The influence of a drag-reducing surfactant on turbulent velocity and temperature field of a 2D channel flow

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ABSTRACT

By means of a two-component LDV combining with a fine-wire thermocouple probe, velocity and temperature fluctuations in thermal boundary layer developing in water and drag-reducing flows by surfactant additive have been measured simultaneously in a two dimensional channel. A cationic surfactant solution, water/CTAC/NaSal system with 30ppm weight concentration of CTAC, was used as the working fluid for drag-reducing flow. The measurements were performed for eight runs, four for Newtonian and four for drag-reducing, with different wall heated flux. Each run was started at the same inlet fluid temperature, 30℃, and at the same Reynolds number, 2.36×10^4 (the maximum DR occurred at 30℃ for 30ppm CTAC solution) based on channel width, bulk velocity and viscosity of water.

From the simultaneous measurements of u, v, and θ, the turbulence transport terms such as Reynolds stress $-\overline{uv}$ and turbulent heat fluxes in streamwise and wall-normal directions, $\overline{u\theta}$ and $-\overline{v\theta}$, as well as velocity and temperature profile and their fluctuation intensity, were investigated. Typical hydrodynamic features for drag-reducing flow by additives, such as thickening of inner region and acceleration of outer flow and depression of Reynolds stress have been clarified. Two layers for thermal field were found, high heat resistance layer with high temperature gradient and the layer with small or even zero gradient, which was consistent with previous measurement. The peak value of streamwise turbulent heat flux normalized by friction velocity and temperature was larger for drag-reducing flow than for Newtonian flow and the peak location shifted away from the wall. The turbulent heat flux in wall-normal direction was depressed in a similar way of the depression of Reynolds stress, i.e., decorrelation between v and θ vs. decorrelation between u and v. Heat transfer reduction being also due to the decrease of $-\overline{v\theta}$ was then conjectured.

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1. INTRODUCTION

It is well known that dilute solution of certain high molecular weight water soluble polymers and cationic surfactants can significantly modify turbulence characteristics in pipe, channel and boundary-layer flows, damping fluctuations of cross-flow velocity, enhancing that of streamwise velocity, attenuating Reynolds stress terms, increasing the space of near-wall low-speed streaks and leading to dramatic drag reduction (DR), e.g., Sadanandan and Sureshkumar 2002, Warholic et al. 1999 and Hetsroni et al.. 1997 and references therein. The experimental investigation of such flows was at first focused on the evaluation of DR as a function of Reynolds number, then extended to the measurement of turbulent velocity fluctuations allowed by the development of laser-Doppler velocimetry (LDV), thereby, higher-order statistics as well as velocity power spectra and turbulent energy production terms have been estimated (e.g. reviewed by Sibilla and Baron 2002).

By means of LDV and particle image velocimetry technique, the turbulence structures (Kawaguchi et al.. 1996, Kawaguchi et al.. 1997a, Li et al.. 2000 and Kawaguchi et al.. 2001) as well as heat transfer characteristics (Li et al.. 1999 and Li et al.. 2001a,b) of two dimensional (2D) channel DR flows by surfactant additive have been studied in detail. They found that the measured velocity fluctuations normal to the wall were greatly reduced and the measured Reynolds shear stress was close to zero in the DR flows by surfactant additive. In consequence, large drag reduction and heat transfer reduction (HTR) occurred due to the turbulent eddy motion being significantly depressed.

Temperature fluctuations in thermal boundary layer were also measured by means of a fine-wire thermocouple probe by Kawaguchi et al. (1997b); they investigated the characteristics of thermal diffusivity in boundary layer of DR flow by surfactant additives. It was found that temperature fluctuation showed unusual features in surfactant solution flow. Three different types of fluctuation frequency exist in different layer region, viz., low fluctuation frequency in near wall region, intermittent feature of fluctuation frequency at the edge of the thermal boundary layer and high fluctuation frequency outside of thermal boundary layer.

