

Experimental investigation on the effects of surfactant on a turbulent boundary layer flow

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Abstract We investigated the influence of low concentration, bio-degradable surfactant solution in a turbulent boundary layer in a flume, by using Particle Image Velocimetry (PIV). The flow was measured in the spanwise-streamwise plane (x - z). The results present a comparison between water and surfactant solution flow at the same flow rate, as characterized by the Reynolds stress, turbulent energy production and auto-correlation functions. The results shown here complement the previously reported effects related to the decorrelation between the streamwise and the spanwise velocity components and following strong suppression of the turbulent kinetic energy production. In the present investigation we extend the existing results related to the Reynolds stresses and the turbulent kinetic energy production term in the streamwise-spanwise plane of a turbulent boundary layer in a flume. In addition, proper orthogonal decomposition (POD) was applied to the fields of out-of-plane vorticity component and the comparison between the linear combinations of the first three POD modes is shown for the water and surfactant solution flows.

1 Introduction

Drag reduction in turbulent boundary layer flows, by low concentrations of polymers, is most widely known phenomenon since the publication of Toms (1948). Recently, bio-degradable surface active agents (surfactants) have appeared as a more appropriate choice of drag reducing additives. These surfactants are environmental friendly and, they are more resistant to mechanical degradation (Zakin and Lui, 1983). The influence on turbulent flow characteristics could be spectacular with only few parts per million (ppm) of surfactant solution, added to the solvent (Ohlendorf et al., 1986, Gyr and Bewersdorff, 1995). The general assumption is that surfactants, like other additives, act directly toward the small turbulent scales (Gyr and Bewersdorff, 1995, Nieuwstadt and den Toonder, 2001, and references therein). The drag reduction effect is due to the modification of the turbulence structure at small scales (e.g. Liberzon et al., 2005). A significant decrease of the Reynolds stresses was observed (Warholic et al., 1999, among others), however without a substantial reduction of the r.m.s values of the velocity fluctuations. In addition, the turbulent kinetic energy production, and the dissipation, were measured and found to be strongly reduced in the drag reduced flow (Tsinober, 1990). Most researches have reported an increase of anisotropy for surfactant solution flows, characterized by a considerable suppression of the wall-normal velocity fluctuations. The common agreement is that the decorrelation of the streamwise (u) and wall-normal (v) components is the main manifestation of the drag reduction effect, which leads to the reduction of Reynolds stresses (Tsinober, 2001). Theoretical models of drag reduction flows concern the stretching of the polymers by the turbulent flow in certain areas, and consequential the local viscosity changes, as the major mechanisms of drag reduction (see review in Gyr and Bewersdorff, 1995). The influence of the additives on coherent motions was investigated experimentally by using motion pictures of dye injection (Donohue et al., 1972), real-time hologram interferometry (Achia and Thompson, 1977), dye visualization (Oldaker and Tiederman, 1977). The researchers found an increase in the spanwise spacing of low-speed streaks and decrease of "bursting events" in drag reduced flows. In the present research, we investigated experimentally the influence of the non-ionic, bio-degradable, non-toxic surfactants, on the turbulent flow in a flume, by means of Particle Image Velocimetry (PIV). Similar experimental studies with PIV were recently performed by Warholic et al. (2001) and White et al. (2003), and in both studies polymers were used as drag reducing additives. The drag reduction in surfactant solution flows exceed Virk's maximum drag reduction limit (Virk, 1971) for polymers, for relatively low concentrations (Myska and Chara, 2001). Therefore, these non-toxic and bio-degradable materials that are also shown to be good drag reducers, have a great potential for many engineering and industrial applications.

2 Experimental set up

The experiments were performed in a flume with dimensions of $4.9 \times 0.32 \times 0.1$ meter, shown in Fig. 1. The entrance and the following part of the flume, up to 2.8 meter downstream, were made of glass. All necessary precautions have been taken to ensure a fully developed turbulent boundary flow: the eddies and recirculating currents were dampened by means of narrow slits in the inlet tank (as presented by dotted lines in the Fig. 1), baffles were installed in the pipe portion of the tank, the inlet to the channel was a converging channel in order

