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PIV measurements in a square backward facing step

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Abstract

The measurements with both 2D/2C and 2D/3C (stereo) particle image velocimetry (PIV) are carried out in a square channel backward-facing step (BFS) in a turbulent water flow at three Reynolds numbers of about 12000, 21000, and 55000 based on the step height h and the inlet streamwise maximum mean velocity U_0. The inlet flow is fully developed before the step change with the expansion rate of 1.2. The effect of the velocity spatial sampling resolution is verified with four different two-dimensional PIV measurement sets in location x/h= 4 by comparing maximum Reynolds stresses. rms and Reynolds shear stress profiles are compared with DNS and RSM data having similar Reynolds number with experimental flow of the slowest velocity. The shapes of the profiles agree well with each other on the separated shear layer region of the backward-facing step but in these profiles both DNS and RSM data show higher values than PIV data. PIV results show that the mean and rms velocity profiles between the experimental flow cases are almost identical when they are non-dimensionalized by U_0.

Introduction

Comparison of PIV data with the computational fluid dynamics (CFD) data is important when there exists remarkable differences in the results but also many similarities. Compared to the previous experimental study of Piirto *et al.* [7] lot of emphasis is given in the design of backward-facing step (BFS) channel loop to guarantee that the inlet flow before the step is fully developed i.e. the channel length is 100 × channel height y_0 (or width) and expansion rate $ER = y_1 / y_0 = 1.2$ ($y_1 = y_0 + h$) is exactly the same with the DNS and Reynolds stress model (RSM) tests. In this work, the emphasis is in the PIV turbulence characterization and the results are compared with both DNS of Le *et al.* [3] and computational data of RSM [2].

PIV system

The stereo PIV system consists of an Nd:YAG double cavity laser with light sheet optics and a 2 × CCD camera of resolution 1280 × 1024 pixels. Water flow is seeded by the glass sphere particles with an average size of 10 µm. The seeding density is about 10 particles / interrogation area when the laser sheet thickness is about 0.5 mm and the size of the interrogation area is 32 × 32 pixels. In the computation of the velocity vectors, the standard discrete window shift (DWS) method is applied. If the discrete part of the window displacement can be determined within 0.5 pixel, the accuracy of the results after the final iteration is very high, even 0.04 pixel [10]. Only few (1-20) erroneous velocity components conflicting with local median criteria are detected. The spurious spanwise velocity vector components are replaced by interpolation. In stereo PIV measurements, an angle of 30^o is set between the cameras with Scheimpflug adapters, and a procedure of Soloff [8] is applied to correct the camera images. The sampling interval between the measurements is 0.25 s, and thus the statistical independency in time domain can be assumed. The measurement samples are 1000 and for the spatial sampling resolution test 2000 vector fields / location. However, spatial averaging in the streamwise direction over seven lines increases these numbers to 7000 and 14000 samples, respectively. This distance of seven vectors corresponds to 0.2h, and in practice within it, the values of the estimates do not change except the noise is decreasing.

Inlet flow

The physical size of the square-channel is 47 × 47 mm and the step height is h = 10 mm. The flow directions 1, 2, 3 are streamwise (x), vertical (y), and spanwise (z), respectively. The corresponding velocities are denoted either by plain variables U, V, W, and their fluctuating parts u, v, w (in graphics). The inlet streamwise maximum mean velocities are $U_0 \cong 1.2$ m/s, $U_0 \cong 2.1$ m/s, and $U_0 \cong 5.5$ m/s and the boundary layer thickness is defined as channel half width (height) $\delta = ½y_0$. The corresponding turbulent boundary layer properties at x/h = -4. i.e. before the step are shown in Table 1. The inlet flow is measured with the same PIV setup as the other measurements in BFS. Due to the distances close to the wall, reliable measurements could not be conducted closer than 0.5 mm to the wall. Thus, a rough estimate of the friction velocity u_τ is solved by fitting the mean inlet velocity profile measured with PIV with Spalding's universal velocity profile for boundary layers [9]. In the flow Case A, the result of the fitting of Spalding's velocity profile to the PIV profile is shown in Figure 1. Inlet velocity rms profiles for the streamwise component in x/h = -3 are shown in Figure 2 and it is compared with DNS of Le *et al.*, DNS of Moser [4] with Re_τ= 590 and with two-dimensional RSM. Reynolds number for RSM is Re_τ= 1170 and it is same with the PIV Case A. In addition, both the DNS computations are performed in the infinite wide channel causing lower turbulence intensities than the corresponding results should be in the bounded channel.