However, the information of turbulent transport flux, such as $\overline{u\theta}$, $\overline{v\theta}$, in DR flow by additives is significantly scarce, thus the scalar transport mechanism in drag-reducing flow is still poorly understood. This may be due to the fact that even for Newtonian flow simultaneous measurement of velocity and temperature fluctuations is extremely difficult comparing to the individual measurement of velocity or temperature field. As for the DR flow by additives, there are much more difficulties in doing so.

In the present study, experiments have been performed for the simultaneous measurement of velocity and temperature fluctuation in boundary layer region of 2D channel DR flow by surfactant additive. Pointed out by Walker and Tiederman 1990 that owing to the viscoelastic nature of drag-reducing polymers, measurements of velocity using hot-wire anemometers, hot-film devices or Pitot tubes can be in error, which leaves the LDV as the only viable method for measuring velocity and turbulence statistics in aqueous DR flows. The same problem may also encountered in the investigation of DR flow by surfactant additive. The fine-wire thermocouple has been proved to be satisfactory in measuring the temperature fluctuations in DR flow by surfactant additive, Kawaguchi et al. 1997b. A 2-components LDV and a fine-wire thermocouple probe are therefore used for measuring velocity and temperature fluctuation respectively in the present experiments.

The coupling between velocity and temperature fields in thermal boundary layer region of a slightly heated 2D channel DR flow is the main object of the present work.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1 Water channel

The closed-circuit water channel used in the present experiment is schematically shown in figure 1. All the components except for the modification of channel length are the same as those described in the work of Kawaguchi and his colleagues. It is known that much longer distance or larger ratio of *L/H*, where *L* is distance from inlet and *H* height of channel, is necessary to reach fully developed turbulent flow region for DR flow by additives than for Newtonian flow. The 2D channel used here has length of 10m, height of 0.04m and width of 0.5m. An electromagnetic flow meter with uncertainty of 0.01 m^3/min is installed upstream of water channel for flow rate measurement. Wall shear stress is estimated from pressure difference measured by a precise differential pressure gage. Details of other parts may be referred to related references.

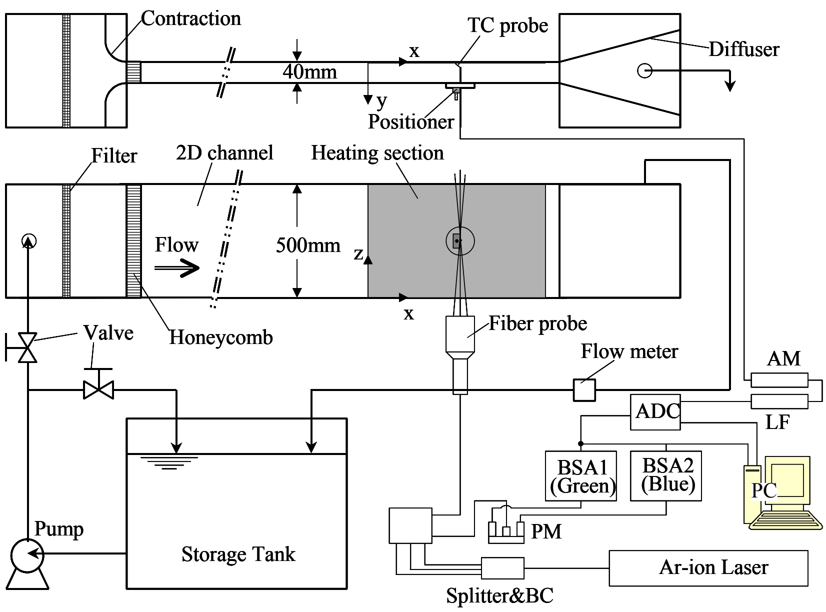

Figure 1. Schematic diagram of the closed-circuit water loop and instrumentations

2.2 Surfactant solution

A dilute aqueous solution of a kind of cationic surfactant, cetyltrimethyl ammonium chloride (CTAC), is prepared for working fluid. Sodium salicylate (NaSal) with the same weight concentration as that of CTAC is used for providing counter ions. Details are given in Table 1. Shown in Table 1 are also the experimental conditions. Note here that Reynolds number of surfactant solution is based on solvent density and viscosity, bulk velocity and channel height.