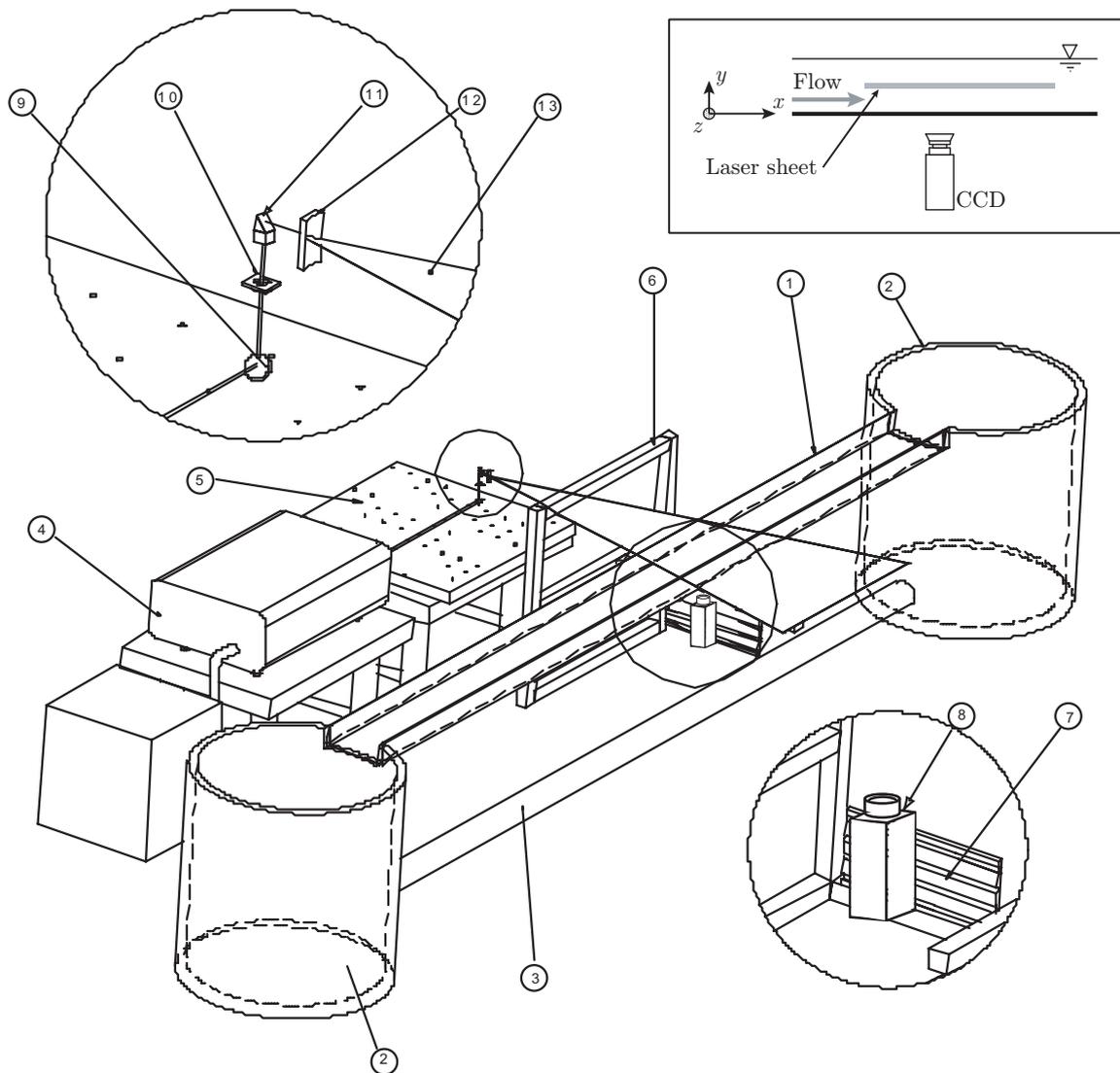


Figure 1: Schematic view of the experimental facility, including the coordinate system and the components: 1) flume, made of glass, 2) reservoirs, 3) pipe, 4) double Nd:YAG laser, 5) optical table, 6) supporting frame, 7) camera plate, 8) CCD camera, 9) 45° mirror, 10) spherical lens, 11) right-angle prism, 12) cylindrical lens, and 13) laser sheet.

to have a smooth entrance, the 0.75 HP, 60 RPM centrifugal pump was isolated from the system by means of rubber joints fitted to the intake and discharge pipes. Flowmeter, with an accuracy of 0.5% of the measured flow rate, continuously recorded the flow rate. In order to make the measurement area long enough and avoid a flow-depth decrease at the end of the flume, an array of cylindrical flow obstacles was placed at the outlet portion. The measurements have been performed with treated and filtered tap water. A detailed description of the flume is given in Hetsroni and Rozenblit (1994).

