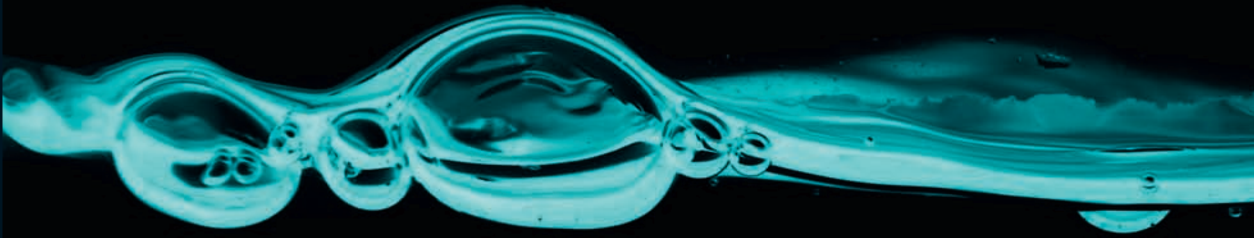
Turbulent Drag Reduction by Surfactant Additives



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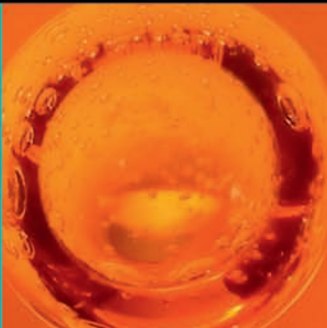

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Preface

The subject of this book is the presentation of detailed information on turbulence characteristics, theories, special techniques, and application issues for drag-reducing flows by surfactant additives, mainly based on state-of-the-art research results by the authors through experimental studies, numerical simulations, and theoretical analyses.

The phenomenon of turbulent drag reduction by additives has attracted the interest of researchers in the fields of chemical engineering, turbulence, fluid dynamics, rheology, petroleum, municipal and environmental engineering, and so on, for more than half a century. Turbulent drag reducing flows are especially complex due to the twofold effects of the turbulence itself and the drag reduction phenomenon induced by viscoelacticity. This complexity, combined with the great potential for drag reduction in industrial applications, has driven researchers to continuously approach the problem in an interdisciplinary fashion. Researchers are working to clarify the mechanism of drag reduction by additives, developing particular research approaches for this unique phenomenon, and exploring the characteristics of drag-reduced turbulent flows. Throughout this process, they have established increasingly exhaustive theoretical descriptions for the rheological properties of the fluid and drag reduction phenomenon of the flow, promoting the applications of this phenomenon in practical systems. This book provides important information on turbulent drag reduction by surfactant additives, particularly information covering introductions to experimental studies using laser techniques (laser Doppler velocimetry and particle image velocimetry), direct numerical simulations with special treatment of constitutive equations for viscoelastic fluid and numerical simulation algorithms, Brownian dynamic simulations of the rheological properties of surfactant solution with consideration of microstructures in the fluid, field tests and other issues associated with practical applications, and elucidations and summarizations of state-of-the-art results obtained from those studies. The contents of this book are the central concerns of the interdisciplinary community related to turbulent drag reduction by additives.

The authors do not claim that they have addressed in this book all the relevant issues of turbulent drag reduction by additives. Particularly unbounded flows with drag-reducing effects, drag-reducing polymer solution flows, the chemistry of drag-reducing additives, and so on were not mentioned or elaborated in detail in this book.

F.-C. Li composed Sections 1.1–1.3, 2.1, 2.2, 2.4, Chapter 3, Section 6.1 and the index. He also coordinated all procedures involved in the publication of this book. He would like to acknowledge the support from National Natural Science Foundation of China (NSFC; Grant No. 10872060 and 51076036) and Fundamental Research Funds for the Central Universities (Grant No. HIT.BRET1.2010008). For Chapter 4, he acknowledges the support from NSFC (Grant No. 50506017, 50876114 and 51134006). J.-J. Wei composed Sections 1.4, 2.3, Chapter 5 and Sections 6.2–6.4. He acknowledges the support from NSFC (Grant No. 51076124 and 50821064). Y. Kawaguchi contributed to modifying the organizations of the book and correcting the contents; he is also one of the key contributors of most of the studies involved in this book.

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1

Introduction

The problems associated with energy sources comprise one of the most important issues accompanying the development of economy all over the world. Energy saving itself has been treated as "the fifth biggest energy source," following coal, petroleum, natural gas, and electricity, by scientists in China [1]. Much more importantly, the utilization of energy saving, that is, "this fifth energy source," does not generate any emission of harmful gases such as CO_2, NO_x, and so on, but the reduction of equivalent amounts of emitted harmful gases can be obtained when gaining the energy source of "energy saving." In developing countries such as China, both the energy consumption for productions and the energy consumption for economic output are much higher than in developed countries. Therefore, the potential of energy saving is huge if energy-saving approaches can be executed in many aspects. Turbulent drag reduction (DR) by additives is one such energy-saving approach used in the long-distance transportation of liquid or in the circulation systems of liquid. It has bright application prospectives.