PIV experimental cases – inlet flow		
Case A	**Case B**	**Case C**
$U_0 \cong 1.2$ m/s	$U_0 \cong 2.1$ m/s	$U_0 \cong 5.5$ m/s
$u_\tau \cong 0.051$ m/s	$u_\tau \cong 0.085$ m/s	$u_\tau \cong 0.2$ m/s
$Re_\tau = u_\tau \delta/\upsilon \cong 1170$	$Re_\tau = u_\tau \delta/\upsilon \cong 2000$	$Re_\tau = u_\tau \delta/\upsilon \cong 4700$

Table 1. Inlet flow boundary layer properties.

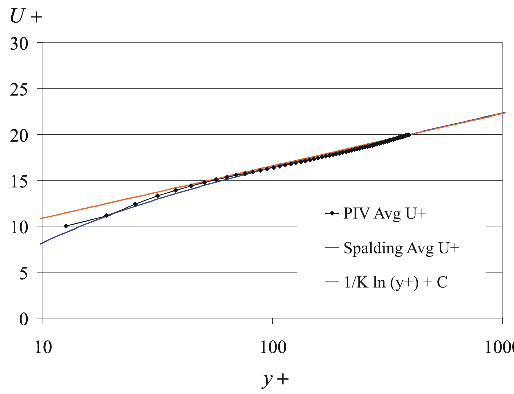

Figure 1. Fitting of Spalding's velocity profile to the PIV mean velocity profile in flow Case A. Log-law parameters are K = 0.405 and C = 5.2.

As can be noticed here, and will be noticed in the turbulence characterization after the step, the upper boundary conditions, i.e. no-stress wall, limit the results in Le *et. al.* Even so, the turbulence intensities by the PIV experiments show lower values than the DNS ones. Especially in DNS of Le *et al.* turbulence intensity maximum is remarkably higher than with DNS of Moser. Because of the square shape of the channel, the sidewalls increase turbulence intensity of the PIV experiments, and for this reason streamwise velocity rms could be about 10% higher than rms of DNS results of Moser between $y/\delta = 0.2 - 1.0$, as can be seen in Figure 2.

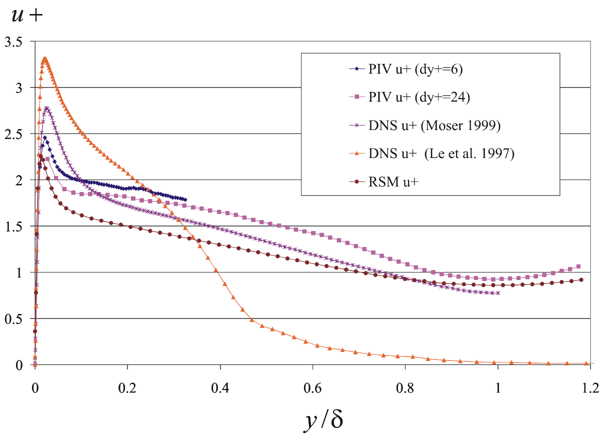

Figure 2. Inlet rms velocity profiles for PIV Case A, DNS of Moser, DNS of Le *et. al.* and RSM at x/h = -4. Spatial sampling resolutions for PIV experiments are $\Delta y = 0.0125h$ ($\Delta y^+ = 6$) and $\Delta y = 0.05h$ ($\Delta y^+ = 24$).