2.3 Test section

The heating section has 0.9m of length. It starts from 8.2m downstream the inlet of water channel. Measurement station is in central plane of spanwise direction and at 9.0m (225*D*) downstream the inlet of channel and 0.8m (20*D*) downstream the front edge of heating section. The coordinate is shown in figures 1 and 2.

Gasljevic and Matthys 1997 reviewed and discussed that the length of development in circular pipe for surfactant solutions is much longer than for polymer solutions (about 100 diameters), but the point at 190 diameters downstream was close to being hydrodynamically fully developed in their experiments. In the present study, the flow at measurement station is in or at least close to the hydrodynamically fully developed region for 30ppm CTAC solution. To be thermally fully developed, DR flow by additives needs much longer distance, e.g., more than 1000*D* for polymer solutions. However, in many heat transfer measurements for DR flows, it showed that the Nusselt number only has large gradient in a short entrance length. An example, in the experimental study of Li et al. 2001a, the Nusselt number decreased significantly only up to about 10*D* for 30ppm CTAC solution; after 10*D*, the local Nusselt number slightly changed (see Fig.6 of Li et al. 2001). It is then believed that at location of 20*D* downstream the entrance of heating section for the present cases, the variation of thermal field has no much effect on the measurements.

The structure of heating section is schematically shown in figure 3. The silicon rubber skinned heater wires (Nichrome) are glued at backside of a copper plate by an electrically insulating but highly heat conducting adhesive (Shin-Etsu Silicone, Shin-Etsu Chemical Co., Ltd., Japan). Five heater wires are used. Its workable temperature is from -60℃ to 180℃. Each wire has length of 12 meters, with the maximum heating power of 1000W. The other side of copper plate acts as the inside channel wall. Between the back-plate made of acrylic resin and the heater wire, glass fiber cushion is put for heat resistance. Thermocouple for measuring wall surface temperature locates at backside of copper plate. Heat resistance of copper with thickness of 3mm is so small that the temperature difference on the two-side surfaces is negligibly small. Alternating current is used for heating power.

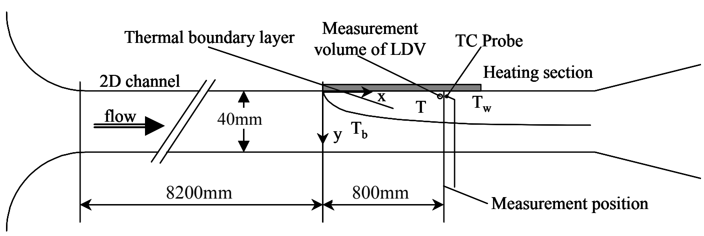

Figure 2. Schematic diagram of the test section (top view)

2.4 LDV system

Velocity measurements are performed with a two-component LDV system (two color, three beam mode) using 488 and 514.5 nm wavelength of a Coherent INNOVA 308C Model argon ion laser source. The light is transmitted from the source to emission-reception head by 4m-long optical fiber. The optics (Dantec) to focus laser beam into channel center has focusing front lens with focal length of 600mm. The dimensions of measurement volume (m.v.) are 0.1, 0.1 and 3.6 mm in the streamwise, normal and spanwise direction respectively. Fringe mode with frequency shift of 40MHz by using a Bragg cell, is

used to eliminate directional ambiguity in velocity measurement. Backscatter mode is adopted. The velocity signals are acquired by two Burst Spectrum Analyzers (BSA 57N21, Dantec).

The position of LDV m.v. is three dimensionally adjusted by a stage controller (Sigma Koki Co., LTD.) in wall-normal and spanwise directions respectively within ±5μm and by a microscale in streamwise direction within ±1μm .