1.1 Background

The turbulent DR technique is of great significance for improving energy utilization efficiency, protecting the ecological environment, and so on. In recent years, the international and academic community has been attaching more and more importance to fundamental and applicable studies on turbulent DR. Every year, specific academic conferences associated with turbulent DR are held or symposiums are opened for topics related to turbulent DR in the international conferences (or congresses) on fluid dynamics or fluid engineering. Turbulent DR has been a hot research topic in the field of fluid mechanics and fluid engineering. As an important branch of the field of turbulent DR, "turbulent DR by additives" herein refers to the liquid transportation technique that adding a minute amount (generally at a level of

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Turbulent Drag Reduction by Surfactant Additives, First Edition. Feng-Chen Li, Bo Yu, Jin-Jia Wei
and Yasuo Kawaguchi.

parts per million, or ppm) of additives may reduce the frictional drag greatly. Compared with other turbulent DR techniques, the salient features of this approach are its most obvious turbulent drag-reducing effect, its price (the lowest), and ease of operation.

As early as 1931, Forrest and Grierson [2] found that flow resistance could be reduced at the same flow rate when pulp fibers floated in the water turbulent flow in a pipe. But this phenomenon did not receive enough attention. The first one who observed the turbulent DR phenomenon by polymer additives was the American scholar Mysels [3,4]. Mysels and his assistants found that after dissolving aluminum disoap into the gasoline flow in a pipe, the flow drag could be decreased at the same flow rate. However, due to the Second World War, this discovery wasn't published until 1949. In the first International Rheological Congress held in 1948 (its proceedings were published in 1949), the English scholar Toms reported the turbulent DR phenomenon of dilute polymer solution flow [5]. Hence, the turbulent DR phenomenon is often named the Toms effect. Since then, a large amount of investigations have been carried out all over the world on the mechanisms of turbulent DR and the real applications of the turbulent DR technique. The turbulent DR phenomenon has been well recognized, and significant progress for this technique has been made in real applications.

A typical example of a commercial application of the Toms effect was reported in 1982. Polymer additives were utilized to obtain the effects of reducing drag and increasing flow transportation efficiency in US Alaskan petroleum pipelines [6]. A relatively dense polymer solution was injected into the petroleum transportation piping system at four different pumping stations, which increased 25% of the flow rate of petroleum. For the Alaskan petroleum transportation piping system with an inner diameter of 48 in, the transportation capacity has been enlarged by 100 000 barrels. Presently, the turbulent drag-reducing effect of polymer additives has been widely used for long-distance petroleum transportation systems in order to increase their transportation capacity. However, exerted with some factors such as strong shear stress and high temperature, the flexible long-chain structure of polymer molecules, which plays the main role in the turbulent drag-reducing effect, can be destroyed. The destroyed structures cannot self-repair, resulting in the permanent loss of their drag-reducing effect. Therefore, polymer drag reducer is usually inapplicable for a liquid circulation system with a pump.

From about the 1970s, it was found that some kinds of surfactant additives also have the effect of reducing the frictional drag for turbulent flow. In later investigations, it was observed that the key factor for turbulent drag-reducing effect is the microstructures formed in the surfactant solution, that is, the so-called shear-induced structures (SIS). This is because after surfactant is dissolved into water, with the aid of a stabilizer (e.g., providing counterions for the cationic surfactant), the rod-like microstructures can be formed from the small molecules, which can further form the network microstructures under proper shear stress. Like the flexible long-chain microstructures in the polymer solution, the network microstructures formed in the surfactant solution can generate the so-called viscoelasticity rheological property, making the solution flow display non-Newtonian fluid characteristics. This kind of fluid is thus named “viscoelastic fluid.” Due to the viscoelasticity generated in the solution flow, which then interacts with turbulence, the turbulent drag-reducing effect is brought forth. Since the microstructures in solution are essentially formed with small molecular units of surfactant, when exerted with strong shear stress (e.g., when passing through the centrifugal pump in the liquid-recirculating system), the network microstructures in the solution can also be disassociated and destroyed. But after the disappearance of the strong shear, the microstructures can be automatically reformed within a short time in the order of seconds. This indicates that the microstructures in surfactant solution have self-reparability, and so does the turbulent drag-reducing effect. Based on this phenomenon, in a real liquid recirculation system with a pump, surfactant drag reducer is more appropriate to use for the purposes of reducing the flow friction drag in the long term and saving the pumping power. However, surfactant drag reducer also has an effective temperature range. Out of this temperature range, it loses its drag-reducing effect only temporarily. Once the fluid temperature returns back to its effective range, the drag-reducing ability can be automatically recovered.

