polymerization,  $N$ , through equation (1.1) and (1.2) as,

$$\Pi = \delta / (c_p / M)^{\frac{1}{2}}, \quad (1.1)$$

$$\Pi = \kappa N^{\frac{3}{2}}, \quad (1.2)$$

where  $\kappa$  is proportionality constant apparently dependent upon the species skeletal structure,  $c_p$  is polymer concentration and  $M$  is molecular weight of polymer. Virk (1971) also discovered that the onset, which implied incipient interaction between the turbulent flow and the polymer molecule in solution depended on the polymer random coil size in solution and occurred when the ratio of polymer to turbulent length scales reaching to some characteristic value,  $R_g u_* / \nu = \Omega$ , where  $u_*$  was the critical friction velocity which defined as  $(\tau_* / \rho)^{1/2}$ ,  $R_g$  was radius of gyration,  $\nu$  was kinematic viscosity,  $\rho$  was density. Lumley (1973) observed that this mechanism was unlikely, since the smallest turbulence scale at onset was several orders of magnitude larger than the size of the polymer molecules. As an alternative, Lumley proposed that

onset occurred when the ratio of smallest flow time scale  $\nu/u_*^2$  to the polymer molecular relaxation time  $T_1$  is of order one.

A similar but more extensive experiment was completed by Berman and George (1974); the onset of drag reduction was observed in turbulent pipe flow for dilute solutions of Polyox WSR N-80 in three different glycerol-water solutions. The time scale onset hypothesis  $\rho u_*^2 [\eta]$  was found to be much more consistent with the data than the length scale onset hypothesis  $u_* / \nu$ .

Tiederman et al. (1985) studied drag reduction using flow visualization methods. They discovered that the drag reducing additive used (SEPARAN AP-237) had a direct effect on the velocity field in the buffer region and the linear sublayer appeared to have a passive role in the interaction of a turbulent wall layer.

Ryskin (1987) developed a theory considering the transient nature of the macromolecular extension. The basic idea of Lumley for increased viscosity was modified with a yo-yo model. In the yo-yo model, polymer molecules did not deform affinely with fluid, but unraveled in flow field. The central portion of the chain was straightened, while the end portion remained coiled. When the flow field became weak, the chain curled back into coil. The stretched yo-yo caused a dramatic increase in local solution viscosity and led to reduce drag. Using this proposed model, he calculated the effective viscosity enhancement in turbulence due to unraveling macromolecules by equation (1.3) and (1.4),

$$v_{urb} = v_s (1 + \zeta_{urb}), \quad (1.3)$$

$$\zeta_{urb} = 0.05 \alpha^3 N_A a^3 N^2 c_p / M_a, \quad (1.4)$$

where  $M_a$  is the molecular weight of a repeat unit,  $N$  is degree of polymerization,  $c_p$  is polymer concentration,  $N_A$  is Avogadro's number,  $a$  is length of a repeat unit and  $\alpha$  is the ratio of chain length to that of a fully extended chain. He also derived a relation between this viscosity enhancement and drag reduction parameter ( $\delta$ , Virk's slope increment) by equation (1.5) as,

$$\delta = 2(1 + \zeta_{urb})^{\frac{1}{2}} - 2. \quad (1.5)$$

De Gennes (1990) developed a cascade theory of drag reduction. He suggested several scenarios in which drag reduction may occur. The approach of de Gennes was based on the Kolmogorov energy cascade model of turbulence. In this model, each coil behaves like a small spring when deformed attains a certain elastic energy. When the elastic energy of the molecule is equal to the kinetic energy of the turbulent disturbance, the cascade is truncated. In the first scenario, polymer molecules are only partially stretched and interact with the smallest Kolmogorov eddies. In the second scenario, molecules are strongly stretched and would interact with larger scale disturbances. In this scenario, Lumley's model of increased viscosity might be dominant. In third scenario, the deformed coil length might become comparable to the eddy size. It was far more difficult to perceive what would happen at even smaller scales. In practice, the third scenario should occur only if turbulence even at very small scales was achieved, with extremely large Reynolds numbers.

