International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:2, 2016

Effects of Upstream Wall Roughness on Separated Turbulent Flow over a Forward Facing Step in an Open Channel

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***Abstract*—**The effect of upstream surface roughness over a smooth forward facing step in an open channel was investigated using a particle image velocimetry technique. Three different upstream surface topographies consisting of hydraulically smooth wall, sandpaper 36 grit and sand grains were examined. Besides the wall roughness conditions, all other upstream flow characteristics were kept constant. It was also observed that upstream roughness decreased the approach velocity by 2% and 10% but increased the turbulence intensity by 14% and 35% at the wall-normal distance corresponding to the top plane of the step compared to smooth upstream. The results showed that roughness decreased the reattachment lengths by 14% and 30% compared to smooth upstream. Although the magnitudes of maximum positive and negative Reynolds shear stress in separated and reattached region were $0.02U_e$ for all the cases, the physical size of both the maximum and minimum contour levels were decreased by increasing upstream roughness.

***Keywords*—**Forward facing step, open channel, separated and reattached turbulent flows, wall roughness.

I. Introduction

SEPARATED and reattached flows have received significant research attention in the past few decades. Due to their diverse engineering and environmental applications (for example, in pipe flows, combustors, airfoils and wind turbines), the fluid engineering community has put a significant emphasis on these topics. Although numerous experimental and numerical studies have been performed on the separated and reattached flows, understanding on these flows is still incomplete. Most of the previous investigations were undertaken to characterize the effects of Reynolds number, Re_h on backward facing step (BFS), forward facing step (FFS), ribs and fences in wind tunnels or closed channels. However, the effects of the upstream roughness on the separation and reattachment phenomena in open channels have not yet been investigated. Thus, the motivation of the present study is to investigate the effects of upstream wall roughness on a FFS immersed in an open channel turbulent flow.

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The flow field over a FFS can be divided into three distinct regions: an upstream recirculation region before the step, a primary recirculation region on top of the step and a redevelopment region after the reattachment. Fig. 1 shows a schematic of the FFS with the nomenclature used and the three flow regions alluded to earlier. It also shows the Cartesian coordinate system employed in the present study: the x-coordinate, parallel to the streamwise direction, starts from the leading edge of the step and the y-coordinate, perpendicular to the streamwise direction, starts from the upstream surface of the channel. The upstream mean free stream velocity is indicated by U_e, the boundary layer thickness is δ and the height of the step is denoted by h. Due to the adverse pressure gradient caused by the step, the flow first separates and then reattaches on the front wall of the step. The height and length of this separation and reattachment is denoted by h_u and l_r respectively. The flow then separates at the leading edge of the step and reattaches after some distance on top of the wall of the step. This distance is defined as the reattachment length, L_r and the maximum height of this recirculation bubble is denoted by h_d. After the reattachment, a new shear layer forms and develops into a new boundary layer.

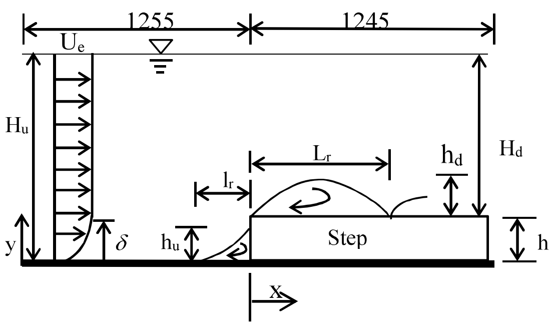

Fig. 1 Different regions of FFS and nomenclature

The flow characteristics over a forward facing step are affected by several dimensionless parameters such as the Reynolds number based on step height $Re_h = U_e h/\nu$ (where ν is the kinematic viscosity), aspect ratio, $AR = W/h$ (where W is the width of the channel), blockage ratio, $BR = h/H_u$ (where H_u is the upstream channel height), upstream turbulence intensity (T_u) and equivalent sand grain roughness Reynolds number (k_s^+). For example, [1] studied the effects of Reynolds number on the FFS ranging from 1400 to 19000 and boundary layer to step height ratio (δ/h) ranging from 0.83 to 2.5. They used different blockage ratios ranging from 0.032 to 0.097 with an upstream turbulence intensity of 1.43%. They found that the reattachment length, L_r increased linearly with Re_h up to a threshold value of 8500. After this value, L_r was found to be independent of the Re_h, although they used different Re_h and δ/h combinations. In open channel flows, Froude number, $Fr_h = U_e/\sqrt{(gh)}$ is another important parameter on which the flow characteristics may depend.

