# EXPERIMENTAL INVESTIGATION OF VISCOUS DRAG REDUCTION BY FLOW CONTROL OF LAMINAR TO TURBULENT TRANSITION USING MICRO-GROOVE SURFACE PATTERN

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## Abstract

The stabilizing effect of surface embedded grooves on the laminar boundary layer development is studied experimentally in the inlet region of a channel flow. The stabilization is thought to be due to the ability of a grooved surface to suppress the velocity fluctuations in the spanwise direction on a restricted portion of the wetted surface which prevents vorticity development close to the solid surface. This control strategy is implemented in a groove-modified channel flow in which the front part has a grooved surface structure. The results of pressure drop measurements indicate that grooved surfaces can effectively delay laminar to turbulence transition, leading to significant reduction of the viscous drag. In the rear flat part of the groove-modified channel test section, a maximum drag reduction of $\mathrm{DR} \simeq 35\%$ was measured. This corresponds to an overall drag reduction of $\mathrm{DR} \simeq 16\%$ at a length Reynolds number of $Re_x \simeq 10^6$. The drag reduction effect persisted in a narrow range of flow velocities and for the reported experimental conditions corresponds to groove dimensions between 1.5 and 2 viscous length-scales.

## 1 Introduction

The present authors have recently shown that a significant reduction of turbulent drag can be obtained by using surface-embedded grooves in a fully developed turbulent channel flow (Frohnapfel, Jovanović and Delgado, 2007a). In a series of experiments, drag reduction was deduced from pressure measurements in a groove-modified channel flow. Measurements have shown that the magnitude of the drag reduction far exceeds what has been achieved so far but exists only in a narrow range of flow velocities corresponding to groove dimensions of less than one viscous length-scale. In the present paper we show that the same surface pattern, that was successfully used for turbulent flow control, can also be employed to stabilize the laminar boundary layer development.

Similarities between fully developed turbulence and laminar to turbulence transition and therefore between turbulent drag reduction and stabilization of the laminar boundary layer have been reported in the literature before (Hinze, 1975; Laufer, 1975, 1982; Jovanović and Pashtrapanska, 2004). In our previous work we focused on the importance of turbulent dissipation for viscous drag reduction and in the following it will be summarized how this analysis leads to the conclusion that similar surface structures can be used for both cases, turbulent drag reduction and laminar boundary layer stabilization.

The average total energy dissipation rate $\overline{\Phi}$:

$$\overline{\Phi} = \underbrace{\frac{1}{V}\int_V \nu \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right)\frac{\partial \overline{U}_i}{\partial x_j}\mathrm{d}V}_{\mathrm{I}} + \underbrace{\frac{1}{V}\int_V \overline{\nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}}\mathrm{d}V}_{\mathrm{II}} = \frac{A_w \tau_w U_B}{\rho V}$$

is composed of direct (I) and turbulent dissipation (II) and can be evaluated form the work done against the wall shear stress, $\tau_w$, per unit mass of the working fluid, $\rho V$, where $A_w$ is the wetted surface area and $U_B$ is the bulk velocity. An order of magnitude analysis shows that in turbulent flows the largest contribution to $\overline{\Phi}$ is due to turbulent dissipation which reaches a maximum at the wall as shown in Figure 1. Therefore, large turbulent drag reduction can be expected if the turbulent dissipation at the wall is minimized. It can be shown that kinematic constraints imposed by local axisymmetry on the velocity fluctuations near the wall force the turbulent dissipation rate to vanish at a solid surface (Jovanović and Hillerbrand, 2005). Since near-wall velocity fluctuations are always two-component and the required axisymmetry is in respect to the axis

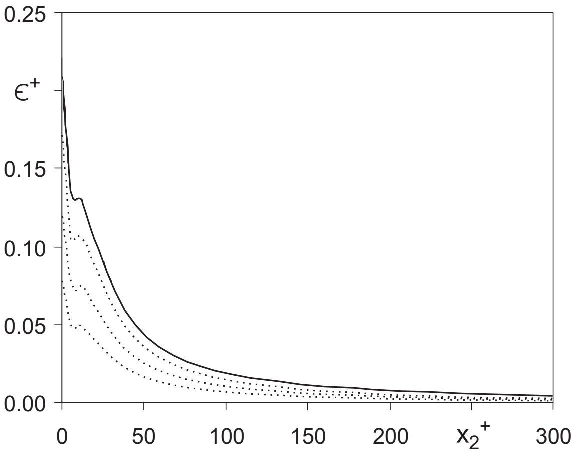


Figure 1: Distribution of the turbulent dissipation rate versus wall distance normalized with the wall shear velocity and the kinematic viscosity of the flow medium for a plane channel flow. The upper solid line corresponds to the DNS data at $Re_\tau = 395$ by Moser, Kim and Mansour (1999); the lower dotted lines show sketched estimates of $\epsilon^+$ profiles for decreasing turbulent dissipation at the wall and increasing drag reduction, which reaches a maximum when $\epsilon_{\text{wall}} \to 0$.

