Experimental Study on Drag Reduction by Surfactant Additives in Turbulent Pipe Flow

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Many additives, surfactants and polymers are considered as excellent drag reducing agents. In this work we study the aqueous solution of Cetyltrimethyl ammonium chloride (C16H33N(CH3)3Cl) and sodium salicylate in turbulent pipe flow. Drag reduction experiments were carried out for different temperatures and different pipe diameters. At the same time measurements on the spatial velocity distribution of the surfactant solution were carried out using particle image velocimetry (PIV).

Viele Zusatzstoffe, wie Tenside und Polymere, sind als hervorragende Mittel für die Schleppspannungsverminderung bekannt. In dieser Studie wird die Auswirkung der wässrigen Lösung, bestehend aus Hexadecyl-trimethylammoniumchlorid (C16H33N(CH3)3Cl) und Sodium Salicylat, bei turbulenter Rohrströmung untersucht. Experimentelle Versuche zur Schleppspannungsverminderung wurden für verschiedene Temperaturen und Rohrdurchmesser durchgeführt. Zeitgleich wurden Messungen zur räumlichen Geschwindigkeitsverteilung an der Tensidströmung mit der Hilfe eines PIV-Systems (particle image velocimetry) durchgeführt.

Keywords: surfactant solution, drag reducing fluid, turbulence structure, pipe flow, PIV

1 Introduction

Dissolving small amounts of additives in water, such as polymers or surfactants (surface active agents), can reduce frictional drag in pipe or channel flow by 70%-80%. Surfactant solutions are less affected by mechanical degradation (Gyr and Bewersdorff., 1995). Literature research (Li and al., 2005) resulted that even low concentrations of (25ppm) CTAC exhibit effective drag-reduction. Therefore, surfactants are now being considered as particle drag reduction additives.

The aim of this work is to study the effect of an aqueous surfactant solution (CTAC/NaSal at 75ppm) on drag reduction and on the flow pattern in the temperature range of 10 to 40°C.

The measurement set-up used in the pressure drop measurement was developed in our laboratory. A PIV system is used in order to analysis the internal flow properties.

2 Measurement set-up

The surfactant used in the present study was cetyltrimethyl ammonium chloride ($C_{16}H_{33}N(CH_3)_3Cl$) dissolved in tap water which is belonging to the cationic group of surfactants and is less affected by metallic ions in water. Sodium salicylate (NaSal) was added to provide counter ions with a weight concentration equivalent to that of CTAC (Li and al., 2005). For the present study we use CTAC/NaSal at a concentration of 75 ppm.