As noted earlier, the majority of the previous studies were conducted in wind tunnels or closed channels and over smooth surfaces. Reference [2] and [3] studied the effect of a smooth upstream surface with a rough FFS in a wind tunnel. They used particle image velocimetry (PIV) to conduct measurements at Re_h = 3450 and δ/h = 8. By changing the slopes of the roughness from negative to positive on top of the step, Ren and Wu [2] observed that the flow characteristics were significantly dependent on the roughness topography employed on the specific slopes. Reference [4] is another study in which the roughness effect on a FFS was investigated. In this study, PIV measurements were performed to examine the effects of upstream roughness on a smooth FFS in a closed channel. They used a fixed blockage ratio of 0.2 but varied the Reynolds numbers from 2040 to 9130. They conducted quadrant decomposition to investigate the contribution of the Reynolds shear stress to the flow and concluded that upstream roughness decreased the ejections and sweeps but the inward and outward interactions are independent of upstream roughness.

The objective of the present study is to investigate the effects of upstream roughness on characteristics of the separation and reattachment regions over a FFS placed in a shallow open channel turbulent flow. A series of experiments were performed in which the Reynolds number, Froude number, blockage ratio and channel aspect ratio were all kept constant but the upstream wall condition was varied from a reference smooth wall, to two different rough walls made from sandpaper 36 grit and sand grains. A PIV technique was used to conduct detailed velocity measurements, and the velocity data were post-processed to characterise how changes in the upstream wall roughness affect the separation bubbles, and also the mean velocity and higher order turbulence statistics in the separation and reattachment regions.

II. Experimental Procedure

The experiments were performed in a recirculating open channel. A schematic of the test section is shown in Fig. 1. The length of the test section was 2500 mm and the inner width was 186 mm. For easier optical access, the test section was made with transparent acrylic plates. The water depth was 60 mm prior to the step in the channel. The FFS used to induce the flow separation in this experiment was made of smooth acrylic plates of height, h = 12 mm. The FFS was positioned 1255 mm downstream from the inlet section of the channel. A 3.5 mm trip, spanning the width of the channel was placed on the inlet wall to ensure that the flow becomes fully developed before encountering the step. The aspect ratio (AR = W/h) was 15.5 which is larger than 10 required to make the flow two dimensional at the mid span of the channel [5], [6]. The blockage ratio was 0.2 and the Reynolds numbers based on the upstream water height and step height were, respectively, $Re_H \approx 17000$ and $Re_h \approx 3400$, which were all kept constant throughout the experiments. The Froude number was kept at $Fr \approx 0.8$, and this enabled the establishment of a wave-free or calm free surface necessary for implementation of high quality PIV measurements.

The smooth upstream wall investigated (hereafter referred as SM) was made of 6 ± 0.1 mm thick acrylic plates. The rough walls were made by gluing 1.5 mm thick roughness elements consisting of either sandpaper 36 grit or sand grain (hereafter referred as SP and SG respectively) onto 4.5 mm thick acrylic plates resulting in a combined height of 6.0 ± 0.1 mm. To obtain the topographical information of the roughness elements, a Veeco Wyco NT9100 optical profilometer was used. This particular profilometer uses white light interferometry with sub-micron vertical accuracy. The surface statistics for the two roughness elements are summarized in Table I; where k_t is the average of ten maximum peak-to-trough roughness heights, the root-mean-square roughness height is denoted by k_{rms}, Sk and Ku are the skewness and flatness of the roughness probability density function, respectively. The equivalent sand grain roughness for each of the roughness elements was determined using (1) proposed by [7]:

$$k_s = 4.43 k_{rms}(1 + Sk)^{1.37} \quad (1)$$

TABLE I
SURFACE TOPOGRAPHY OF THE ROUGH WALLS

Rough elements	k_t (mm)	k_s (mm)	k_{rms} (mm)	Sk	Ku
SP	1.12	1.37	0.16	0.61	3.23
SG	1.83	1.91	0.42	0.02	2.13