The largest potential application area in industry and daily life for the turbulent drag-reducing effect of surfactant additives is a district heating and cooling recirculation system. There have been successful application examples for this case. For example, in July 2002, surfactant drag reducer was utilized in a central water-cooled air-conditioning system with 60 m^3 capacity in the Tochigi factory of the Sony Corporation, Japan. During the first year, the average DR reached 57%. The saved electricity used for driving the pump was 0.61 million kWh. Calculated with the local price per unit of electricity as 12 yen/kWh, the saved money for one year was 7.32 million yen (about 0.55 million RMB) [7]. The expenses for the first injection were, however, only 0.65 million yen (about 50 000 RMB). Presently, this water-cooled air-conditioning system in Sony Corporation’s Tochigi factory is still operating normally. Although periodically, due to leakage of the system, an additional injection of additive is needed to keep the system’s concentration of DR, and considering the effective lifetime of the additive itself and other cost factors, the cost savings from reducing the pumping power are much larger than the consumption cost of additives. The authors of this book performed, for the first time in China, a field test of drag-reducing effect by surfactant additives in a real district heating system in December 2007 [8]. The expected energy-saving effect has been obtained. At the same time, some practical problems to be solved have also been found. This application test has established a foundation for spreading out the real applications of the turbulent drag reduction technique by additives in a district heating system. Details of this application test will be described in Chapter 6.

This book mainly summarizes and generalizes turbulent drag reduction theories and techniques systematically, covering several aspects including the characteristics of surfactant drag reducers, mechanisms of turbulent DR, characteristics of the convective heat transfer of turbulent drag-reducing flows, practical application studies, and so on, combining this with research conducted by the authors for many years. It is aiming at establishing a relatively complete system for the field of turbulent DR by surfactant additives.

1.2 Surfactant Solution

Whether or not the surfactant solution displays drag-reducing effect depends on whether or not the shear-induced rod-like and then network microstructures can be formed. Such microstructures are essentially micelles composed of small surfactant molecules. The characteristics of microstructures in a solution of surfactant drag reducers have already been depicted in detail in several review papers [9–11]. The surfactant molecule has its hydrophobic “tail” and hydrophilic “head” spontaneously. In general, the hydrophobic tail is a long chain of alkyl bases, while the hydrophilic head is ionizable, being polar or polarizable. When surfactant molecules are in an aqueous environment, the hydrophilic heads prefer to stay in the water phase while the hydrophobic tails try to leave the water phase. There are only two choices for preventing the hydrophobic tails from contacting the water phase. One is that the hydrophobic tails orient to the nonpolar phase, for example the gas phase, nonpolar solid phase, or liquid phase with hydrophobicity. The other is that the surfactant molecule groups realign and reassemble to form micelles, and so the nonpolar parts (hydrophobic tails) of molecules are concentrated in the center while the polar parts (hydrophilic heads) of molecules are concentrated at the surface and in contact with the water phase. Figure 1.1 schematically shows the formed microstructures.

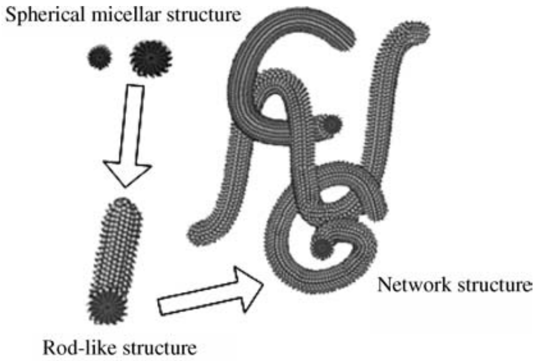

Figure 1.1 Schematics of microstructures formed in the surfactant solution. Surfactant molecules assemble to form spherical and rod-like micelles, and then form network structures under shear in the flow

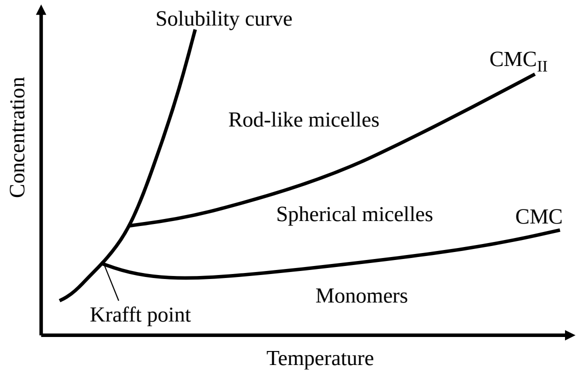

Figure 1.2 Schematic phase diagram for surfactant solution [9]

The ability to form micelle structures is the typical feature that the surfactant solution displays after it exceeds the critical micelle concentration (CMC). Above the CMC, the surfactant monomer molecules and the formed micelle structures are always in a thermodynamic equilibrium state. Figure 1.2 schematically shows a simplified phase diagram [9]. Based on Figure 1.2, Zakin *et al.* made the following summarization in reference [9]. The surfactant in its solution will be partially in the crystal or gel state when the temperature is lower than the so-called Krafft point. When the temperature is higher than the Krafft point, surfactant molecules will aggregate and form spherical micelles at concentrations over the CMC; with further increase of the solution concentration to be over the CMC$_{II}$, surfactants become rod-like micelles. Figure 1.2 also shows that the CMC of aqueous solution of surfactant has nearly no change in temperature, whereas CMC$_{II}$ enlarges with increases in temperature. Per the hydrophilic or polar head of the surfactant molecule, it can be categorized into two groups: ionic and nonionic surfactants, respectively. The former can be further categorized into two types: anionic and cationic surfactants. The latter can be further categorized into three groups: zwitterionic, semipolar, and single-bond surfactants [12].