The PIV system included a double pulsed Nd:YAG laser (170 mJ/pulse, 15 Hz) operating at 532 nm, a sheet forming optics, and 8 bit, 1024 × 1024 pixels, 30 frames-per-second CCD camera. The camera was located 0.2 m under the flume, with imaging axis normal to the laser light sheet, as shown in the top-right insert of Fig. 1, along with the coordinate system of the experiment. The velocity fields were measured at streamwise - spanwise plane. The laser sheet was located 0.01 m above the bottom wall, which is equivalent to $y^+ = 80$ (the friction velocity was estimated in another set of experiments in the streamwise-wall normal plane published elsewhere (Liberzon et al., 2004, Gurka et al., 2006)). The time separation between the two laser pulses was adjusted according to the mean streamwise velocity value and was equal to 2×10^{-3} seconds. Hollow glass spherical particles with an average diameter of 11.7 μm and a density of 1100 kg/m^3 , were used for seeding. The calibration procedure and the PIV cross-correlation analysis were performed by using Insight 5.10 software TSI® Inc. (2002). In all cases an interrogation area of 32 × 32 pixels with 50% overlapping was used. The spatial resolution of the camera was 80 μm per pixel, and the field of view was approximately 80 mm × 80 mm. The analysis produced about 3000 vectors per map, filtered by using standard median and global outlier filters. The quality of the instantaneous velocity data, achieved through the PIV measurement technique is approximately 2%, according to the error analysis proposed

by Raffel et al. (1998). The results of the experiments and uncertainty analysis have been discussed in Gurka et al. (2004, 2006), and omitted here for the sake of brevity.

In the present study we used the dilute solution of Agnique PG 264-U surfactant (also known as Agrimul PG 2062), from Alkyl Polyglycosides. The surfactant is based on plant-derived chemicals (Carbohydrate molecular structure), it is readily biodegradable, non-toxic and non-ionic. It has the density of 1070 kg/m^3 and the dynamic viscosity of $17 \text{ kg/m}\cdot\text{s}$ at 25°C . The surfactant molecules consist of a hydrophobic and a hydrophilic part. In water these molecules tend to assemble to micelles, and above the critical micelle concentration (CMC), globular micelles are usually formed, typically linked to drag reduction (e.g. Gyr and Bewersdorff, 1995). The CMC value for the Agnique PG 264-U is close to 20 ppm, which is the concentration used in the present study. A semi-dilute surfactant solution was prepared by mixing of Agnique PG 264-U with 500 mL of water, heated up to 80°C and stirred for 30 minutes, then added to the outlet water tank.

3 Results and discussion

We investigate the influence of the surfactant solution on the turbulent flow by means of a comparative analysis for water and drag reduced flow. The results were compared for the same flow-rate velocity $U_q = Q/A$, where Q is the flow rate and A is the cross-sectional area of the flow. Hereinafter we denote the mean quantities by capital letters, instantaneous values by lower case letters, and turbulent, fluctuating quantities by the apostrophe, e.g. $u = U + u'$. All the experiments were conducted for a constant flow rate of $5.8 \times 10^{-3} \text{ m}^3/\text{s}$, which is equivalent to $U_q = 0.2 \text{ m/s}$ and $Re_h = U_q h/\nu = 20,000$, where h is the water height, and ν is the kinematic viscosity of the water.

Figure 2 presents an instantaneous maps of the fluctuating velocity fields: of water flow (left) and of the flow with surfactant (right). The flow direction is from top to bottom, and the coordinates in the streamwise and