aligned with the flow direction, the resulting near-wall turbulence corresponds to a one-component state with the streamwise velocity component much larger than in the other two directions.

The examination of numerical databases of wall-bounded flows reveals that whenever turbulence approaches the one-component limit near the wall, such a tendency is accompanied by: (i) an increase in the smallest scale of motion defined in terms of Kolmogorov's length-scale, $\eta_K = (\nu^3/\epsilon)^{1/4}$; (ii) a consequent decrease in the spectral separation, $L/\eta_K$, which represents the ratio between the large, $L$, and smallest scale, $\eta_K$, of motion; (iii) a reduction in the turbulent Reynolds number $R_\lambda = q\lambda/\nu$ based on Taylor's micro scale which is related to $\epsilon$ by $\epsilon \simeq 5\nu q^2/\lambda^2$. Conclusion (iii) can be drawn since the ratio $L/\eta_K$ can solely be approximated in terms of $R_\lambda$ which decreases as $R_\lambda$ decreases (Jovanovic *et al.*, 2006a). These deductions are in close agreement with the results of direct numerical simulations with forced boundary conditions which display high drag reduction when turbulence in the viscous sublayer is manipulated to tend toward the one-component state in an axisymmetric fashion (Lee and Kim, 2002; Frohnapfel *et al.*, 2007b).

Based on the considerations summarized above, the surface topology for turbulent drag reduction was designed to force turbulence at the wall to tend towards the one-component state by inserting grooves (as shown in Figure 2) which, on a restricted part of the surface, suppress velocity fluctuations in the normal and spanwise directions almost in the same fashion (Frohnapfel, 2007).

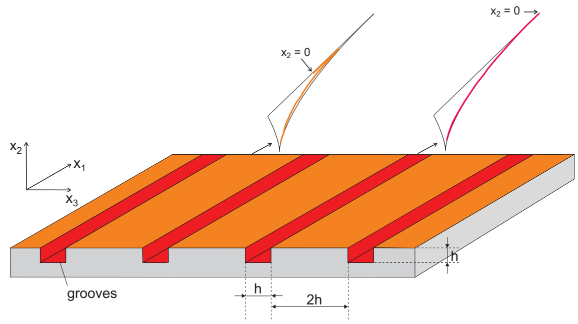


Figure 2: Surface topology capable of producing a smart interface between the flowing fluid and the solid boundary which promotes a large viscous drag reduction under particular circumstances: grooves are inserted in the wall and are aligned in the flow direction with the aim of forcing turbulence in the grooves towards the one-component limit. Sketched are the expected trajectories across anisotropy-invariant maps for each portion of the surface.

For laminar boundary layer control a qualitative analysis of the transport equations for statistical properties of small disturbances can provide interesting insight. Assuming that the disturbances are statistically axisymmetric and neutrally stable so that equilibrium exists between production and viscous dissipation during the period of stable laminar flow development, one deduces that high values of anisotropy in the free stream have a stabilizing effect on the boundary layer development. A comparison of existing experimental data and the theoretical prediction support this deduction (Jovanovic *et al.*, 2006b). This analysis is not restricted to the influence of anisotropy in the free stream but in addition includes the behavior of disturbances in the near-wall region. As the wall is approached, $x_2 \to 0$, the energy of the disturbances, $k = 1/2q^2$, increases as $k \to (\epsilon_{wall}/\nu)x_2^2/2)$. If disturbances in the near-wall region are fixed at the one-component state, the turbulent dissipation at the wall cannot develop ($\epsilon_{wall} = 0$) and we may expect that the disturbances cannot be amplified so that the spectral energy transfer will never be initiated.