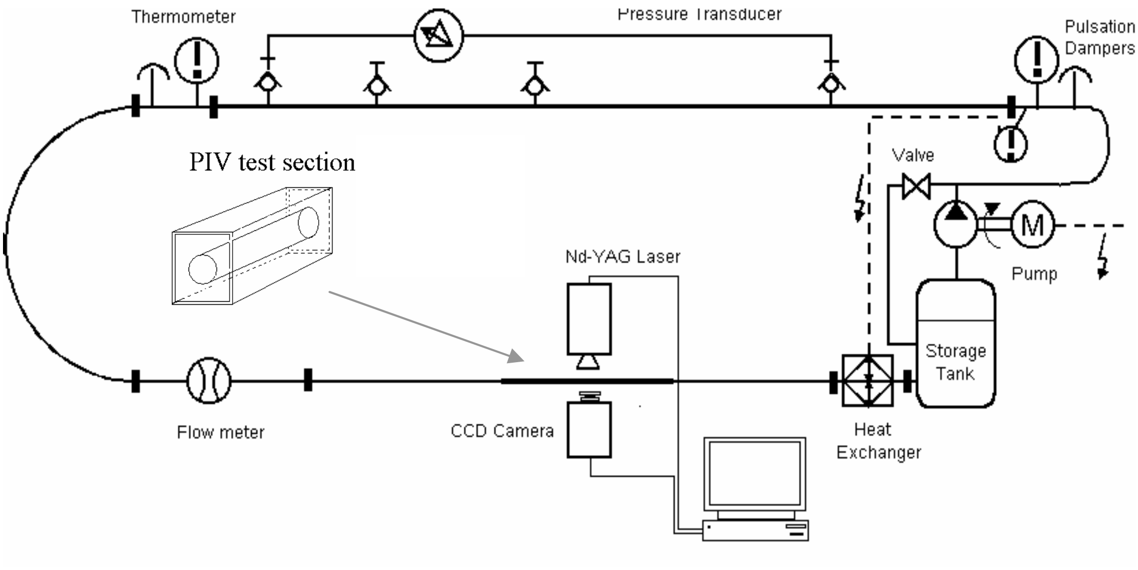

Figure 1: Schematic designer of the experimental set-up

The experiments were performed in a horizontal closed loop circuit (Figure 1). The circuit consists of two long linear sections. The first a stainless steel (304L) pipe equipped with a deferential pressure transducer (DRUCK,PDCR 2111) connected at 2 pressure taps 6m apart. For this section two pipe diameters have been investigated (17 and 10 mm). The downstream part of the second section is a 1.2 metres long borosilicat pipe (17mm diameter). The fluid flow is driven by a volumetric pump (PCM, MR13I10) and a pressure damper is also installed. Temperature is controlled by a shell and tube counter flow heat exchanger and measured by two sensors (ANALOG DEVICES, AD592CN). All data (temperature, pressure gradient, flow rate) are sampled in a computer.

In order to performe the PIV measurement, the test section of the glass tube was enclosed in a rectangular Perspex box filled with water in order to reduce the optical curvature effect. The measurements were carried out at location of about L_b =70 cm, where L_b is the length from the glass pipe inlet to the test section. The flow is seeded with solution particles (hollow glass particles) of 15 µm diameter. Illumination source is a double pulsed Nd-Yag laser. Laser sheet is positioned according to the symmetry plane of the pipe. Flow images are recorded perpendicularly by CCD camera (1024×1280 pixels). Velocity fields are obtained through a particle image velocimetry method using the DaVis software (from La Vision). The double frame are processed using adaptive cross correlation FFT on 32x32 pixels final windows size with an overlap of 50%. Finally, Average velocity fields are calculated from 1000 instantaneous fields.

3 Results and discussion

3.1 Friction Factor and Drag Reduction

The fanning friction factor is defined as the ratio of the wall shear stress and of the kinetic energy of the flow by relation (1), where U represents the bulk velocity and ρ is the flow density. The wall shear stress τ_w is linked (Equation 2) to the pressure drop ΔP (which is measured) along the pipe of length L and of diameter D.

$$f = \frac{\tau_W}{\frac{1}{2} \times \rho \times U^2} \quad (1) \qquad\qquad \tau_W = \frac{\Delta P \times D}{4 \times L} \quad (2)$$

Drag reduction occurs if, at the same flow rate, the pressure drop is reduced or if, at the same pressure drop, the flow rate is increased. This implies two kinds of definition of the drag reduction rate. As Zakin et al. (1998), we define the Drag reduction rate at constant flow rates by equation (3), where f_S and f_{DR} represent respectively the friction factor for the solvent alone and for drag reducing solution (respectively). So the friction factor is plotted as a function of the Reynolds number based on the bulk velocity, the diameter of the pipe and the solvent's viscosity.