A planar particle image velocimetry (PIV) was used to conduct detailed velocity measurements in x-y planes situated in the mid span of the open water channel. The flow was seeded with 10 μm fluorescent tracer particles and a double-pulsed Nd:YAG laser (120 mJ/pulse) was used to illuminate the flow. The scattered light from the particles were captured by a 12-bit charge couple device (CCD) camera with 2048 × 2048 pixel array and 7.4 pixel pitch. The camera was equipped with an orange filter with band pass wavelength of 570 nm which improves the quality of the velocity vectors close to the walls by reducing the glare. The field of view was set to 70 mm × 70 mm. Detailed velocity measurements were performed in three planes; an upstream plane PA that spanned from -25h to -19.2h, P0 spanning from -4h to 1.8h and P1 spanning from -1.5h to 4.3h. PA was chosen to characterize the approach boundary layer and P0 and P1 were chosen to capture the flow fields within the separation and reattachment regions. Following a thorough convergence test, a sample size of 5000 instantaneous image pairs was acquired and the adaptive correlation option in DynamicStudio version 4.10

(Dantec Dynamics Inc.) was used to post process the data. An interrogation area of 32 pixels × 32 pixels with 50% overlap was used in the adaptive correlation. The spacing between adjacent vectors was 0.046h in both x and y direction. The time between image pairs and the size of the integration area were chosen to ensure that the average displacement of particles was less than one quarter of the length of the integration area.

To reduce the bias and precision errors associated with the PIV system, precautionary guidelines and advanced evaluation algorithms described by [8] were used. Using the procedure recommended by [9], the uncertainty at 95% confidence level in the mean velocities was 1.4% of the streamwise velocity. The uncertainty for the turbulence intensity and Reynolds shear stress was 2% and 2.8% respectively.

III. Results And Discussion

A. Upstream Approach Boundary Layer

The velocity measurements performed in the upstream plane of the reference smooth wall (SM) and two rough walls (SP and SG) were analyzed to properly characterize the state of the boundary layers prior to encountering the smooth FFS. The distributions of the streamwise mean velocity show that the profiles over the rough wall are less uniform than over the smooth wall. This can be attributed to higher drag as well as mass and momentum deficit produced by wall roughness. The roughness effects were observed to be more severe over the sand grains than the sand paper. At $y = h$, for example, the mean streamwise velocity is 0.762U_e for SM whereas for SP and SG it is 0.747U_e and 0.690U_e respectively. This comparison suggests that, relative to the SM wall, the SP and SG walls reduced the approach velocity by 2% and 10% respectively. The boundary layer shape factor ($H = \delta^*/\theta$) and Reynolds number based on the momentum thickness (Re_θ) for the three upstream wall conditions are summarized in Table II. The shape factor was increased by the wall roughness from 1.33 to 1.62 which agrees well with previous studies at comparable Re_θ [1], [10]. It was found that the ratio of the boundary layer to step height, δ/h is 4.7 ± 0.3 for all three test conditions. The Clauser plot technique was used to determine the friction velocities, U_τ and skin friction coefficient, C_f. The values of C_f and equivalent sand grain roughness Reynolds number, k_s^+ are also presented in Table II. The higher C_f values for SP and SG compared to SM are indication of higher drag the flow experienced over the rough walls than over the smooth wall. The results also demonstrate that the roughness condition of SP is in transitional rough regime ($k_s^+ < 70$) but for the SG it is in fully rough regime ($k_s^+ > 70$). Wall roughness was also observed to increase both the streamwise and wall-normal turbulence intensities particularly in the wall region. At the same height of the step ($y = h$), the turbulence intensities for SM, SP and SG are 0.065U_e, 0.074U_e and 0.088U_e respectively.