If we agree that the essential feature of turbulence is related to its ability to create motions at different scales and that the promotion of rapid mixing is caused by an increase in the spectral separation (which under common circumstances increases with increasing Reynolds number), then we should be able to postpone the breakdown to turbulence by controlling disturbances in the proximity of the wall. For a practical approach this conclusion suggests that a laminar boundary layer can be stabilized if disturbances are forced to approach a one-component state at the wall. Since a similar forcing was intended in the previous work in fully developed turbulent channel flows and promising results were obtained with surface grooves it was decided to carry out similar experiments for laminar flow control.

The aim of this paper is to contribute towards an improved understanding of the fundamentals of laminar flow control by studying the stabilizing effect produced by surface-embedded grooves on the laminar boundary layer developing naturally along the front section of a two-dimensional channel. An experimental effort is made to provide the evidence for delay of laminar to turbulence transition caused by a grooved surface.

## 2 Experimental facility and measuring procedure

The two-dimensional channel and the related equipment that were used in the present experiments are similar to the ones employed in the previous investigations of flow control in fully developed turbulence. The corresponding description can be found in Frohnapfel, Jovanović and Delgado (2007a). The air flow was produced with a multi-purpose flow facility constructed according to DIN 24 163 requirements. It consists of a large circular housing 2.2 m in diameter and 7 m in length equipped with a centrifugal fan and a speed-controlled d.c. motor unit, a set of five Venturi nozzles manufactured according to DIN 1952 for determination of the volume flow rate, an assembly of honeycomb and screens and an outlet module which allows connection of the chamber housing to the experimental test section. This general-purpose facility provides well-controlled flow rates, good flow uniformity and a satisfactory turbulence level at the entrance of the experimental test section. While a tripping device at the channel inlet ensured a fully developed turbulent state in the previous investigations, the channel was now equipped with a two-dimensional nozzle having a contraction ratio 8:1 which was flush mounted with the channel top and bottom walls. The set-up thus provided natural development of boundary layers along the test section walls.

Two different arrangements of the test sections were used for the experiments, one with flat walls and the other with groove-modified walls, where a grooved surface is installed in the front part of the channel test section as shown in Figure 3*(a,b)*.

To investigate the potential stabilizing effect of the grooved surface topology on the initial boundary layer development, a surface structure with groove dimensions $h = 150\ \mu\mathrm{m}$ and separation $2h = 300\ \mu\mathrm{m}$ was employed (see figure 2). The physical dimensions of the surface grooves are the same as used for the previous experiments on turbulent drag reduction. The surface pattern was produced my machine milling and mechanically polished after the manufacture to eliminate irregularities in the surface pattern produced during the milling process.

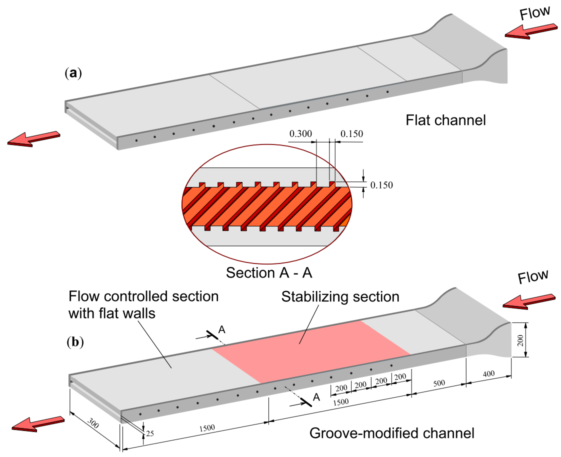


Figure 3: Two-dimensional channel flow with flat and groove-modified test section arrangements. (a) Reference test section configuration. (b) Configuration of the test section for laminar flow control.

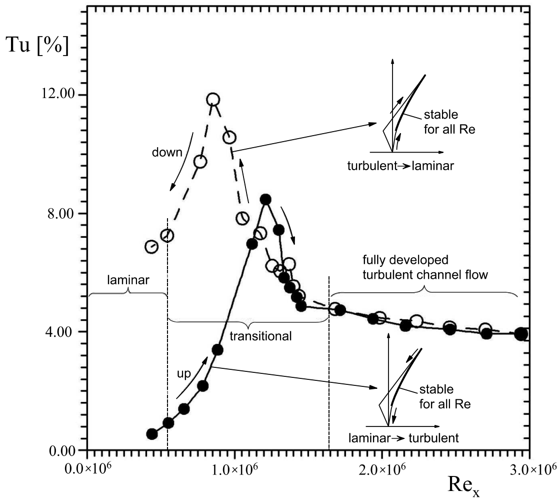


Figure 4: Different faces of transition: intensity of turbulence normalized by the mean velocity $Tu = \sqrt{\overline{u^2}}/\overline{U}_c$ measured at the channel centerline for increasing (•) and decreasing (○) flow rates as a function of the Reynolds number $Re_x$. Inserts provide a possible interpretation of the experimental results in terms of anisotropy variations during forward and reverse transitions across the anisotropy-invariant map following the study by Jovanović *et al.* (2006b).