2.5 Thermocouple probe

Temperature fluctuation in the fluid is measured by a fine-wire k-type thermocouple (TC) (Omega

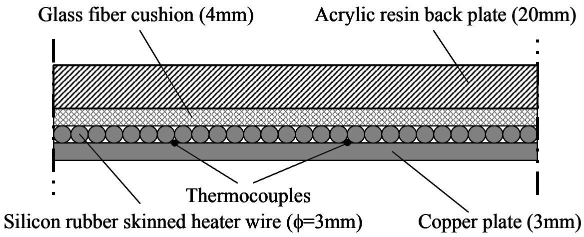

Figure 3. Structure of heating section

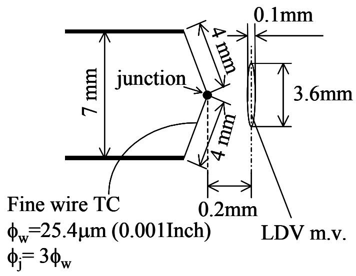

Figure 4. Positioning of the LDV m.v. with respect to fine-wire TC probe

Co.) in diameter of 25.4μm (0.001 inch) and supported by prongs made of the same type thermocouple wire sized in diameter of 200μm. The junction/wire diameter ratio of TC is 3. The prongs and TC wire are shaped in that shown in figure 4 for preventing the interference of lower prong with laser beam when LDV m.v. closely approaching to the TC junction. Using the heat transfer correlation for flow past a sphere given in Whitaker 1972 and for water flow at Reynolds number of 10^4 based on channel width, the TC time constant is calculated to be around 5×10^{-4}s for water flow. Also under the aforementioned Reynolds number, Kolmogorov time scale is estimated to be about 2.7×10^{-3}s. Although time constant of TC and Kolmogorov time scale vary with Reynolds number, such fine-wire TC can be confidently used for measuring temperature fluctuations for the present case.

The juxtaposition of LDV m.v. and junction of fine-wire TC probe is another important parameter. It must be sufficiently close to provide the correct cross-correlation between velocity and temperature fluctuations, but at the same time not interfere with each other. The position of fine-wire TC probe is adjusted by a digital micrometer head in wall-normal direction within ±1μm. The separation distance between fine-wire TC junction and LDV m.v. is set to be 0.2 mm (about 4 times Kolmogorov length scale and 5.5 and 3.0 wall units for water and CTAC solution flow respectively in the present measurements) for each run. Details are shown in figure 4. In Kang et al. 2001, LDV coupling with a cold-wire were used for simultaneously measuring the velocity and temperature fluctuations of liquid Refrigerant-113 in a vertical annular channel. 0.25mm (≅15-30 wall units depending upon the flow rate) was chosen in their measurements and was found to be a good choice.

The output voltage of fine-wire TC probe is amplified by a DC Amplifier and signals with frequency higher than 1kHz are screened out by a Low-pass Filter, before transferring to an analog digital converter (AD-converter). A time delay of 0.2ms incurred by Amplifier and Low-pass Filter is accounted for when processing the acquired data. AD-converter is synchronized with and triggered by the master BSA.

Wall temperature of heating section is measured by K-type TCs. All the TCs including fine-wire TC probe are calibrated with ±0.1K of uncertainty.

2.6 Procedures

Both for water and CTAC solution flow, the measurements are performed at inlet temperature of 30.0□ (with ±0.1K uncertainty) and at Reynolds number of 2.36×10^4 (the maximum drag-reduction is obtained at this Reynolds number for 30ppm CTAC solution flow at 30□).

It is known that the LDV measurement will be strongly affected by the local change of optical properties of fluid. In the heating cases, the temperature gradient especially in the near wall region generates changes of fluid optical property, e.g., refraction index, consequently disables the LDV measurement. It is found that LDV signal in CTAC solution flow is affected by heating much more seriously than water flow (see discussion for temperature profiles). Lower heating power is adopted for CTAC solution flows. In the present experiments, wall surface is at first determinied by scanning LDV m.v. in no-heating case, then LDV m.v. is moved to away from the wall to a fixed distance (recorded by the stage controller) as starting point of measurement. Fine-wire TC probe is positioned with LDV m.v. at the starting point before each run. Approaching to the wall, LDV data qualities, data validation and data rate, become worse and worse. An “acceptable measuring distance” for LDV, i.e., distance of the last measuring point to the wall surface, is then determined for each case by monitoring LDV signal. After that, data are sampled only for temperature (triggered by velocity signal at a location far from the wall).