TABLE II
UPSTREAM BOUNDARY LAYER PARAMETERS AND REATTACHMENT LENGTHS

Wall topography	U_e (mm)	Re_θ	H	C_f	k_s^+	L_r/h	h_d/h
SM	0.267	1930	1.33	0.004		1.78	0.16
SP	0.272	2000	1.35	0.005	13	1.53	0.12
SG	0.283	2250	1.62	0.010	176	1.26	0.09

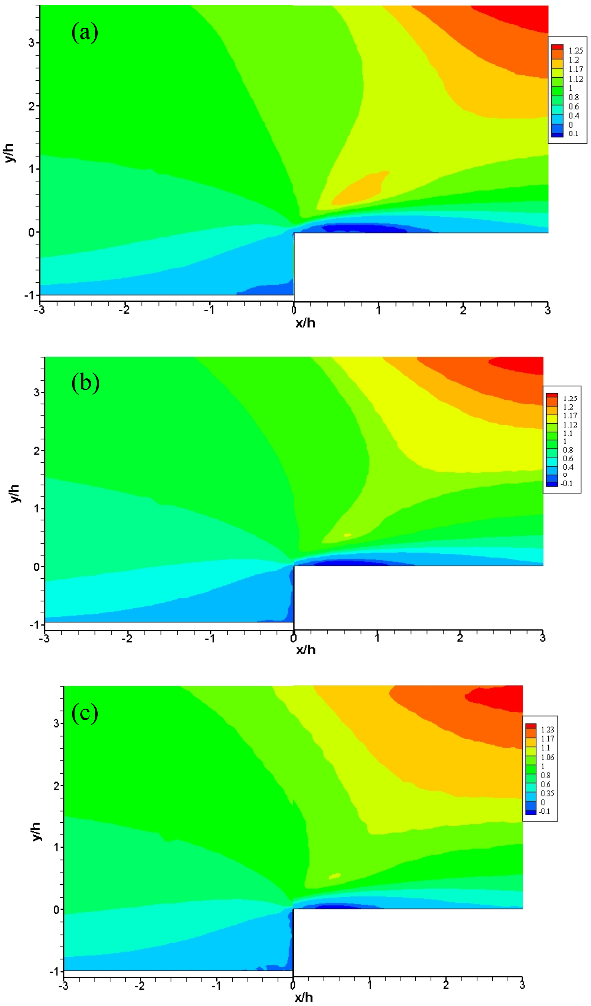

Fig. 2 Contour plots of streamwise mean velocity in the recirculation region for (a) SM, (b) SP and (c) SG

B. Separated and Reattached Region

The streamwise and wall-normal mean velocities, turbulence intensity and Reynolds shear stress are used to examine the effects of upstream roughness on the recirculation bubble. Fig. 2 shows the contour plots of streamwise mean velocity in the separated and reattached region. The physical size of the recirculation bubble is defined as the region enclosed by the U/Ue = 0 contour level and the top surface of the step. The mean reattachment length over step height, L_r/h and the mean reattachment height over step height, h_d/h are decreased with the increasing upstream roughness condition due to the larger momentum deficit and higher turbulence level produced by wall roughness. Specifically, SP and SG, respectively, showed a decrease of 14% and 30% in L_r/h

compared to the smooth wall value. These are clear indications that upstream wall roughness condition has a significant impact on the separation and reattachment phenomenon, and the impact increases with increasing roughness effects.