To quantify the stabilizing effect of a structured surface which is expected to produce a decrease in the pressure loss, measurements of pressure differentials were made along two channel test sections. A Scanivalve pressure scanner and a calibrated Höntzsch pressure transducer with a combined range of 0-1 kPa were used to for this propose with a resolution of $0.1\%$ full-scale. Special care was taken to maintain the transducer drift as small as possible, since this could produce significant measuring errors resulting in misleading conclusions. For all reported results, the drift was within $0.3\%$ of full-scale deflection. The pressure signals were averaged over a period of $300$ s, which was found to be sufficiently long to achieve good measuring accuracy at all Reynolds numbers.

To clarify the character of the transitional flow regime in the test section, preliminary measurements of turbulence were performed using hot-wire anemometry. These measurements were made at the channel centerline and very close to its exit by systematically increasing the flow rate, starting from the minimum up to the desired maximum value and subsequently by decreasing the volume flow rate from the maximum towards the minimum value. For naturally developing flow conditions, statistical quantities and the transition Reynolds number exhibit a large hysteresis effect, i.e. differences for increasing and decreasing flow rates (Fischer, 1999). These differences can be clearly seen in Figure 4 and suggest that laminar flow control experiments must be made consistently in the same fashion and with identical flow conditions at the channel inlet in order to obtain meaningful conclusions from the experimental results. Since it is well known that a delay of the breakdown leading to turbulence is far more easy to achieve for a low intensity of free stream turbulence, all experiments in this study were performed by slowly increasing the flow rate in the channel.

During the present investigations several hundred measurements have been made in which a wide range of different parameters have been explored. Flow conditions were successively refined until the optimum parameters for successful drag reduction measurements were achieved. Only a small sample of experimental results is reported in the paper.

## 3 Experimental results

Experiments were conducted at channel bulk velocities between $2.3$ and $11.8\ \mathrm{m\,s^{-1}}$, corresponding to the Reynolds number range $Re_x = 0.5 \times 10^6 - 2.8 \times 10^6$. Since experiments were done for developing flow conditions, the representative Reynolds number $Re_x = U_B L/\nu$ is based on the bulk velocity, $U_B$, the entire test section length, $L = 3.5$ m, and the air viscosity, $\nu$. The local pressure drop measurements along the flat and groove-modified test sections are presented as the difference with respect to the pressure measured at the first pressure tap located $0.7$ m from the test section inlet as shown in figure 3.

For the groove-modified channel the pressure drop measurements made at the first six points in the flow direction correspond to the front part of the channel test section where the structured surface was placed. The following seven pressure measurements correspond to the rear part of the test section with smooth channel walls as shown in Figure 3($b$). In all plots presented in Figure 5 it can be observed that the pressure drop for the last measuring location in the grooved part of the test section is slightly higher than expected based on the surrounding measuring locations. However, this difference does not seem to affect the pressure drop over the entire test section.

The nonlinear variations in pressure drop distributions shown in Figure 5($a$,$b$), which correspond to the laminar regime and relatively low Reynolds numbers, indicate that the flow is developing. From these distributions, it appears that in the laminar flow regime there is no noticeable difference in the pressure losses between flat and grooved surfaces, suggesting that an increase in the wetted area has no impact on the viscous drag if the grooves are smaller than about one viscous length-scale (see Figure 7). Therefore, it might be concluded indirectly that in laminar flow small grooves induce negligible wall shear stress along the side walls of the grooves compared with the wall shear stress which acts along the bottom walls of the grooved surface.