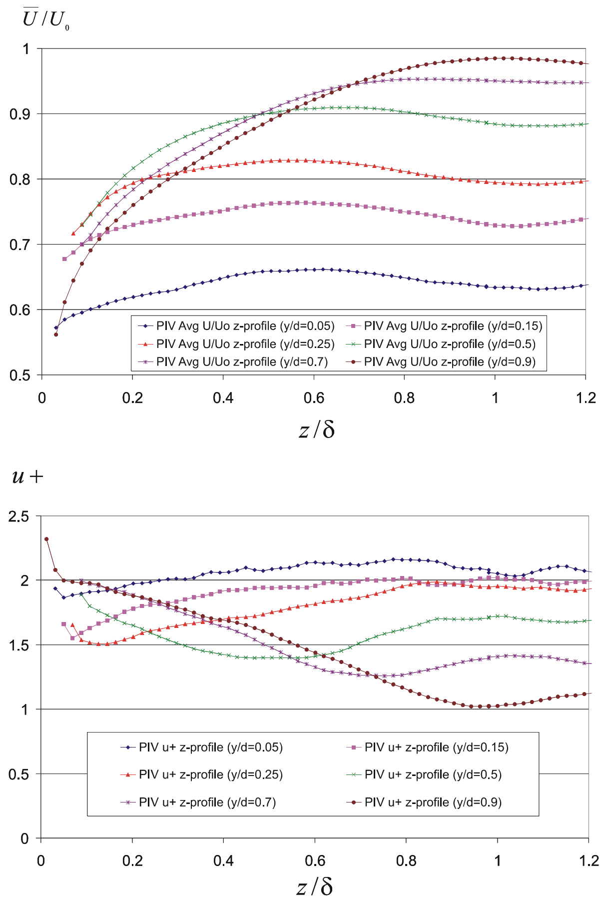

Figure 3. Off-center inlet mean and rms velocity profiles at x/h=-3 and y/δ = 0.05, 0.15, 0.25, 0.5, 0.7, and 0.9 for PIV flow Case B. Spatial sampling resolution is $\Delta y = 0.05h$.

In addition to this, in the PIV results the higher measurement resolution $\Delta y = 0.0125h$ ($\Delta y^+ = 6$) gives slightly higher turbulence intensity than the lower resolution of $\Delta y = 0.05h$ ($\Delta y^+ = 24$) which is the spatial distance between two measurement samples (overlapping 50%) and also the half size of the interrogation area. With the higher resolution also the turbulence intensity peak is found and it is about $u^+ = 2.5$. For DNS of Moser it is $u^+ = 2.7$ and for RSM it is $u^+ = 2.25$. In Figure 3 is shown the off-center profiles for the streamwise mean velocity and rms for the Case B and the lower resolution of $\Delta y = 0.05h$.

Re-attachment point

Reattachment point after the step change in flow Cases A, B and C are 5.3*h*, 5.6*h*, and 5.7*h*, respectively. In the previous study of Piirto *et al.* [7] it is 6.2*h* but the flow geometry is slightly different and inlet flow is not fully developed. According to DNS of Le *et al.* it is 6.3*h* but again no-stress wall upper boundary condition may have an increasing effect on it. In Figure 4 is shown streamwise mean velocity and the location in which the direction of flow changes. The distance from the wall is approximately the highest spatial resolution $\Delta y = 0.0125h$ which is in the wall units $\Delta y^+ = 6$ for the Case A, $\Delta y^+ = 11$ for B, $\Delta y^+ = 25$ for C. With the computational model corresponding to the Reynolds number of PIV Case A, RSM gives re-attachment length 4.5*h,* and in three-dimensional case the effect of the sidewalls will only decrease it.

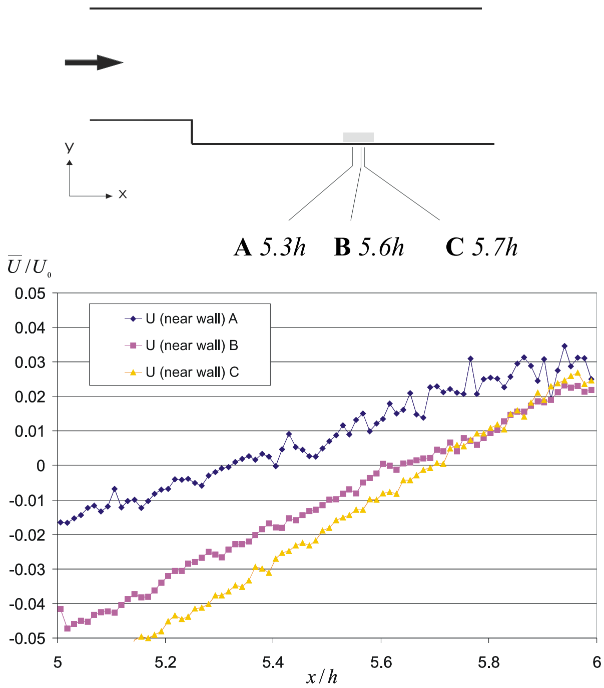

Figure 4. Streamwise mean velocity by the re-attachment point with the highest spatial sampling resolution $\Delta y = 0.0125h$ which is also the rough distance from the wall.