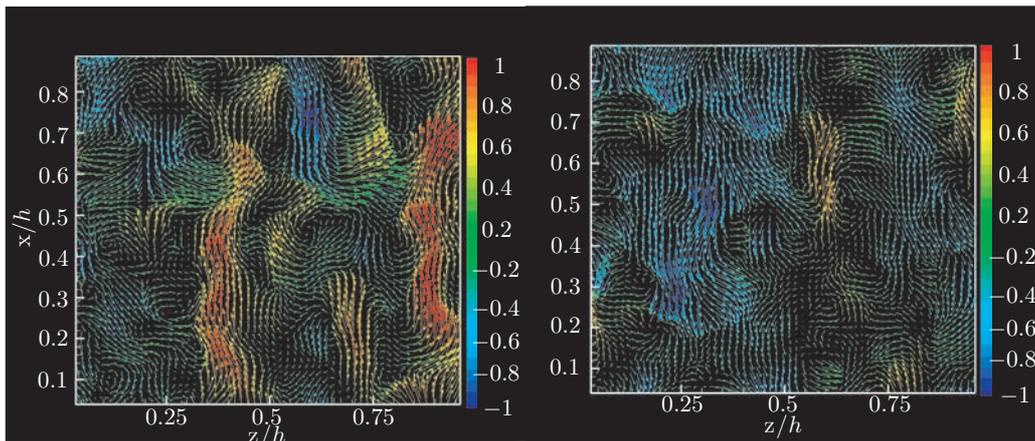


Figure 2: The fluctuating velocity field in the streamwise–spanwise plane of the water flow (left) and the flow with surfactant (right). The color scale represents the values of the streamwise velocity fluctuations in $\text{cm}\cdot\text{s}^{-1}$ (i.e., $-1 \leq u' \leq 1 \text{ cm}\cdot\text{s}^{-1}$).

the spanwise directions are normalized in respect to the water height, h . Arrows represent the two-component fluctuating velocity vector field, $u' - w'$. The colors emphasize the high- and low-speed regions: the blue stands for fluctuating streamwise velocity which is higher than mean velocity, and red is for the low-speed regions. A negative value corresponds to a high speed region, since the positive z (spanwise direction) is defined from left to right and the positive streamwise direction, x , is from the top to the bottom. Figure 2 shows qualitatively the effect of surfactant, as one observes weaker streamwise velocity fluctuations (right panel) than in the solvent counterpart (left panel). In this manuscript we extend our recent observations (Gurka et al., 2004) in which we focused on the correlation analysis with an emphasis on the spatial characterization of the Reynolds stress and turbulent kinetic energy production fields. Turbulent intensity and auto-correlation function of streamwise velocity showed the suppression of the turbulent activity in the flume when surfactant was introduced to the flow (Gurka et al., 2004).

Most of the reported results on the drag reducing flows have shown the suppression of Reynolds stress in streamwise - wall-normal ($x - y$) plane, $\langle u'v' \rangle$. Here we present the a comparison between water and drag reducing flows in terms of one-point correlation of streamwise and spanwise velocity components, $\langle u'w' \rangle$, which is the Reynolds stress in the plane of investigation. The spatial distribution of the Reynolds stress field is shown in Fig. 3. The absolute quantities (i.e., color contours) are less important than the fact that both sides of the figure use the same contour level, and the visual comparison is an easy task. It is clear that the Reynolds stress is significantly reduced in the surfactant solution flow. For the water flow case, the Reynolds stress presents an expected symmetrical distribution across the spanwise direction, with the axis of symmetry located in the center

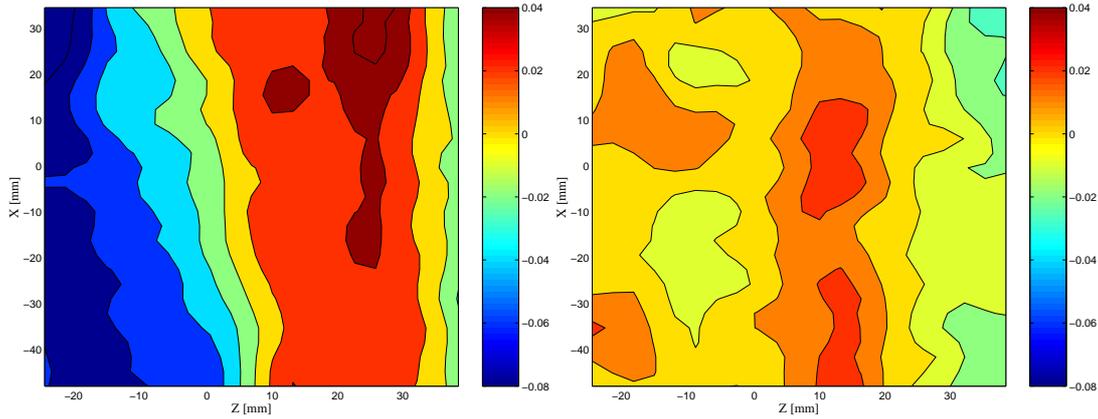


Figure 3: Ensemble average of the one-point correlation between streamwise and spanwise velocity fluctuations $\langle u'w' \rangle$ for the water (left) and surfactant solution (right).