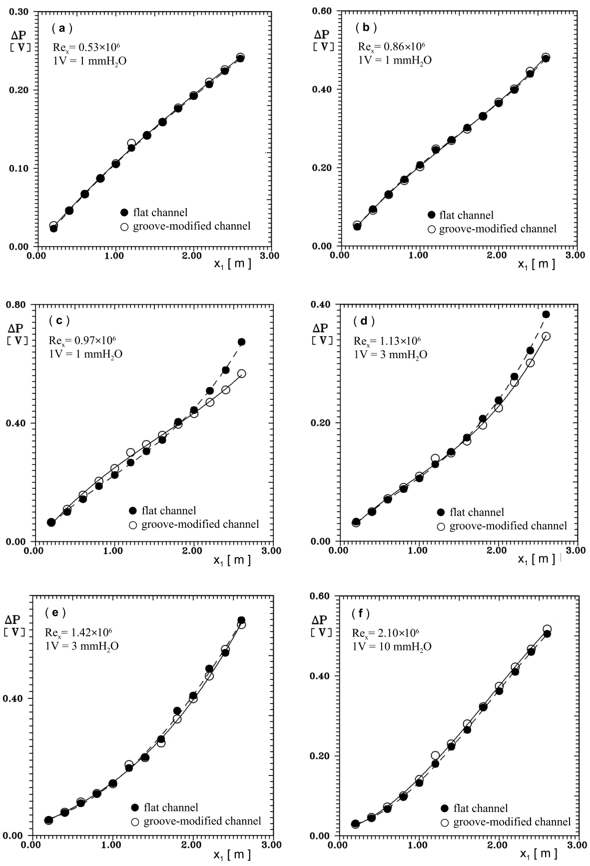


Figure 5: Comparisons of pressure drop distributions measured over flat and groove-modified test sections at different Reynolds numbers. The Reynolds numbers are based on the bulk velocity and the test section length.

In Figure 5(*e,f*) the pressure drop distributions approach a linear trend, for the last few measuring stations which indicates that the flow tends towards a fully developed state. Therefore, it may be concluded that the pressure drop measurements in the rear part correspond to the turbulent regime.

Comparisons of these measurements carried out in flat and groove-modified test sections display no difference, implying that the grooved surface has no impact on the pressure loss if the groove dimensions are larger than about 2.5 viscous length-scales. These results are in fair agreement with our previous experiments made in a fully developed turbulent channel flow at low Reynolds numbers, in which a large turbulent drag reduction was measured only in a narrow range of flow velocities which corresponds to groove dimensions slightly lower than one viscous length-scale (Frohnapfel, Jovanović and Delgado, 2007b).

Noticeable differences in the pressure drop measurements between flat and groove-modified test sections can be observed in the transitional regime as shown in Figure 5(*c,d*). In the front part of the test section (i.e. the first six measurement points in the flow direction) which consists of flat channel walls in the reference case and a grooved surface structure in the groove-modified channel, the pressure drop is slightly increased in the groove-modified test section. However, in the rear part of the test section which consists of smooth channel walls in both cases the pressure drop is reduced such that the pressure drop over the entire test section is smaller for the groove modified channel. The slightly increased pressure drop in the front part of the test section can be interpreted as interaction of groove structures with near-wall disturbances which results in a stabilizing effect for the further flow development over the rear flat part of the channel. The results confirm indirectly that grooves can act to delay breakdown leading to turbulence through favorable action of the structured surface which is designed to prevent the growth of disturbances very close to the wall. Figure 6 stresses the details of Figure 5(*c*) and shows that maximum gain resulting in a large reduction of the pressure drop is achieved by stabilizing the boundary layer development over the rear flat part of the groove-modified test section.

On the basis of the theoretical considerations, it is expected that the structured surface as shown in Figure 2 can effectively delay transition to turbulence only under a relatively narrow range of flow conditions. The experimental results shown in Figure 5 support this conjecture and suggest that without attempting to vary the flow conditions in small steps it is not possible to detect the regime for which grooves favorably influence the transition delay (Bushnell, Hefner and Ash, 1977).

By comparison of the pressure drop measured in the flat and groove-modified test sections respectively, drag reduction due to the stabilizing effect of the

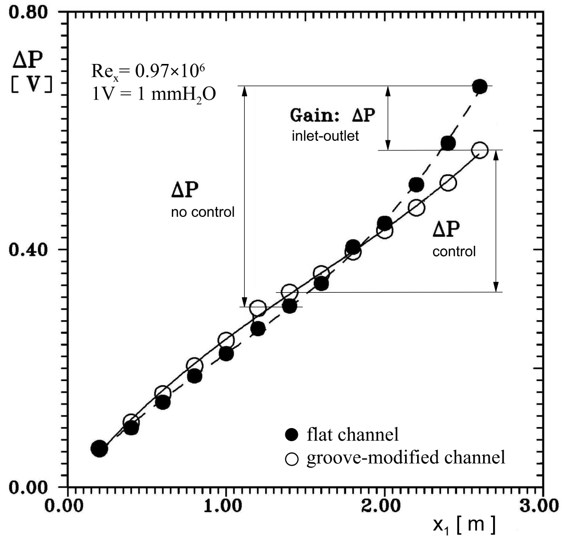


Figure 6: Comparison of pressure drop distributions in flat and groove-modified test sections for maximum drag reduction effect.

