Introduction

It is well known that dissolution of certain high molecular weight polymers or cationic surfactants in channel/pipe flows can significantly modify Newtonian turbulence characteristics, leading to dramatic reduction in friction factors (Lumley 1969; Virk 1975; Sureshkumar et al. 1997; Dimitropoulos et al. 1998; White 1967; Elson and Garside 1983; Olendorf et al. 1986; Rose and Foster 1989; Smith et al. 1994; Myska et al. 1996; Zakin et al. 1996; Lu et al. 1998; Usui et al. 1998; Lin et al. 2000 and references therein). The dynamic interactions between turbulence and polymer chain conformation play a significant role in promoting drag reduction. Specifically, even dilute solutions of long chain polymers exhibit viscoelastic behavior with extensional viscosity (or Trouton ratio) much larger than that of the Newtonian solvent, thereby inhibiting dynamical events that lead to the production of turbulent kinetic energy (Lumley 1969; Sureshkumar et al. 1997; Dimitropoulos et al. 1998). Recognition of this has also resulted in investigations on the use of polymers in more complex processing flows such as single and multiphase flows in stirred tanks, showing that dissolution of long
chain polymer molecules leads to significant reduction in the power requirements (Quraishi et al. 1976).

One of the major technological impediments in the use of polymeric additives for drag reduction applications in chemical processing flows is polymer degradation, especially in flows that involve moving machine parts and/or particulates. Recent investigations have shown that certain cationic surfactant additives can significantly reduce turbulent friction in pipe/channel flows (White 1967; Elson and Garside 1983; Olendorf et al. 1986; Rose and Foster 1989; Smith et al. 1994; Myska et al. 1996; Lu et al. 1998; Usui et al. 1998; Lin et al. 2000). Drag reduction capability of surfactants has been attributed to the formation of flow-induced elongated micelle structures that render the fluid viscoelastic. Since the formation of these structures is a reversible process, surfactants have the potential to be used for drag reduction applications in processing flows. However, interaction between micelles and turbulence is a complex phenomenon especially sensitive to the chemical environment, concentration, diffusion effects, and potential for phase separation. Recently, Lu et al. (1998) presented a systematic investigation of drag reduction in turbulent pipe flows caused by cetyltrimethyl-ammonium chloride (CTAC) in presence of 2-, 3-, or 4-chloro benzoic acid (CB) counter-ions. Their investigations showed that drag reduction observed depended strongly on the type of counter-ion used, temperature of the system, and the average wall shear rate. The relatively large concentration of CTAC used in their studies (≈ 5 mmol/l), allowed for rheological characterization of linear and nonlinear viscoelastic properties. It was shown that the alignment of chlorine in 3- and 4-CB towards the hydrocarbon core allows for the formation of stable elongated micelles that induce viscoelastic effects. Similar sensitivity to the counter ion type and the orientation of the substituent chemical groups has been observed with other surfactants as well (Elson and Garside 1983; Olendorf et al. 1986; Rose and Foster 1989; Smith et al. 1994; Myska et al. 1996; Lu et al. 1998; Usui et al. 1998; Lin et al. 2000).

Due to reversibility of micelle formation in a wide range of temperatures, surfactants could be used for drag reduction and for manipulation of mixing patterns in more complex, processing-type flows. The ability to manipulate structure formation by varying the chemical environment can also be used advantageously. However, this requires the understanding of mechanisms that couple the fluid motion, micelle formation, and surfactant concentration. For instance, in stronger flows, i.e., flows in which the mean rate of deformation has shear and extensional components, stable elongated microstructures could form at concentrations much lower than that reported for shear flows. Moreover, micelles formation and their interaction with turbulence could be significantly different in the presence of a mean elongational velocity gradient (Walker et al. 1996). Furthermore, the additive could change the qualitative features of the mean flow itself. Our present understanding of these issues is very limited. In this work we investigate the influence of CTAC surfactant additives in complex swirling flows in closed systems where the mean velocity fields are fully three-dimensional. It is our objective to identify the key changes in the mean flow, turbulence intensity, and mixing patterns that are caused by the additives and to probe the influence of additive concentration and flow type on the observed changes. These observations are used to develop plausible mechanisms and models that could provide guidelines for the use of such additives in process engineering. This paper is organized as follows. The experimental system is illustrated in Sect. 2. In Sect. 3 we discuss the experimental results. In Sect. 4 we present our concluding remarks.

**Details of experimental setup**

Figure 1 illustrates the flow geometry. The flows are generated by the rotation of either a circular disk or a circular disk equipped with N square-shaped vertical blades (N = 2, 3, 4, or 6) in a cylindrical vessel. Baffles were not used in the case of disk impeller.