of the flume. However, no symmetry is observed in the the surfactant solution flow. Moreover, the Reynolds stress values are smaller compare to the one calculated for the water (almost four times smaller in magnitude). Because the strong suppression of the Reynolds stress takes place without substantial reduction of the turbulent fluctuations Gurka et al. (2004), we might conclude that the reduction is, for the most part, due to the decorrelation of the velocity components, which is in agreement with the previous results (Tsinober, 2001, and references therein).

Furthermore, we demonstrate the distribution of the turbulent kinetic energy production term, $\langle u'w' \rangle S_{uw}$, which is associated with Reynolds stress, in Fig. 4. The suppression of the production term is even more notable

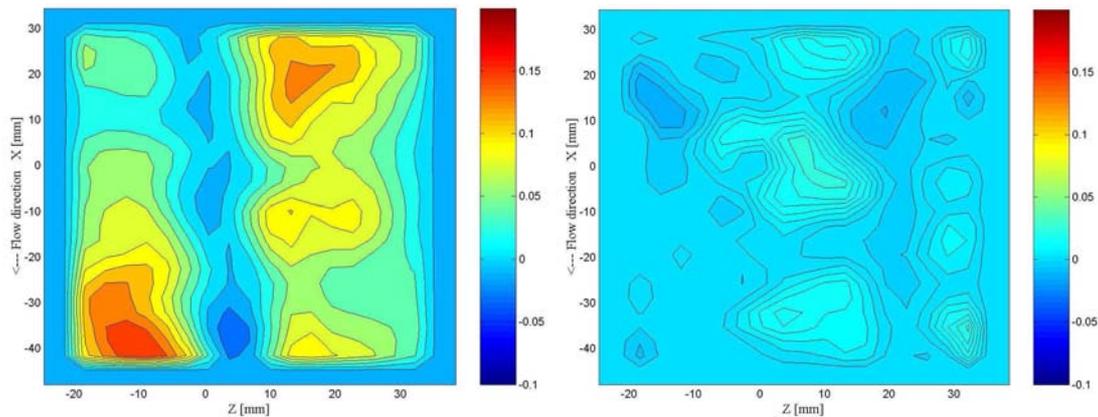


Figure 4: Ensemble average of the turbulent kinetic energy production term $\langle u'w' \rangle S_{uw}$ for the water (left) and surfactant solution (right).

than the Reynolds stresses, presented in Fig. 3. The result implies that surfactant, in addition to the decorrelation between the velocity components, also reduces the mean rate-of-strain (at least the measured component, S_{uw}) in the flow. Similar results were presented, for example, by Wei and Willmarth (1992). They found a reduction of the turbulent kinetic energy production term in the $x - y$ plane in the near-wall region at $40 \leq y^+ \leq 200$.

The mean rate of strain component in the streamwise-spanwise plane, S_{uw} , contains the two terms $\partial U/\partial z$ and $\partial W/\partial x$, while the former is significantly larger than latter. Figure 5 compares the ensemble average of $\partial u/\partial z$ for the water and the surfactant solution. The difference between the extremum points for water flow as we deduce from Fig. 5 are higher, compared to the surfactant solution. This explains that the streamwise velocity gradients decrease with an addition of surfactant. This leads to the conclusion that the significant decrease of the turbulent energy production is not solely due to the decrease of the Reynolds stress, but associated with the change of the velocity gradients field.