Cases & Key symbols	C (ppm)	T_i (□)	q_w (W/m^2)	y_{min}/y^+_{min} (mm/-)	Re ($\times10^4$)	T_w (□)	u_τ (m/s)	T_τ (□)	DR (%)	HTR (%)
Water WA:○	0	30	0	0.1/2.8	2.36	30.0	0.022	-	-	-
WB:△	0	30	2114	0.2/5.5	2.36	31.0	0.022	0.023	-	-
WC:□	0	30	4795	0.5/13.8	2.36	32.4	0.022	0.052	-	-
WD:▽	0	30	6246	0.8/22.1	2.36	33.1	0.022	0.067	-	-
CTAC CA: ●	30	30	0	0.1/1.5	2.36	30.0	0.012	-	69.9	-
CB: ▲	30	30	568	0.5/7.5	2.36	30.9	0.012	0.011	69.9	69.4
CC: ■	30	30	1230	1.2/18.0	2.36	31.9	0.012	0.024	69.9	68.6
CD: ▼	30	30	2073	2.2/32.9	2.36	33.3	0.012	0.041	69.9	69.5

Table 1. Test conditions

This distance is designated by y_{min}/y^+_{min}, as shown in Table 1. Detailed test conditions are also given in the table.

3. RESULTS AND DISCUSSIONS

Experimental results from the eight cases, four Newtonian and four drag-reducing, are presented in this section. In each run, about 1000 to 10000 (depending on distance from measuring point to the wall or on the data quality in heating cases) synchronized data sets are sampled. All the presented terms have been non-dimensionalized using the friction velocity or friction temperature or the both of that run and the viscosity of water for hydrodynamic or thermal parameters respectively and plotted in semi-logarithmic coordinates with abscissa of the wall unit. Presented as follows are streamwise mean velocity profiles, streamwise velocity fluctuation intensities, mean temperature profiles, temperature fluctuation intensities, Reynolds shear stress profiles, and turbulent heat fluxes in streamwise and wall-normal directions for both water and DR surfactant CTAC solution flows.

3.1 Influence of drag-reducing surfactant on streamwise velocity field

The measured mean velocity profiles for eight runs and that for the commonly accepted turbulent velocity law-of-the-wall are shown in figure 5. Confirmed from the figure that, the mean velocity profiles for the Newtonian flow agrees fairly well with the law-of-the-wall profile, nevertheless for the heating cases, there is a slight leveling-up of velocity near the wall (y^+<10). The mean velocity profiles of CTAC solution flow are close to that of water flow up to y^+=15. Away from 15 wall-units, the profiles show the typical characteristics of DR flows, i.e., a thickening of inner region and the acceleration of the outer flow. These are consistent with the earlier investigations, e.g., Kawaguchi 1996 and Kawaguchi 1997a.

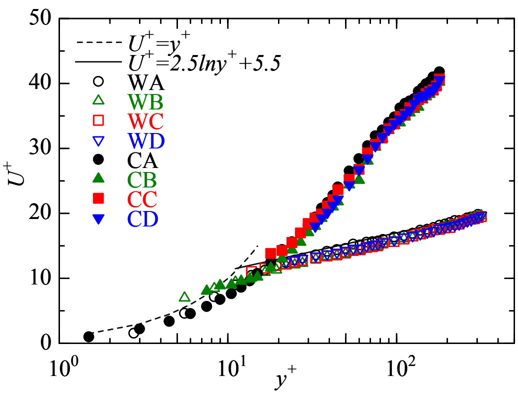

Figure 5. Mean streamwise velocity profiles for both water and aqueous CTAC solution flows.

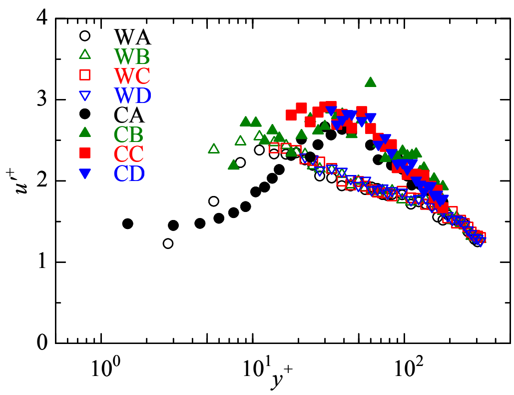

Figure 6. Streamwise velocity fluctuations for both water and aqueous CTAC solution flows.