$$DR(\%) = \frac{f_S - f_{DR}}{f_S} \quad (3)$$

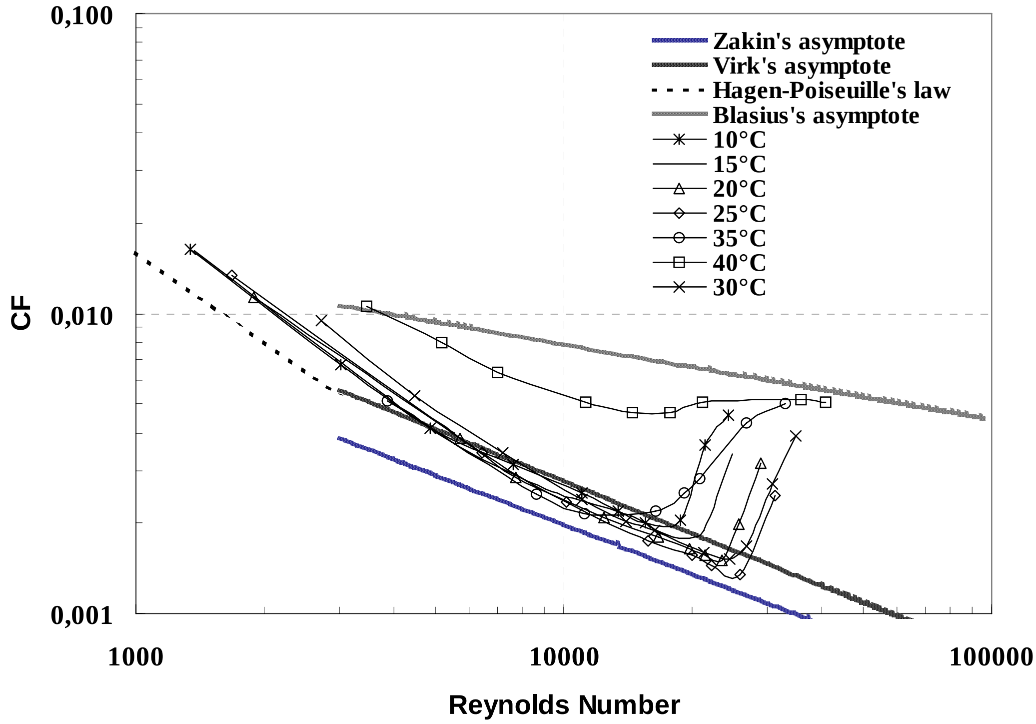

Figure 2 : Friction factor with CTAC solution for different temperatures

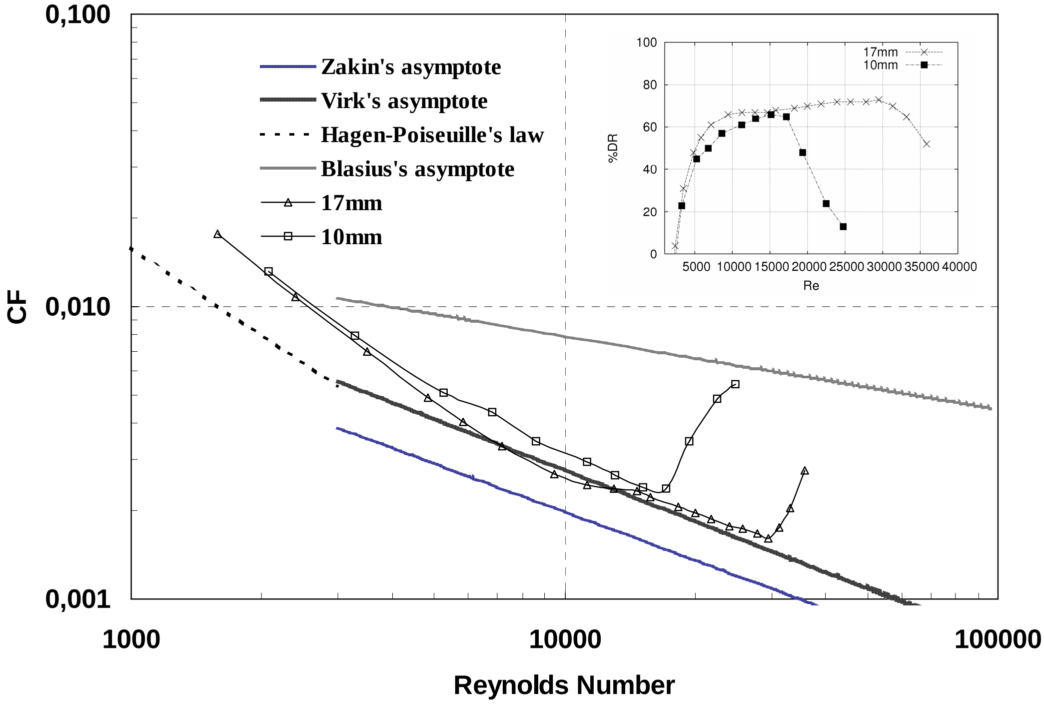

Figure 3: Friction factor with CTAC for 17 and 10mm at 20°C

We report an figure 2 and 3 results of the friction factor for several temperatures and diameters. For the pure water flow, the friction factor is decreasing with increasing Reynolds number according to Blasius's law ($Cf = 0{,}0791Re^{-0{,}25}$). When regarding the curve for the surfactant solution we see that at low Reynolds numbers it is falling steeply till it approaches Zakin's asymptote (Zakin et al., 1998) ($Cf = 0{,}32Re^{-0{,}.55}$). When the Reynolds number is continually increased it reaches a point where the drag reduction breaks down (we note this state the *break-down point*). Such a behaviour is described by Bewersdorff H.W. and D. Ohlendorf (1988) for higher concentration surfactant solutions (700ppm). After this critical Reynolds number friction coefficient increases again till it reaches Blasius's line. Afterward, there is no drag reduction effects.