3.1 Proper Orthogonal Decomposition (POD) results

Further investigation of the velocity gradients is possible by applying proper orthogonal decomposition (POD) method to the fields of vorticity component, ω_y . We use the procedure proposed by Liberzon et al. (2005), Gurka et al. (2006) to identify coherent patterns in turbulent flows. Typically, the analysis based on POD, is implemented on the fluctuating velocity fields assuming that large coherent structures contain the main fraction of the turbulent

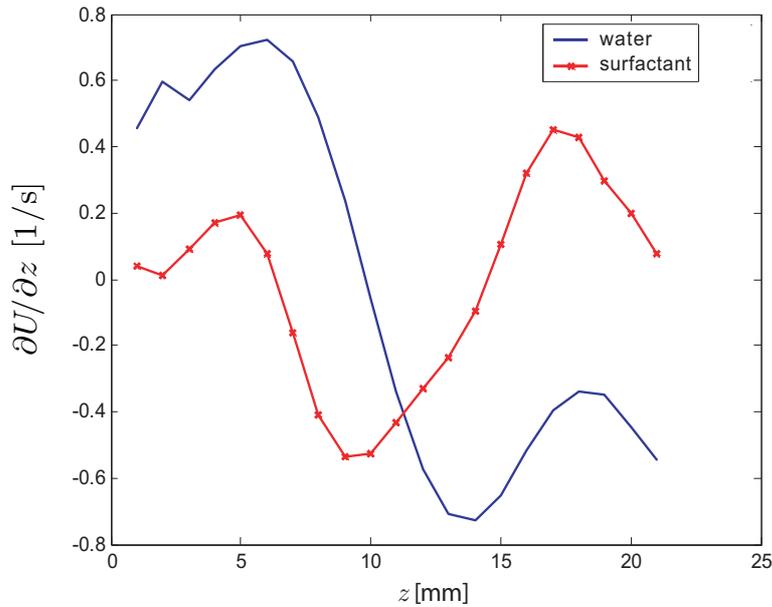


Figure 5: Streamwise average of the derivative of the streamwise velocity component in the spanwise direction, $\partial U/\partial z$, measured in the streamwise-spanwise plane for the water (left) and the surfactant solution flow (right).

kinetic energy (Holmes et al., 1996). However, it was noted in our recent study (Gurka et al., 2006), among others, that the vorticity fields are more pertinent for the identification of coherent motions. The suggested method resembles, in some sense, the "characteristic eddy" concept of Lumley (1970). The "large scale structure" is the "characteristic eddy" and it is identified through a linear combination of the first POD modes of vorticity.

Figure 6 presents the linear combination of the first three POD modes of ω_y , for the surfactant solution and water flows. There is a change in topology of the patterns obtained for the surfactant solution flow compared with the water flow. We refer to the patterns as the footprints of coherent structures and we observe that they change their shape and shattered. Recalling the results of the turbulent kinetic energy production term and those of the Reynolds stress component, we understand that the structure does not vanish, meaning that the turbulence mechanisms still work. However, most of the turbulent energy is transferred directly to the surfactant and not by means of turbulence production. It also suggests that the surfactant can absorb the turbulent energy of the fluid, similar to the results obtained, for example, by den Toonder et al. (1997), in which direct numerical simulation (DNS) of turbulent pipe flow with dilute polymers, modelled as a rigid rod aligned with the velocity vector and a spring that represented the elasticity effect.

4 Summary

The drag reducing effect of a dilute solution of bio-degradable (Agnique PG 264-U) surfactant from the Alkyl Polyglycosides was investigated experimentally. In the present study, particle image velocimetry (PIV) was applied to the investigation of a flow in the streamwise–spanwise plane of a turbulent boundary layer in a flume at $y^+ = 80$. The influence of the surfactant solution on the turbulent flow and its structure is clearly seen in different distributions of a one-point correlation fields of $\langle u'w' \rangle$ and turbulent kinetic energy production $\langle u'w' \rangle S_{uw}$. The bio-degradable surfactant was shown to be an efficient drag reducing solution, acting in parallel on the fields of Reynolds stress component, and mean shear $\partial U/\partial z$. The presented results support the explanation of the mechanisms responsible for the drag reduction, reviewed by Tsinober (2001). The qualitative and quantitative results, that demonstrate the effect of the surfactant are summed up as follows:

- The analysis of distribution of the fluctuating velocity suggests that the fluctuations in the drag reducing flow are only slightly decreased;
- The Reynolds stress component $\langle u'w' \rangle$ is suppressed more significantly than the r.m.s of the streamwise velocity fluctuations, $\sqrt{\langle u'^2 \rangle}$ (Gurka et al., 2006), which points to the decorrelation effect;
- The turbulent kinetic energy production term in the streamwise–spanwise plane diminishes, similarly to the known effect in the streamwise–wall normal plane;
- Proper orthogonal decomposition (POD) shows that the coherent structure of the flow does not disappear when the surfactant is introduced, but changes its spatial characteristics, i.e. from elongated regions of