Figure 6 shows the turbulent intensity profiles for streamwise velocity fluctuations. It is seen that the location of the maximum value of u'/u_τ shifts further away from the wall surface in the DR flow than in the Newtonian flow although some data near the wall are scattering due to the poor data quality for heated CTAC solution case; additionally the maximum value itself becomes larger in DR flow, which are also the typical features of DR flow by additives when the drag reduction is large enough, see also others earlier investigations of DR surfactant flows, e.g., Kawaguchi 1997a, Warholic et al. 1999, etc.

3.2 Influence of drag-reducing surfactant on turbulent temperature field

The measured mean temperature *($\Theta=T_w-T$)* profiles for both Newtonian and DR flows are plotted in figure 7. It shows that the mean temperature profiles for water flows agree quite well with the commonly accepted profile in a channel or pipe for Newtonian fluid flow compiled by Kader (1981). For the CTAC solution flow, however, the mean temperature profiles are significantly different than those of water flow. A large temperature gradient appears in the layer between about y^+=5 and y^+=40. In outer layer region, about y^+>40, the gradient of temperature profiles for DR flow becomes very small and nearly zero from about y^+=50, which implies that the thermal boundary layer may have ended from about 50 wall units for CTAC flow in the present tests.

Comparing the temperature profile in high-gradient layer for the case of CD with the temperature profile in thermal conductive layer, $\Theta^+=Pr*y^+$ (Pr=5.42 for water at 30.0□ is used) it is noticed that they possess similar gradient. It can thus be conjectured based on this similarity that the HTR for DR flow may occur in this layer, due to the heat transfer mechanism being possibly close to that in laminar flow. Kawaguchi et al. 1997b also states the same conjecture of HTR in another way.

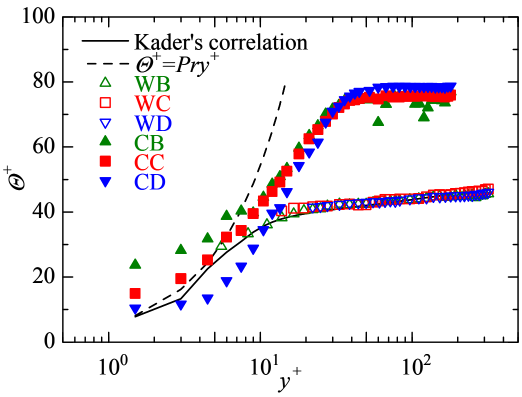

Figure 7. Mean temperature profiles for both water and aqueous CTAC solution flows.

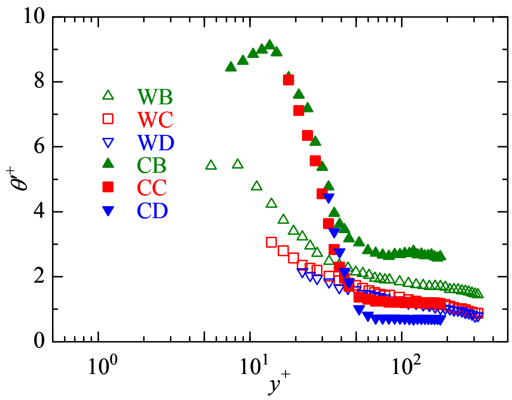

Figure 8. Temperature fluctuations for both water and aqueous CTAC solution flows.

In addition, the larger temperature gradient in layer between y^+=5 and y^+=40 for the DR surfactant flow may results in stronger natural convection in this region, so that, comparing to the water flow, LDV measurement is contaminated much more seriously for CTAC solution flow when heated.