At the early stage, anionic and nonionic surfactants are considered to be turbulent drag-reducing candidates. However, in experimental studies on mechanisms of turbulent drag-reducing flows up to the present, overwhelmingly researchers have been using cationic surfactant, with the addition of other additives, as turbulent drag reducers. Since a cationic surfactant molecule usually involves tetra-ammonium and its anaerobic degradation is very slow, some environmental supervising organizations have begun to appreciate the negative side of using cationic surfactant in district heating and cooling systems as a turbulent drag reducer. Therefore, in recent decades, researchers have made efforts to exploit some representative surfactant drag reducers and found that the zwitterionic and amphoteric surfactants are more appropriate for use in district heating and cooling systems for energy-saving purposes. In reference [10], different kinds of surfactants suitable for turbulent drag reduction have been reviewed and summarized.

1.2.1 Anionic Surfactant

In earlier experimental studies on turbulent drag-reducing flows, several anionic surfactants were used as drag reducers. For example, Pilpel investigated the viscoelastic rheological properties of sodium oleate, sodium chloride, and C_6–C_{12} alcohols and found that the salt and the alcohols had the ability to help the micelles formed by surfactant molecules to change from spherical structures to long and cylindrical ones [13]. Although Pilpel did not measure the turbulent DR of the solution flow of his investigated surfactants, the existence of viscoelasticity itself had proved that this kind of fluid can be used as a turbulent drag reducer. In 1967, Savins reported the earliest experimental results about turbulent DR using anionic surfactant [14]. He used an aqueous solution of 10% potassium chloride dissolved with 0.2% sodium oleate as working fluid and obtained an 82% turbulent DR rate. Tsujii *et al.* reported that partially neutralized alkenylsuccinates solution also displayed strong viscoelasticity and so can also be used as a turbulent drag reducer [15]. But the optimum viscoelastic behaviors of this surfactant solution were at a pH of about 6; hence, it was basically precluded from use in steel tubes for turbulent DR due to its strong corrosion rate at that acidic state.

1.2.2 Cationic Surfactant

When used as a turbulent drag reducer, the cationic surfactant usually needs to be aided by additional additives for providing counterions. The paper published in 1967 by White was one of the earliest reports on turbulent DR flow of aqueous solution of cationic surfactant [16]. The drag-reducing fluid used in this study was 508 ppm cetyltrimethylammonium bromide and 1-naphthol. At that time, White already observed an important phenomenon: Turbulent DR stops at a critical Reynolds number at a certain concentration of surfactant solution and a certain pipe diameter. This phenomenon was clarified afterward: Because of the microstructures in the surfactant solution responsible for generating viscoelasticity, the turbulent drag-reducing effect will be destroyed at a critical Reynolds number (critical shear rate), which makes the solution flow lose its viscoelasticity and drag-reducing ability. This phenomenon has recurred in a later large amount of experimental studies on turbulent drag-reducing surfactant solution flows, including those done by the present authors [17–20]. This is of particular importance in determining the solution concentration of drag reducer and other related flow parameters (pipe diameter, flow speed, etc.) when turbulent drag-reducing effect is applied to real systems. An important advance in the turbulent DR of cationic surfactant was to use aromatic compounds instead of 1-naphthol as the additions to tetra-ammonium surfactant solutions. For example, Gravsholt reported in his paper published in 1976 that aqueous solution of cetyltrimethylammonium salicylate showed viscoelastic rheological properties at a concentration as low as 67 ppm [21], indicating that this kind of fluid has turbulent drag-reducing ability. In later experiments on turbulent drag-reducing flows of cationic surfactant solution, aromatic compounds were then mostly utilized as additional additives to provide counterions; for example, in a series of experimental studies on turbulent DR by additives performed by the present authors, sodium salicylate (NaSal) was chosen to supply counterions for cetyltrimethylammonium chloride (CTAC) surfactant, and both were used to make aqueous solution with turbulent drag-reducing effect [17–20].