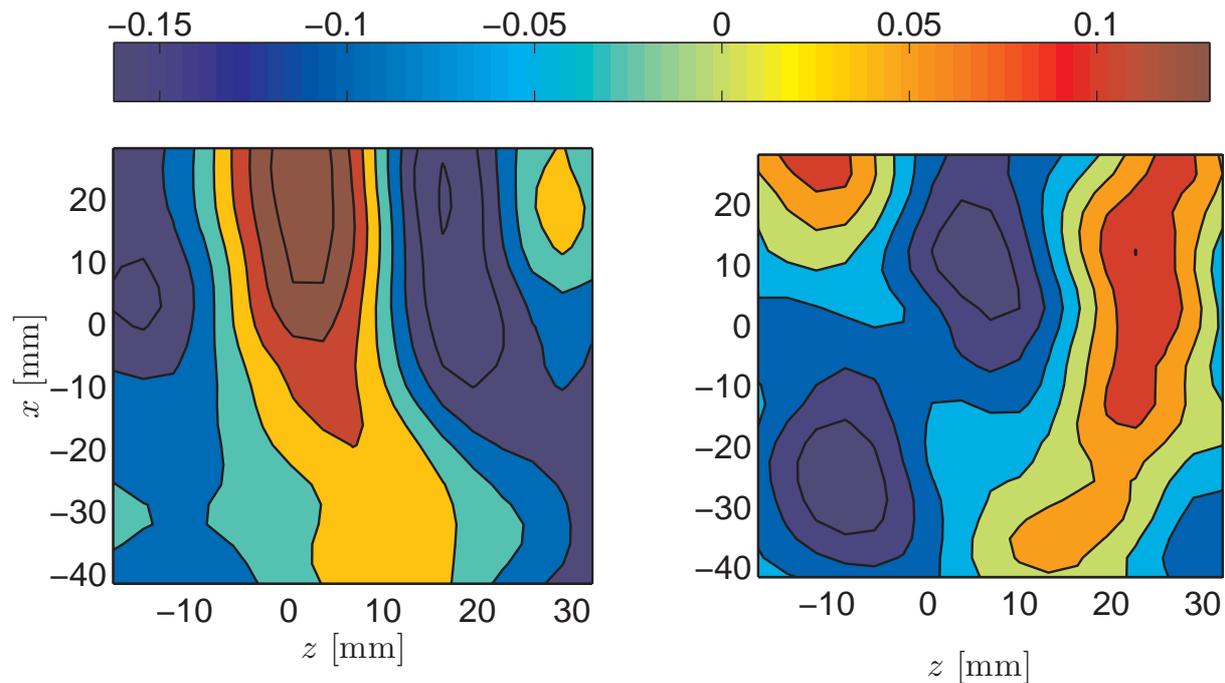


Figure 6: Linear combination of the first three POD modes of the wall-normal vorticity component, ω_y , measured in the streamwise-spanwise plane for the water (left) and the surfactant solution flow (right).

alternating positive/negative strips (Liberzon et al., 2005) to the less regular spots of wall-normal component of vorticity, ω_y .

5 References

References

- B.A. Toms. Some observation on the flow of linear polymer solutions through straight tubes at large Reynolds numbers. *Proc. 1st Intl. Congr. on Rheology*, Vol. II:135–141, 1948.
- J. L. Zakin and H. L. Lui. Variables affecting drag reduction by nonionic surfactant additives. *Chemical Engineering Communications*, 23:77–80, 1983.
- D. Ohlendorf, W. Inherthal, and H. Hoffman. Surfactant systems for drag reduction: physico-chemical properties and rheological behaviour. *Rheol. Acta*, 26:468–486, 1986.
- A. Gyr and H.-W. Bewersdorff. *Drag Reduction of Turbulent Flows by Additives*. Fluid Mechanics and its Applications. Kluwer, Netherlands, 1995.
- F.T.M. Nieuwstadt and J.M.J. den Toonder. Drag reduction by additives: A review. In A. Soldati and R. Monti, editors, *Turbulence Structure and Modulation*, pages 269–316. Springer, NY, 2001.
- A. Tsinober. *An informal introduction to turbulence*. Kluwer, Netherlands, 2001.
- A. Liberzon, M. Guala, B. Lüthi, W. Kinzelbach, and A. Tsinober. Turbulence in dilute polymer solutions. *Phys. Fluids*, 17:031707, 2005.
- M. D. Warholic, M. S. Gavin, and T. J. Hanratty. The influence of a drag-reducing surfactant on a turbulent velocity field. *J. Fluid Mech.*, 388:1–20, 1999.
- A. Tsinober. Turbulent drag reduction versus structure of turbulence. In A. Gyr, editor, *Structure of Turbulence and Drag Reduction*, pages 313–334. Springer, 1990.
- G. L. Donohue, W. G. Tiederman, and M. M. Reischman. Flow visualization of the nearwall region in a drag-reducing channel flow. *J. Fluid Mech.*, 56:559–57, 1972.
- B. U. Achia and D. W. Thompson. Structure of the turbulent boundary in drag-reducing flow. *J. Fluid Mech.*, 81: 439–464, 1977.