Figure 8 presents the temperature fluctuation intensity profiles for water and CTAC solution flows. One salient feature seen from the figure is that similar to the velocity fluctuation intensity profiles the location of maximum dimensionless temperature fluctuation intensity also shifts away from the wall surface and the value itself become larger for DR flow than for Newtonian flow. This observation is the same in trend as obtained in Kawaguchi et al. 1997b. However, it should be noted here that the magnitude of θ', i.e., the dimensional value, is approximately consistent for water and CTAC solution flows. This can be easily known by concerning about the friction temperature shown in Table 1 for different cases. Corresponding to the coming of end of high-gradient layer, the temperature fluctuation intensity profiles drops quickly until lower than that for water flow. The comparatively high θ'/T_τ in outer layer for the case of CB is probably caused by the scattering of data in that run, see figure 7.

3.3 Influence of drag-reducing surfactant on turbulence transport

From the simultaneous measurements of u, v, and T, the turbulence transport terms such as Reynolds shear stress $-\overline{uv}$ and turbulent heat flux in streamwise and wall-normal directions, $\overline{u\theta}$ and $-\overline{v\theta}$, were estimated.

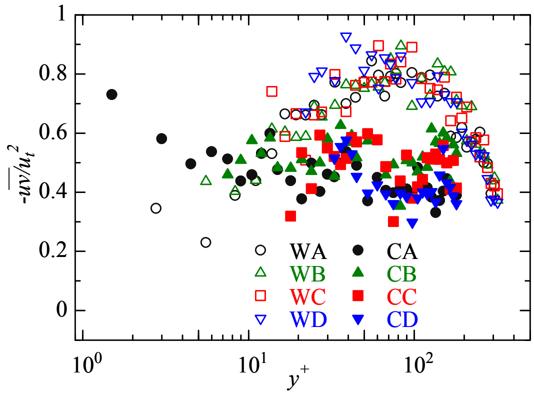

Figure 9. Reynolds shear stress profiles both water and aqueous CTAC solution flows.

Reynolds shear stress profiles for the eight runs are presented in figure 9. In general, a substantial decrease in Reynolds shear stress profile occurs for DR flow by additive of polymer or surfactant, which has been testified to be mainly due to the loss of correlation between the two velocity components. The same phenomenon also appears in the present measurement as shown in figure 7.

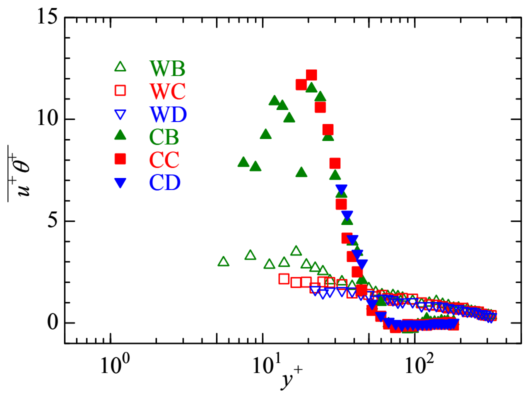

Figure 10. Streamwise turbulent heat flux profiles for both water and aqueous CTAC solution flows.

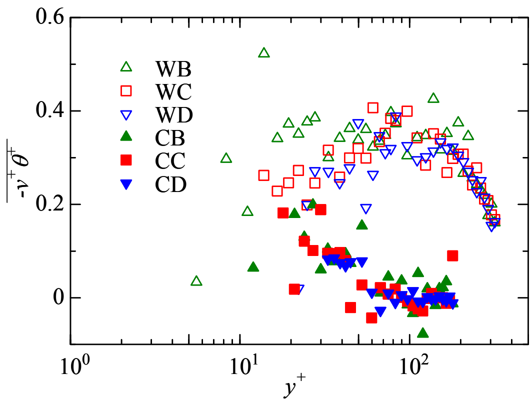

Figure 11. Wall-normal turbulent heat flux profiles for both water and aqueous CTAC solution flows.