1.2.3 Nonionic Surfactant

In 1972, Zakin and Chiang for the first time reported the turbulent DR characteristics of a nonionic surfactant solution flow [22]. They dissolved the ethoxylated mixture of C_{12} and C_{14} alcohols into water and obtained an aqueous solution with 1% concentration. With the further addition of sodium sulfate, they found that, at a constant temperature of 30°C, the flow of this solution showed turbulent DR phenomena after the added salt concentration was larger than 0.1 M, and the turbulent drag-reducing effect was best when the salt concentration reached 0.175 M. This kind of nonionic surfactant belongs to the class of hydroxyethyl fatty alcohol ethoxylates. Another group of nonionic surfactant with turbulent drag-reducing effect is hydroxyethyl fatty acid amide ethoxylates. In the compound of fatty acid mono-ethanolamide hydroxyethyl, when the degree of ethoxylation reaches a certain level, its aqueous solution flow can display turbulent DR, and the effective temperature of its turbulent drag-reducing effect can even extend to below 0°C. Also, a mixture of the above-mentioned two types of nonionic surfactants can possess excellent turbulent drag-reducing effects [10].

1.2.4 Amphoteric Surfactant

"Amphoteric surfactant" refers to those surfactants with both acidity and alkalinity. Reactions between alkane epoxide and sodium sarcosinate may generate amphoteric surfactant. When the aqueous solution of such a product is at a state of $\mathrm{pH} < 9$, it is found to be viscoelastic, implying that its flow may display a turbulent drag-reducing effect; for example, Harwigsson and Hellsten obtained turbulent DR in their experimental study on aqueous solution flow of amphoteric surfactant [23].

1.2.5 Zwitterionic Surfactant

Since the 2-hydroxyalkyl sarcosinates display viscoelasticity and turbulent drag-reducing ability only in the zwitterionic structure, researchers were then reminded to investigate and develop zwitterionic surfactant drag reducers. Saul *et al.* studied a mixture of hexadecyl dimethyl ammoniopropane sulfonate and sodium dodecyl sulfate and found that their aqueous solution showed obvious viscoelasticity when the molar ratio of these two chemicals was 1.7:1 [24]. Tsuji *et al.* [25] and Iwasaki *et al.* [26] also investigated viscoelastic properties of the mixture of different kinds of zwitterionic surfactants and anionic surfactants, respectively. Harwigsson and Hellsten [23] and Myska and Chara [27] measured the turbulent DR characteristics of an aqueous solution flow of N-alkylbetaine and sodium dodecyl benzene sulfonate at a molar ratio of 4:1 in their experimental studies. In the later studies, it was found that both alkyl sulfates and alkyl polyglycol ether sulfates, together with N-alkylbetaine, can be used as anionic surfactant drag reducers [10].

1.3 Mechanism and Theory of Drag Reduction by Surfactant Additives

Although the application study, or industrial application of chemical drag reducers (herein particularly high-polymer drag reducers and surfactant drag reducers) has been considerably explored and some influencing factors on DR have been understood, the mechanism of turbulent DR caused by the addition of drag reducers has actually not been so clear up to now due to the nonthorough understanding of turbulence itself. Some hypotheses and models have been proposed for the DR mechanism. But there is no single theory that can fully explain all the experimental phenomena appearing in turbulent drag-reducing flows by additives, so further studies are needed on the mechanism of turbulent DR. Explanations about the turbulent DR mechanism that provide the viewpoint of the physics of turbulence apply to both polymer and surfactant drag reducers. Therefore, the statements below will not be classified based on categorizations of chemical drag reducers, though some turbulent DR mechanisms have been proposed for polymers. When qualitatively explaining the mechanisms of turbulent DR from the viewpoint of microstructures in drag reducer solution, however, it is different for polymer and surfactant drag reducers. In this book, only surfactant drag reducers will be mentioned in this respect.

1.3.1 Explanations of the Turbulent DR Mechanism from the Viewpoint of Microstructures

The microstructures in drag-reducing surfactant solutions might be worm-like micelles only, network structures formed by worm-like micelles with branches or vesicular structures. Each microstructure with a different form may impart different rheological properties into the solution and result in different extents of turbulent drag-reducing effect. Zakin *et al.* [11] classified surfactant drag reducers into three categories according to the above-mentioned three possible microstructure forms at the static state, and correlated the turbulent drag-reducing effect with rheological properties.

At the static state, worm-like micellar structures can be formed in most of the surfactant drag reducer solutions. Exerted with shear stress, the worm-like micellar structures are apt to align with the flow direction, resulting in the occurrence of turbulent drag-reducing effect and a larger critical shear stress or critical Reynolds number (the turbulent DR rate increases with the increase of the flow Reynolds number at first and reaches the maximum level at the critical Reynolds number; after that, the DR rate decreases with the further increase of the flow Reynolds number until it reaches zero). Surfactant drag reducer solutions with inner worm-like micellar structures usually display obvious rheological properties, such as relatively large zero-shear viscosity, shear thinning properties (the shear viscosity decreases with the increase of shear rate), large viscoelasticity, a rapid rebounding phenomenon after the cease of rotation driving, a large ratio of extensional viscosity to shear viscosity (normally larger than 100), and so on.