- D. K. Oldaker and W. G. Tiederman. Structure of the turbulent boundary layer in drag reducing pipe flow. *Phys. Fluids*, 20:S133–S144, 1977.
- M.D. Warholc, D.K. Heist, M. Katcher, and T.J. Hanratty. A study with particle-image velocimetry of the influence of drag-reducing polymers on the structure of turbulence. *Exp. Fluids*, 31:474–483, 2001.
- C.M. White, V.S.R. Somandepalli, and M.G. Mungal. The turbulence structure of drag-reduced boundary layer flow. *Exp. Fluids*, 36:62–69, 2004.
- P.S. Virk. Drag reduction in rough pipes. *J. Fluid Mech.*, 45:225–246, 1971.
- J. Myska and Z. Chara. The effect of a zwitterionic and cationic surfactant in turbulent flows. *Exp. Fluids*, 30: 229–236, 2001.
- G. Hetsroni and R. Rozenblit. Heat transfer to liquid-solid mixture in a flume. *Int. J. Multiphase Flow*, 20:671–689, 1994.
- A. Liberzon, R. Gurka, and G. Hetsroni. XPIV - multi-plane stereoscopic particle image velocimetry *Exp. Fluids*, 36(2):355–362, 2004.
- TSI® Inc. *INSIGHT™ 5.10 PIV Evaluation Software*. TSI Inc., Shoreview, MN, U.S.A., 2002.
- M. Raffel, C.E. Willert, and J. Kompenhans. *Particle Image Velocimetry: a Practical Guide*. Springer-Verlag, Berlin, 1998.
- Y. Kawaguchi, T. Segawa, Z.P. Feng, and P.W. Li. Experimental study on drag-reducing channel flow with surfactant additives - spatial structure of turbulence investigated by piv system. *Int. J. Heat and Fluid Flow*, 23(5): 700–709, 2002.
- T. Wei and W.W. Willmarth. Modifying turbulence structure with drag-reducing polymer additives in turbulent channel flow. *J. Fluid Mech.*, 245:619–641, 1992.
- R. Gurka, A. Liberzon, and G. Hetsroni. Characterization of turbulent flow in a flume with surfactant *J. Fluids Eng.*, 126(6):1054–1057, 2004.
- P. Holmes, Lumley, J. L., Berkooz, G. *Turbulence, coherent structures, dynamical systems and symmetry*. Cambridge Monographs on Mechanics. Cambridge University Press, Cambridge.1996
- R. Gurka, A. Liberzon, and G. Hetsroni. POD of vorticity fields: A method for spatial characterization of coherent structures *J.Heat Fluid Flow*, 27(3):416–423, 2006.
- A. Liberzon, R. Gurka, and G. Hetsroni. Spatial characterization of the numerically simulated vorticity fields of a flow in a flume *Theor. Comp. Fluid Dyn.*, 19(2):115–125, 2005.
- J. L. Lumley, *Stochastic Tools in Turbulence*. Vol. 12 of Applied Mathematics and Mechanics. Academic Press, New York, 1970.
- J.M.J. den Toonder, M.A. Hulsen, G.D.C. Kuiken, and F.T.M. Nieuwstadt. Drag reduction by polymer additives in a turbulent pipe flow: numerical and laboratory experiments. *J. Fluid Mech.*, 337:193–231, 1997.