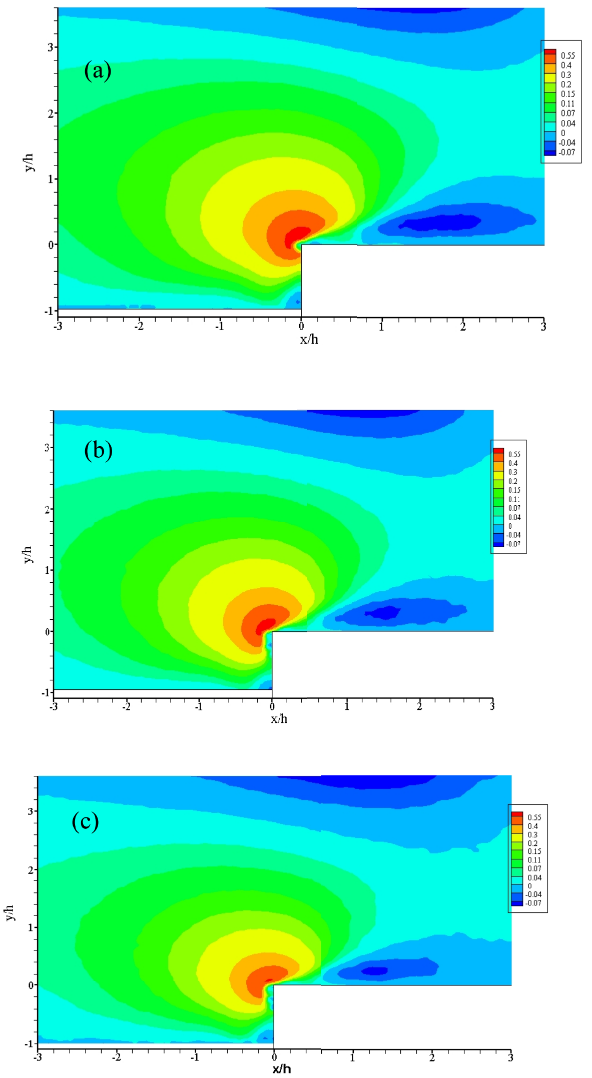

Fig. 3 Contour plots of wall-normal mean velocity in the recirculation region for (a) SM, (b) SP and (c) SG

In the vicinity of the leading edge of the step, high streamwise mean velocities are observed for each test case. SM has a higher local velocity of $1.17U_e$ compared to $1.12U_e$ for SP and $1.06U_e$ for SG. This is not surprising because of the greater momentum fluid over the smooth wall which caused the flow to deflect more aggressively into the separated shear layer over the step compared to the smaller momentum fluid of SP and SG. There is a backflow inside of the recirculation bubble. It is observed that the maximum backflow for SM, SP and SG is $0.21U_e$, $0.20U_e$ and $0.15U_e$ respectively, whereas [10] reported a maximum backflow of $0.19U_e$ with $\delta/h < 1$ for smooth wall.

The contours of wall-normal mean velocities are examined in Fig. 3. At the vicinity of the leading edge of the step, the flow is deflected due to the presence of the step. This creates a high positive wall-normal velocity, $0.55U_e$ in that region for all the test cases, but as the roughness increases the physical size of this contour level decreases. The decrease in the size of the contour levels due to the roughness indicates that for the rough upstream, the ability to permeate into the outer high-speed flow by the low momentum fluid is less than the smooth upstream. After the deflection, when the flow is coming downwards, it entrains the freestream into the separated shear layer which causes the negative wall-normal velocities to occur. The maximum negative wall-normal velocity is $0.07U_e$ for all the test cases but similar to the positive portion, the size of contour level decreases with the upstream roughness. Similar observations were reported in [11].