In some turbulent drag-reducing fluid systems, worm-like micellar structures with branches, that is, worm-like structures with three branches joined together, can be formed. When the energy necessary for forming the semispherical head of a micellar structure becomes high enough to form a saddle-shaped branch joint, the branch structure can thus be generated. Comparing this with the former case, the number of ends of the worm-like micellar microstructures in the solution decreases. It has been observed from experiments that the joints of branches can freely move along the axial direction of the worm-like micellar structure. Hence, when exerted by shear, the shear stress can be immediately released, and so the shear viscosity of solution decreases [28]. The turbulent drag-reducing effect is also obvious for the surfactant solution flow with branched microstructures. But its maximum DR rate is smaller compared with that of nonbranched microstructures, while its critical Reynolds number is larger. Moreover, the complicated behavior of the free movement of the branch joints along the axial direction of micellar structures also induces much more complex rheological properties for such surfactant solutions.

There are also some kinds of surfactant solutions in which vesicular or crystal structures can be formed at the static state. In turbulent flows, when the exerted shear rate exceeds the critical value, these structures can change to worm-like micellar structures and make the surfactant solution flow display the turbulent DR phenomenon. This transition process of surfactant solution, from a state without drag-reducing effect to one with drag-reducing effect, is analogous to the inception process of DR in a turbulent flow of surfactant solution. The difference is that the inception of DR cannot be observed when the critical shear rate for the change of microstructures in surfactant solution is smaller than the critical wall shear for the laminar-to-turbulent transition. For the normal rheology measurements, if the applied shear rate by rheometer is usually not large enough to reach the critical shear rate for the change of microstructures in surfactant solution, the measured solution may display Newtonian fluid properties, that is, a relatively small shear viscosity, no generation of SIS, the first normal stress difference is 0, a relatively small ratio of extensional viscosity to shear viscosity, and so on [29].

1.3.2 Explanations of the Turbulent DR Mechanism from the Viewpoint of the Physics of Turbulence

Several typical theories for turbulent DR published up to the present are summarized below.

1.3.2.1 Pseudo-plasticity

Early on, Toms [5] proposed that polymer solutions have pseudo-plasticity. The larger the shear rate is, the smaller the apparent viscosity of a polymer solution becomes. Hence, when a solution flows in a pipe, its apparent viscosity decreases with proximity to the wall due to the local large shear rate, and so the flow resistance is decreased. From then on, through a large amount of experimental and theoretical studies, it has been shown that the mechanisms of turbulent DR by polymer additives are much more complicated, and this theory is currently denied.

1.3.2.2 Effective Slip

Virk proposed the elastic sublayer model [30] based on velocity measurement results for pipe flows. This model states that an elastic sublayer is formed in between the laminar substrate layer and turbulent bulk region with the addition of polymer. The velocity gradient in this layer is large, and so the velocity profile in the turbulent bulk region is elevated to some distance (i.e., the increment of velocity level in the turbulent bulk region) as compared with that of Newtonian fluid flows. This distance or increment of velocity level was then named “effective slip” (as schematically shown in Figure 1.3). Since the velocity in the turbulent bulk region is increased, the flow rate is thus increased at the same flow conditions (the same driving power herein), indicating the occurrence of DR. Here, the elastic sublayer is the region where polymer molecules react with the flow, that is, the region where DR occurs.

According to Virk’s hypothesis, the thickness of the elastic sublayer is increased with the increase of drag reducer solution concentration. When the elastic sublayer is extended to the pipe axis, the DR rate reaches its maximum value. This hypothesis was successful in explaining the phenomenon of maximum DR and the diameter effect. Based on Virk’s hypothesis, the concentrations corresponding to the maximum DR and maximum heat transfer reduction (HTR), respectively, should be the same; however, the experimental results showed that they were different.

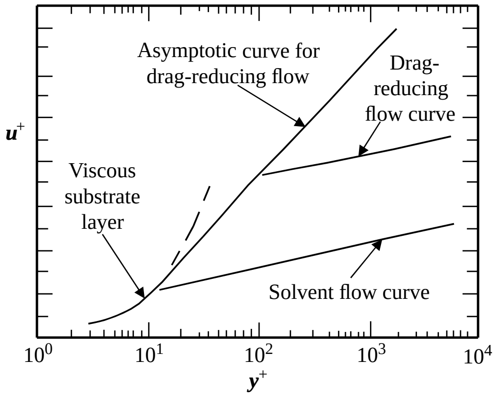

Figure 1.3 Model of elastic sublayer [30]