The turbulent heat flux profiles in streamwise direction are plotted in figure 10. It clearly shows that the variation of $\overline{u^+\theta^+}$ profile influenced by DR surfactant additive closely couples with variation of velocity and temperature fluctuation intensities, referred to figure 6 and 8. The location of the maximum of u'/u_τ and θ'/T_τ all shift away from the wall and the maximum values are also enlarged in DR flow, so does for $\overline{u^+\theta^+}$ profile. It is also seen that turbulent temperature fluctuation governs the transport term of $\overline{u^+\theta^+}$ more than velocity fluctuation does. The DR surfactant additive shifts the location of maximum of θ'/T_τ and $\overline{u^+\theta^+}$ to almost the same value of $y^+\cong 20$, but not for u'/u_τ. After this peak value, the streamwise turbulent heat flux drops sharply until zero or even slightly negative value. The beginning of low heat flux $\overline{u^+\theta^+}$ region right corresponds to the end of high-temperature-gradient layer in CTAC solution flow, see figure 7 and 8.

The variation trend for wall-normal turbulent heat flux affected by DR surfactant additive is, however, quite different than that for streamwise turbulent heat flux, as shown in figure 11. The term $-\overline{v^+\theta^+}$ seems to be influenced by DR additive in the same way as for the term $-\overline{uv}/u_\tau^2$. This can be expected from the close similarity between the variation of Reynolds stress profiles and wall-normal turbulent heat flux profiles from Newtonian flow to DR flow, by comparing figure 9 with figure 11. The wall-normal turbulent heat flux is decreased in the whole measured region for the present test, which should be also mainly due to the loss of correlation between temperature fluctuation and wall-normal velocity component fluctuation because the temperature fluctuation is locally enhanced by DR additive. Actually, the enhancement of $\overline{u^+\theta^+}$, as shown in figure 10, means that the fluctuations of u and θ are in phase and the decrease of $-\overline{uv}/u_\tau^2$, as shown in figure 9, means that the fluctuations of u and v are out of phase, which evidently reduces to that θ and v are also out of phase. The loss of correlation between temperature and wall-normal velocity component, consequently the decrease of wall-normal turbulent heat flux, should be responsible for the HTR, just the same as that the loss of correlation between streamwise velocity component and wall-normal velocity component, consequently the decrease of Reynolds stress, should be responsible for the DR for DR flow by additive. Reminding the analysis on temperature profile in last section, it seems that HTR may occur at all the flow region except for layer A.

To confirm the aforementioned conjecture more precisely, further experiments are necessary, for example, to take much more simultaneous data sets for velocity and temperature.

4. CONCLUSIONS

The simultaneous velocity and temperature fluctuations for both of water and CTAC solution flow in a 2D channel are measured by means of a 2-component LDV combining with a fine-wire thermocouple probe successfully. Based on the coupled velocity and temperature fluctuation data sets, the turbulence transport terms such as Reynolds stress $-\overline{uv}$ and turbulent heat flux in streamwise and wall-normal directions, $\overline{u\theta}$ and $-\overline{v\theta}$, as well as velocity and temperature profile and their fluctuation intensity, are calculated.

Typical hydrodynamic features of drag-reducing flow by additive, such as thickening of inner region and acceleration of outer flow and the depression of Reynolds stress have been reproduced.

From measured temperature profiles for DR flow, two layers for thermal field are observed. From y^+=5 to y^+=40, the temperature profile has large gradient similar to that of the temperature profile in thermal conductive layer for Newtonian flow. Out of this layer, temperature profile has small gradient even near to zero from about y^+=50, which means ending of the thermal boundary layer for CTAC flow in the present tests. Heat transfer reduction for DR flow may occur in the high-temperature-gradient layer based on the analysis on temperature profile. In addition, the existence of this layer may be the main reason of contaminating the LDV measurement.

The maximum value of streamwise turbulent heat flux profile normalized by friction velocity and temperature was enlarged by DR surfactant additive and the location of the peak shifts to away from the wall, which is similar to the phenomena appear in u' and θ' profiles. However, the turbulent heat flux in wall-normal direction is depressed in the whole region of the measured range, in a similar way of the depression of Reynolds stress, i.e., decorrelation between v and θ vs. decorrelation between u and v. HTR being also due to the decrease of $-\overline{v^+\theta^+}$ was then conjectured.

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