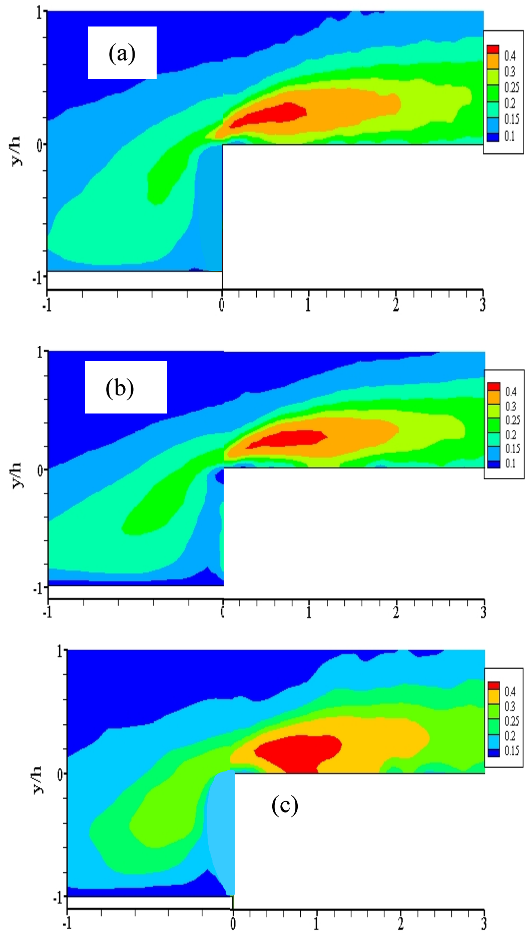

Fig. 4 Contour plots of streamwise turbulence intensity in the recirculation region for (a) SM, (b) SP and (c) SG

Fig. 4 shows the contour plots of streamwise turbulence intensity. The maximum turbulence intensity for all the cases is $0.4U_e$ which is observed just after the leading edge of the step though the physical size of the contour level increases with the increase of roughness.

Fig. 5 shows the contour plots of Reynolds shear stress. At the vicinity of the step, maximum negative $\langle -u'v' \rangle$ can be observed and after about one step height from the leading edge of the step the maximum positive $\langle -u'v' \rangle$ can be observed. The position of the negative and positive $\langle -u'v' \rangle$ coincides with the position of positive and negative wall-normal mean velocity contour plots which can be related to the transport of low and high momentum fluid upward and toward the wall respectively. The magnitude of both maximum negative and positive $\langle -u'v' \rangle$ was $0.02U_e$ irrespective of the upstream wall roughness although the upstream roughness decreased the size of both the maximum positive and negative $\langle -u'v' \rangle$ contour levels.

One dimensional profiles of streamwise mean velocity, wall-normal mean velocity, streamwise turbulence intensity and Reynolds shear stress are shown in Figs. 6 (a)-(d) respectively)). These profiles are obtained at selected locations (x/h = 0, 1, 2 and 3) inside of the recirculation regions and after the reattachment points of corresponding cases. All the profiles are normalized by the upstream mean free stream velocity U_e. Close to the top surface of the step, upstream wall roughness seems to have more effect on streamwise velocity profiles than the profiles away from the wall. In all the test conditions, the streamwise mean velocity profiles close to the wall slowly recovered from the disturbance caused by the severe adverse pressure gradient of the step. The wall-normal mean velocity shows a sudden peak value at the separation but after the recirculation region there is little variation among the three test conditions. The streamwise turbulence intensity profiles show some interesting events. The maximum peaks for all the three test cases occurred at the leading edge of the step. The continuous variation in the turbulence intensity corresponds to the generation of large scale structures by separation and breakdown of those structures in the streamwise distance. The Reynolds shear stresses show negative peaks at the leading edge of the step but become positive in the recirculation region. It also shows that at x/h = 1, the magnitude of positive peak of SM is not significantly different from two rough cases which is consistent with the conclusions drawn from the contour plots of Reynolds shear stress.

IV. Concluding Remarks

A series of experimental investigations were conducted using particle image velocimetry technique to investigate the effects of upstream wall roughness on separated and reattached flow characteristics over a forward facing step in an open channel turbulent flow. A reference smooth wall, and rough walls produced from sandpaper 36 grit and sand grain were used in the upstream region. For each wall conditions, Reynolds number, aspect ratio, blockage ratio and Froude number were kept constant to observe the effect of only wall roughness on the results. It was observed that upstream wall roughness increased momentum deficit and turbulence level.