1.3.2.3 Suppression of Turbulent Fluctuations

Polymer and surfactant drag reducers have a drag-reducing effect only when their solution flows are at a turbulent state. Based on this fact, the mechanism for the occurrence of DR has been proposed as follows: The drag reducer suppresses the generation of turbulent vortices, resulting in the decrease of turbulent fluctuation intensity and turbulent kinetic energy, and finally inducing the occurrence of a turbulent DR phenomenon. In connection with the correctness of this proposal, there have been two different statements. In all the reported studies on turbulent drag-reducing flow by additives, it has been concluded that the turbulent intensity of the velocity component in the wall–normal direction is depressed, and some researchers also reported that the turbulent intensity in the streamwise direction is enhanced. The latter statement was based on comparisons between nondimensionalized streamwise velocity fluctuation intensities in Newtonian fluid turbulent flow and turbulent drag-reducing flow [31–34]. Note here that the nondimensionalization mentioned here is based on the friction velocity at its individual flow condition. Li *et al.* analyzed this argument in their paper [17] and thought that it was not so appropriate to use the friction velocity at the individual flow condition as the nondimensionalization parameter, and posited that one should use the bulk velocity (which also reflects the flow Reynolds number) at the individual flow condition. When Li *et al.* re-examined all the reported results using bulk velocity as the nondimensionalization parameter, they found that turbulence intensities in all directions are decreased in turbulent drag-reducing flows. Therefore, the viewpoint of "suppression of turbulent fluctuations" can be thought to be correct in qualitatively explaining the turbulent DR phenomenon. However, it is necessary to point out that the effect of turbulent drag reducers not only depresses the intensities of turbulent fluctuations but also modifies the turbulence structures [19,20,35–37].

1.3.2.4 Decoupling of Turbulent Fluctuations

It has been indicated from many studies that the effect of drag reducer on turbulent flows also appears as the decreased correlation between the axial and radial fluctuations. This effect is named "decoupling." The decoupling of turbulent fluctuations can decrease the Reynolds stress. According to the quantitative relationship between Reynolds shear stress and the turbulent contribution to frictional drag coefficient deduced by Fukagata *et al.* (i.e., the FIK equation) [38], a decrease of Reynolds shear stress directly results in a decrease of the friction factor of turbulent flow, and so turbulent DR. Actually, a decrease of Reynolds stress is caused by twofold effects, that is, the decoupling of turbulent fluctuations and turbulence suppression [17,33,39–41]. This postulation is also correct qualitatively.

1.3.2.5 Viscoelasticity

All polymer and surfactant solutions with turbulent drag-reducing effects display viscoelastic rheological properties. With the development of viscoelastic fluid mechanics, some researchers proposed that the drag-reducing effect of polymer and surfactant solutions is the result of the interaction between viscoelasticity and turbulent vortices. The microstructures (polymer molecule chains or network structures in surfactant solution) in the drag reducer solution at a high-shear-rate region can absorb the turbulent kinetic energy of small vortices within the energy-containing range and store it. When the microstructures are diffused or convected to a low-shear-rate region, they will be relaxed to a random threadlike entanglement and the stored energy will be released to the low-wave-number vortices (large-scaled vortices) in the form of elastic stress waves, which greatly decreases the dissipation of turbulent kinetic energy and induces turbulent DR.

The viscoelastic theory for the mechanism of turbulent DR by additives was proposed by DeGennes [42]. The viscoelasticity postulation not only explains the turbulent DR phenomenon in many polymer and surfactant solution flows with viscoelasticity, but also estimates the DR rate quantitatively. It is also a powerful tool for studying the mechanism of turbulent DR from the viewpoint of the physics of turbulence and developing new quantitative analysis theories for turbulent drag-reducing flows. However, this postulation was challenged by the "anisotropic stresses" hypothesis proposed by Toonder [43].

1.3.2.6 Anisotropic Stresses

The anisotropic stresses hypothesis posited that the main reason for turbulent DR by polymer additives is the anisotropy of stresses induced by the re-orientation of polymer molecules due to stretch in the turbulent boundary layer. In order to verify this opinion, Toonder [43] measured the turbulence statistics and spectra in the near-wall region of turbulent drag-reducing flow by means of laser Doppler velocimetry, through which two models were established. One is the viscous anisotropic stress (VA) model, and the other is the viscoelastic anisotropic stress (VEA) model. Direct numerical simulations were also performed by Toonder to obtain the influence of polymer additives on the near-wall stress tensor. These indicated that the DNS results using the VA model were in good agreement with the experimental data, whereas when using the VEA model with the introduction of elasticity of the polymer molecule, contrarily, the DNS results differed from the experiments quite a bit. Those investigation results re-inforced the anisotropic stresses hypothesis by Toonder, and challenged the conventional visco-elasticity hypothesis.

Bewersdoff *et al.* [44] utilized the small-angle neutron-scattering technique to observe the deformation characteristics of micelles formed in a heavy water solution of surfactant. It was found that the micelle was elliptically spherical in still solution and the longer axis is random in its direction; when the solution flowed in a turbulent flow state, the orientation of longer axes of elliptical spheres became directional. This conclusion is in accordance with the hypothesis of anisotropic stresses. Presently, the conclusions have not yet been finalized in this research area, calling for further studies to clarify whether the viscoelasticity hypothesis or the anisotropic stresses hypothesis is correct.

1.3.2.7 Stabilization of Turbulent Vortices

In turbulent flows, the principal portion of flow resistance stems from turbulent vortices with random sizes and random motions. Although turbulent vortices are randomly generated, they are always decomposed into smaller and smaller vortices (by the cascading of turbulent kinetic energy) until the smallest vortex (a Kolmogorov-scaled vortex) corresponds to the flow Reynolds number, and finally the kinetic energy of the vortex is dissipated by fluid viscosity.