Smith and Tiederman (1991) investigated the mechanism of drag reduction at a high concentration for a high molecular weight polymer to form a single and coherent unbroken thread injected along the centerline of a pipe. This study provided a strong evidence that the drag reduction from a polymer

thread was caused by the transport of very low concentrations of polymer from the thread to the near-wall region.

### **1.2.2 Effect of Molecular Structure on Drag Reduction Effectiveness**

#### **(a) Molecular Weight**

In early drag reduction studies, it was observed that drag reduction can be correlated with increasing molecular weight, but a quantitative understanding of the effect has not yet been obtained.

Virk (1971) correlated onset of drag reduction with radius of gyration, which was a function of molecular weight.

Hunston and Reishman (1975) studied the effects of polydispersity in drag reduction by testing two narrow molecular weight distribution polystyrene samples individually and in mixtures. The results indicated that the largest molecules in the distribution determined the value of the onset point and this value decreased with the increasing molecular weight.

Berman (1977) showed that the drag reduction trajectories for polydisperse polymers were a strong function of the molecular weight distribution.

Zakin et al. (1980) demonstrated the same enhancement of drag reduction by the high molecular weight fraction of polydisperse hydrocarbon-soluble polymers. They suggested that a minimum molecular weight was required before a polymer would effectively reduce drag. The minimum was defined in terms of  $M_c$ . They postulated that the ratio  $M/M_c$  must be greater than or equal to 50 for effective drag reduction to occur.

Gampert and Wagner (1985) found the significance of molecular weight distribution by studying of Polyacrylamide with molecular



weights ranging from 1 to  $9 \times 10^6$  g/mol; addition of a very small number of high molecular weight molecules to a lower molecular weight sample greatly enhanced drag reduction.

### **(b) Associations**

Dunlop and Cox (1977) studied the influence of molecular aggregates on drag reduction using Poly(ethylene oxide) and Polyacrylamide powder in a spinning disk apparatus and explained that the aggregated molecules were more effective drag reducer than the individual polymer molecules themselves.

McCormick et al. (1990) also obtained the similar results. Hydrophobically modified acrylamide copolymers, which exhibited intermolecular associates of increased hydrodynamic volume in dilute solution provided enhanced drag reduction. Polyampholytes which formed intramolecular ionic interactions (collapsed polymer chains), exhibited less effective drag reduction.

### **(c) Effect of Solvent**

Matjukhov et al. (1985) studied poly(ethylene oxide) of varying molecular weight and poly(acrylic acid) of a single molecular weight, and varied the  $R_g$  of poly(acrylic acid) by changing the solution pH. When drag reduction was plotted against  $R_g$  for the two polymers, both systems displayed increasing drag reduction with coil volume.

However expansion of coil volume by solvent also yielded a more rigid polymer structure. McCormick et al. (1990) found that acrylamide copolyelectrolytes did not always exhibit different drag reduction behavior in solvents of varying ionic strength. They suggested that chain-stiffening

intramolecular interactions present in these polyelectrolytes minimized solvent effects.

#### **(d) Effect of Polymer Concentration**

Rocheffort and Middleman (1987) studied the drag reduction behavior of xanthan gum under a variety of concentration, solvent, and shear conditions. They reported enhanced drag reduction for high concentrations ( $c_p > C_p^*$ ) where intermolecular interactions occurred.

Choi and Jhon (1996) demonstrated the linear correlation between polymer concentration and drag reduction for different molecular weight of Poly(ethylene oxide) and Polyisobutylene. The intrinsic concentration  $[c]$  was found to be very useful in normalizing the drag reduction data for different types of polymers, polymer molecular weights, concentrations and rotational disk velocities.

### **1.3 Objectives**

The aims of this research are divided into 3 main topics which are:

- 1 To find a correlation between drag reduction and molecular parameters.
- 2 To construct an appropriate scaling with molecular parameters.
- 3 To test Lumley's and de Gennes theories.

The scope of this work is divided into 3 parts which are:

- 1 Polymer characterization.
- 2 Drag reduction measurement. In this part, the effects of polymer concentrations, salt concentration and molecular weight were studied.
- 3 Scaling Analysis.