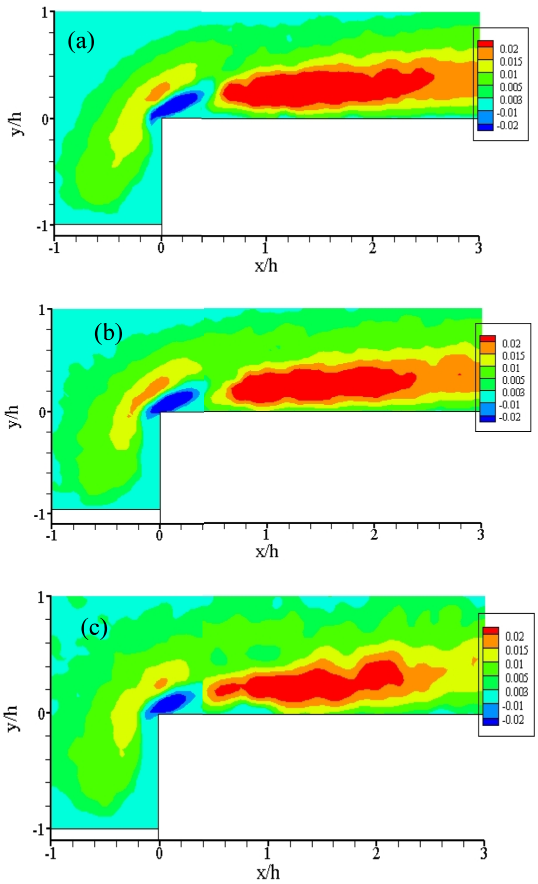

Fig. 5 Contour plots of Reynolds shear stress in the recirculation region for (a) SM, (b) SP and (c) SG

The maximum reduction of the reattachment length by upstream sand grain wall roughness was 30%. The contours of wall-normal mean velocities revealed that the maximum positive wall-normal velocity was at the vicinity of the leading edge of the step for all the cases, but a decrease in the physical size of the contour level represents a decrease in the permeation ability of the low momentum fluid in that area. The upstream wall roughness decreased the physical size of the contour levels of maximum positive Reynolds shear stress at separated and reattached region, however the magnitude remains constant throughout the three cases. Wall roughness has no significant effect on streamwise velocity away from the wall rather than close to the wall. The profiles of Reynolds shear stress showed no significant difference in the maximum peaks inside of the recirculation region. However, the magnitude of negative peak of the smooth case was higher at the separation.

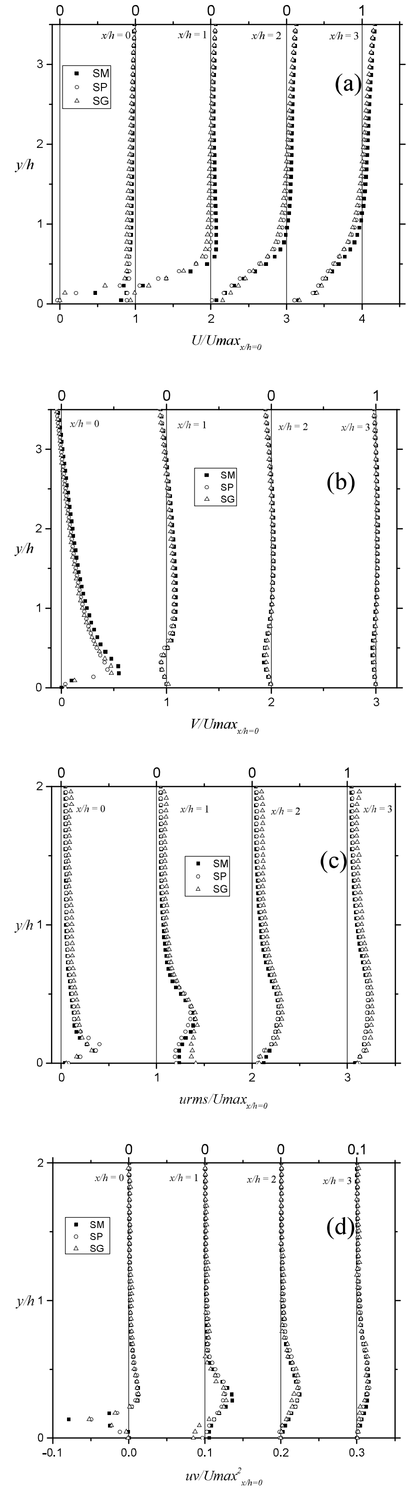

Fig. 6 Profiles of (a) streamwise mean velocity, (b) wall-normal mean velocity, (c) turbulence intensity and (d) Reynolds shear stress in the recirculation region for smooth and rough cases

Acknowledgment

The authors acknowledge the support of this work by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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