As it can be seen in Figure 2, the friction behaviour in the drag reducing surfactant solution depends strongly on temperature. When temperature increases the break-down point shifts towards a larger Reynolds number. After 40°C (for the solution of CTAC considered) drag reduction is lost. According to Gyr and Bewersdorff (1995), the micelles change their form. In Figure 3 measurements for surfactant solution for two different pipe diameters (10 and 17mm) are plotted. One can observe that the diameter has got a real impact onto the friction coefficient in the turbulent flow. This impact is visible on the position of the break-down point. For the first diameter (10mm) the break-down Reynolds number is about 18000, whereas for the second diameter (17mm), it is about 30000. Then, the break-down point shifts to higher Reynolds numbers as the diameter increases.

3.2 Effect surfactants on the velocity

In Figure 4 and 5, the results were averaged in time and in space in order to obtain the mean profiles (mean velocity, Reynolds stress, and axial turbulence intensities). They are obtained with the above mentioned PIV system. Thus, Figure 4 and Figure 5 present the streamwise mean velocity profiles for both water and surfactant solution at the same Reynolds number and temperature (Re≈21000, at 20°C). The mean velocity gradient near the wall for the surfactant solution is lower than the one for the solvent, but near the centre of the pipe we observe the opposite situation. On Figure 5, one can see that the mean velocity profile follows first the viscous sub-layer, then it follows the water buffer layer. For y^+ greater than 20, it increases with a slope between the one of the Chara's ($u^+=23.4*\ln(y^+)-65$) and of the Virk's asymptote ($u^+=11.7 \ln(y^+)-17$). For y^+ greater than 100, it follows the Virk's asymptote, and finally finishes by an horizontal line. It appears that this profile reveals some characteristics of drag reducing solutions described in literature (Zakin et al., 1998, Gyr and Bewersdorff, 1995).

Reynolds shear stress (no presented here) for the CTAC solution are nearly zero in comparison to the ones obtained for the Newtonian flow by PIV. This is an interesting result which corroborates those reported by some authors as Li et al.(2005).

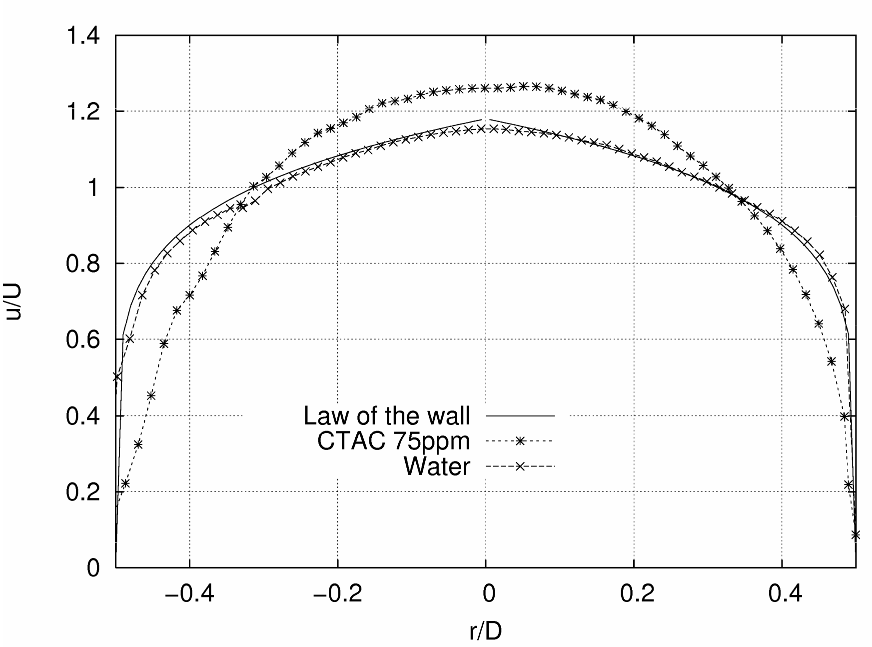

Figure 4: The mean velocity profile normalized by the bulk velocity versus the distance from the axis normalized by the diameter (Re≈21000, T=20°C, D=17mm).