This hypothesis points out that the existence of drag reducer makes the turbulent kinetic energy cascading process change a lot. When the Reynolds stress in the turbulent fluid motions is on a similar order as the elastic stress in drag reducer solution, the cascading process will be truncated and energy dissipation cannot reach the final state, resulting in a decrease of flow resistance [45–47].

1.3.2.8 Random Renewal of Fluids at the Wall Surface

The boundary layer in wall-bounded turbulent flows can be divided into three layers: the viscous substrate layer, buffer layer, and turbulent core region. The viscous substrate is a thin layer closest to the wall surface in which intermittent turbulent fluctuations exist. If the momentum transport boundary layer of wall-bounded turbulent flow is assumed to be composed of a series of momentum transport patches, then these patches are randomly renewed by the fluid elements coming from the turbulent core region, and decompose into new fluid elements to form turbulent eddies. The turbulent energy cascading process thus occurs, and the momentum transport and energy diffusion can be accomplished.

On the basis of turbulent random theory and the wall-surface renewal theory by Dankwests [48], this model posits that, after adding drag reducer into the Newtonian turbulent flow, the drag reducer molecules can form a liquid film on the surface of the pipe wall; the fluid elements in the proximity of the wall are thus difficult to renew, hindering the turbulent eddies being formed and then resulting in the decrease of energy dissipation and so turbulent DR.

In recent years, Li *et al.* [20,49] carried out a series of experimental studies by means of particle image velocimetry. They indirectly measured the occurrence frequency and strength of the near-wall coherent structures in turbulent channel flows (Newtonian fluid turbulent flows and turbulent drag-reducing flows of surfactant solution). The near-wall turbulent coherent structures were then treated as energy quanta and directly contributed to the turbulent portion of frictional drag. Based on this conjecture, the researchers concluded that the turbulent contribution to the friction factor is linearly proportional to the occurrence frequency and strength of the turbulent bursting events (coherent structures). As compared with Newtonian fluid turbulent flows, the occurrence frequency and strength of the near-wall coherent structures are greatly decreased, which directly induces significant decrease of the frictional drag coefficient, that is, the occurrence of turbulent DR.

1.3.2.9 Others

From the viewpoint of molecule deformation, Keyes and Abernathy [50] analyzed the evolution process of vortex tubes in a shear flow. Two effects can be brought about from the deformation motion of large molecules: inhibition of the formation of vortex tubes and inhibition of the growth of the formed vortex tubes.The combined effect of these two aspects is to reduce the bursting event frequency in the turbulent flow of polymer dilute solution, inducing the turbulent DR.

1.4 Application Techniques of Drag Reduction by Surfactant Additives

Although high drag-reducing performance for surfactant drag-reducing flow has been obtained in experimental facilities, some problems must be solved before large-scale industrial applications will be possible. These problems include the scale-up method caused by the pipe diameter effect, heat transfer reduction of surfactant solution, separation and recovery of surfactant and counterion, stability and toxic effects of surfactant, long-term effectiveness and corrosion of the drag reduction system, and so on.

1.4.1 Heat Transfer Reduction of Surfactant Drag-reducing Flow

Surfactant can reduce the frictional drag of the flow by suppressing the turbulence, and thus lead to a large reduction of the heat transfer coefficient. Under some conditions, the heat transfer reduction is much larger than the drag reduction, deteriorating the heat transfer performance of heat exchangers. Although the addition of surfactant can reduce the pump energy consumption, it makes the heat exchanger perform heat transfer very badly, leading to low thermal efficiency of the system, and thus limiting the application of drag reduction technology to the heat transfer field. Therefore, it is necessary to develop an effective method and device with low pressure loss to solve the heat transfer reduction problem.

1.4.2 Diameter Effect of Surfactant Drag-reducing Flow

Even the same surfactant solution may have different drag-reducing effects in pipelines with different diameters, indicating that the friction factor of the drag-reducing flow is related not only to the Reynolds number but also to the pipe diameter. This indicates that the drag reduction data obtained in small-sized pipes cannot be used directly for the application of surfactant drag reduction to real pipe systems. Therefore, it is necessary to develop a universal scale-up method.

1.4.3 Toxic Effect of Cationic Surfactant Solution

To avoid environmental pollution in the large-scale application of surfactant drag reduction, the surfactant solution should be processed by separating the surfactant and counterion from the solution before it is discharged to the environment. Therefore, it is necessary to develop a separation and recovery technology for surfactants. The toxicity of nonionic surfactants is relatively low compared with that of cationic surfactants, and it can be biodegraded rapidly.

1.4.4 Chemical Stability of Surfactant Solution

It has been observed from experiments that drag reduction ability will be weakened after a certain running period of the surfactant drag-reducing flow, and then the drag reduction ability will disappear completely. It was found that surfactant solutions of Harbon G and Ethoquad T/13-50/Nasal have drag reduction