grooved surface on laminar boundary layer development can be estimated as follows:

$$\mathrm{DR} = 1 - \frac{(\Delta p)_{\mathrm{groove-modified\ channel}}}{(\Delta p)_{\mathrm{flat\ channel}}}.$$

Figure 7 shows drag reduction results plotted against the dimensionless groove size according to

$$h^{+} = \frac{\tilde{u}_{\tau} h}{\nu},$$

where the average value of the friction velocity, $\tilde{u}_{\tau}$, was determined from the pressure drop measured over the front part of the test section and the cross-sectional area of the reference channel.

From the experimental results presented in Figure 7, it appears that a high drag reduction was obtained in a narrow range of flow velocities which correspond to the dimensionless size of the grooves between 1.5 and 2 viscous length-scales. The trends in the experimental data reveal that the high drag reduction $\mathrm{DR} \simeq 35\%$ originates from the decrease in the pressure drop over the rear flat portion of the groove-modified test section, resulting in an overall net gain of $\mathrm{DR} \simeq 16\%$. We note a strong similarity between the results presented here and those obtained in fully developed turbulent channel flow by Frohnapfel, Jovanović and Delgado (2007a). This evidence is not accidental and indicates similarity in causative physics hidden behind the mechanism responsible for turbulent drag reduction and the mechanism capable of preventing breakdown of an initially laminar boundary layer leading to turbulence (Bushnell, Hefner and Ash, 1977; Jovanovic *et al.*, 2006b).

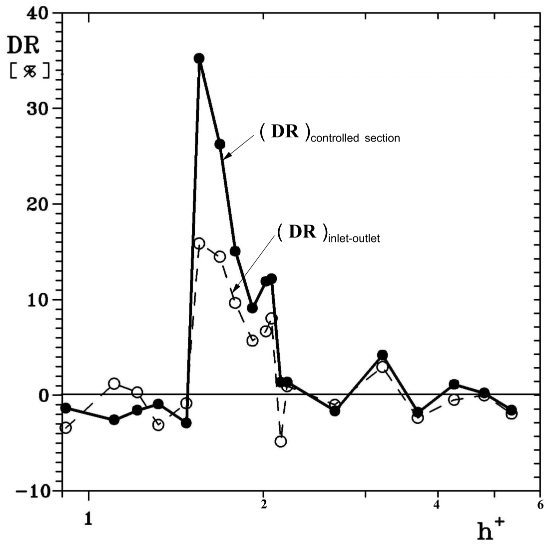


Figure 7: Drag reduction versus non-dimensional groove height: $(\mathrm{DR})_{\mathrm{controlled\ section}}$, drag reduction measured over the flat part of the groove-modified test section; $(\mathrm{DR})_{\mathrm{inlet-outlet}}$, net drag reduction measured over the entire length of the groove-modified test section.

## 4 Conclusions and final remarks

In order to investigate the stabilizing effect of surface-embedded grooves on laminar boundary layer development, drag reduction experiments were conducted in the inlet length of a two-dimensional channel flow. By comparing pressure drop measurements made along flat and groove-modified test sections, the favorable influence of a grooved surface on the delay of the breakdown leading to turbulence was quantified by relatively simple means. A high drag reduction effect was found to persist in a narrow the range of flow velocities corresponding to groove dimensions between 1.5 and 2 viscous length-scales which is wider compared to our previous findings obtained in fully developed turbulent channel flow. Comparisons of pressure drop distributions for high drag reduction indicate that the major effect of the grooved surface on laminar boundary layer development is associated with the ability of grooves to restructure disturbances close to the wall towards the limiting state where they cannot be amplified, resulting in a delay of transition to turbulence.

The experimental results presented in this study provide interesting evidence of the similarity between turbulent drag reduction and the delay of laminar to turbulent transition. In addition, they indirectly support the fundamental deductions that disturbances in laminar boundary layer must be statistically axisymmetric and invariant under rotation about the axis aligned with the mean flow direction in close proximity of the solid boundary in order to ensure that the flow remains laminar during its development (Jovanović, 2004; Jovanović *et al.*, 2006b).

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