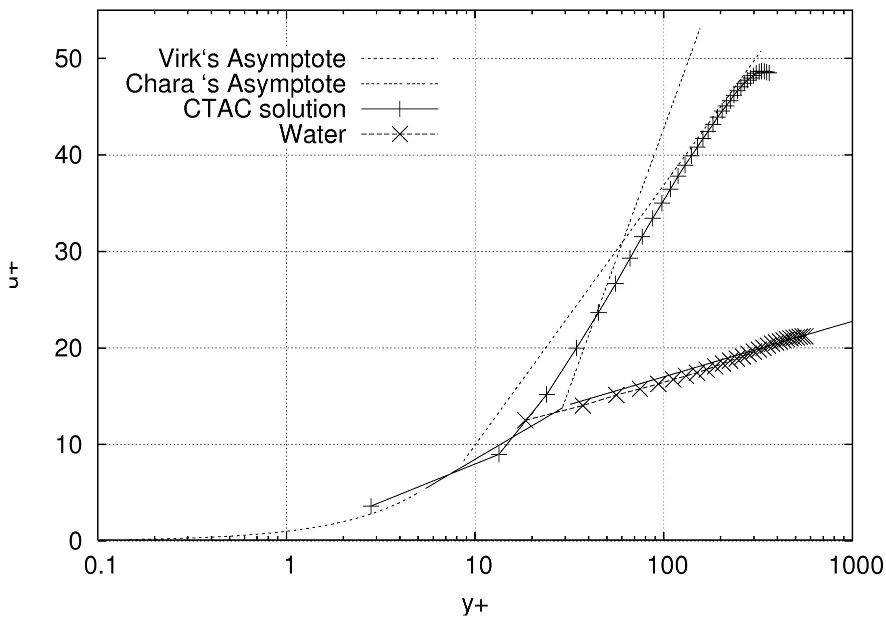

Figure 5 : The mean velocity profile normalized by the friction velocity in wall coordinates system (Re≈21000, T=20°C, D=17mm, $u^+=u(r)/u_\tau$, $y^+=y.u_\tau/\nu$).

Figure 6 shows the distribution of the instantaneous velocity in the surfactant solutions and the water flow with the same Reynolds number (Re≈21000). We observe a weak acceleration of the core region for the surfactant solution. The contour in the surfactant solution is approximately parallel to the mean flow in the near wall region. That comes from a reduction of the velocity gradient near the wall.

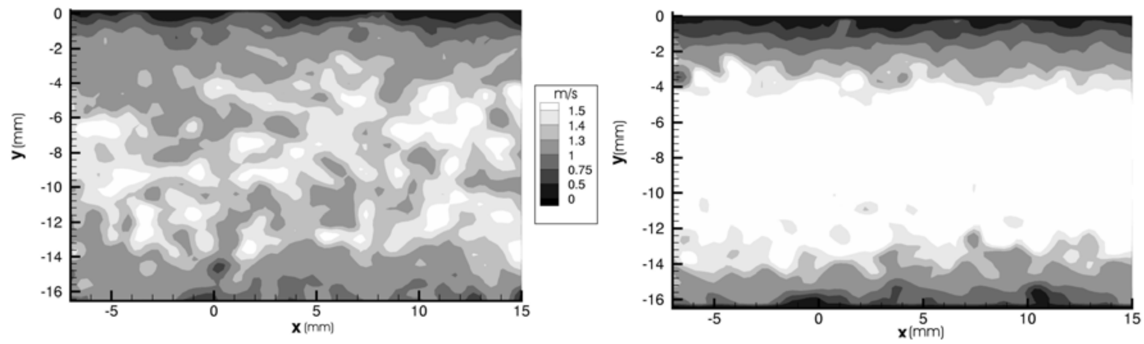

Figure 6: Norme of the instantanous velocity field for the water (left) and the surfactant solution (right) at Re≈21000, T=20°C.

4 Conclusion

In this communication Drag reduction by addition of very small amount of CTAC NaSal (75ppm) was investigated by measurement of the pressure drop and by using a PIV system. Temperature and diameter effects were investigated. In general, this system presents drag reduction rates of about 75 %.

First, it appears that the friction factor in the turbulent flow depends on the temperature and on the diameter. This dependence appears principally on the value of the Critical Reynolds Number (CRN) from which the flow becomes fully turbulent with no drag reduction effects. At lower temperature CRN increases with the temperature (10-35°C). However, for higher temperature the drag reduction is simply lost. The increasing of the diameter shifts the CRN to greater values.

Secondly, for Re=21000 and T=20°C, one observes on PIV’s results that the shape of mean velocity profile for the very low concentrated surfactant solution approaches the one of the single Poiseuille-laminar flow, whereas, the flow is fully turbulent, as it can by seen on the axial turbulent intensity profiles, although the Reynolds stress for the surfactant solution is negligible.

5 Acknowledgement

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6 Literature

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