Turbulence profiles after the step

The shapes of the profiles for mean velocity, rms and Reynolds shear stress agree well with the DNS study of Le *et al.* in the separated shear layer part of flow, but outside that area, the results are not comparable with each other because of the DNS conditions. With RSM, the shape of the profiles agree well with PIV but especially turbulence intensity in vertical direction and Reynolds shear stress are remarkable higher than the corresponding PIV and DNS estimates and their maxima are closer to the wall than the corresponding maxima of PIV and DNS. In addition to this, there exists sudden change in velocity mean of RSM by the wall after about x/h = 3.5, and the peak is too low which is also found in [5]. With PIV and DNS backward streamwise mean velocity peak is about U/U_0 = -0.15. Streamwise rms maximum at x/h = 4, after non-dimensionalized with U_0, is u_0= 0.151 for PIV, u_0= 0.175 for DNS, and u_0 = 0.188 for RSM. The non-dimensional average, rms, and Reynolds shear stress profiles are compared with DNS and RSM at x/h= 4 in Figures 5, 6, 7, 8, and 9. The PIV spatial sampling resolution for these results is Δy = 0.05h. As can be noticed, the shapes of the profiles fit well with each other except DNS between y/h = 1.5 – 6.0. Both the upper boundary condition with stress and the side-wall effects would only increase the maximum of rms of DNS. Thus, it means that there exists clear difference between the experimental values and DNS results. For the spanwise velocity rms, the difference is the opposite, and the higher estimates of PIV than of DNS can be explained by the sidewall effect of the square-channel. It is interesting to compare the RSM results with the three-dimensional RSM for the square-channel, because it will give an certain understanding about the the sidewalls effects in turbulence quantities, especially at the re-circulation region. According to the initial two-dimensional and three-dimensional air computations, which compuatational time is much less than with water, the increase is between 5 – 10% for the velocity rms profile maxima and about 20% for the Reynolds shear stress maximum at x/h = 4. These values are only hints, but anyhow the effect of the sidewalls will only take DNS and RSM turbulence intensity and Reynolds shear stress profiles further off from the PIV ones, except the spanwise velocity rms profile which will get closer with the PIV profile. Unfortunately, the three-dimensional RSM computations by water have not been finished yet.

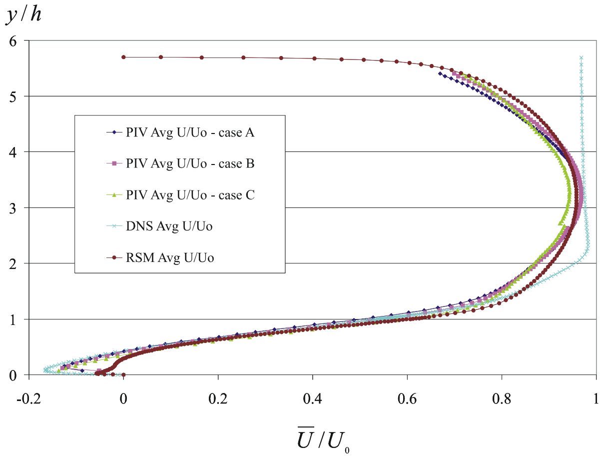

Figure 5. Mean velocity profiles at x/h = 4 for PIV, DNS and RSM.

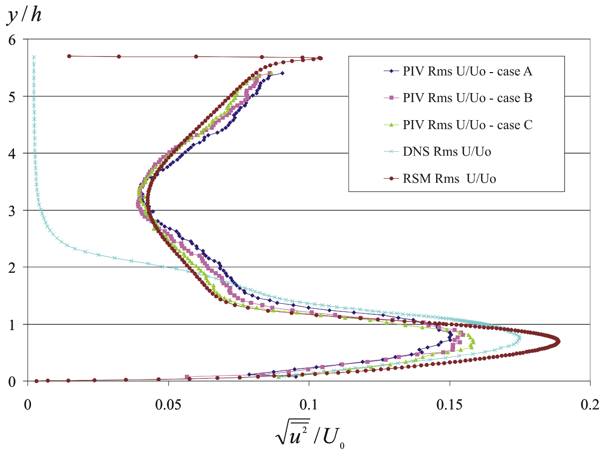

Figure 6. Streamwise velocity rms profiles at x/h = 4 for PIV, DNS and RSM.

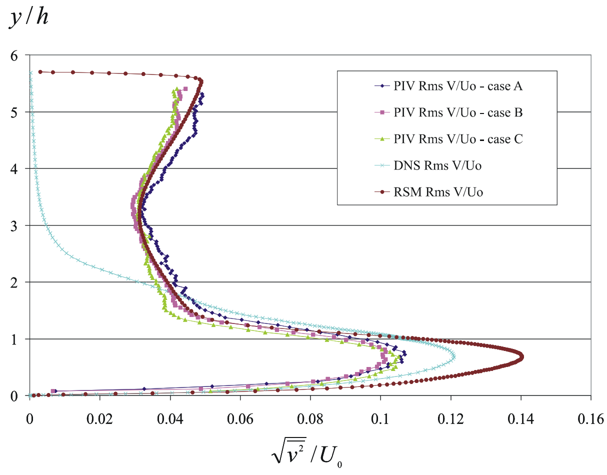

Figure 7. Vertical velocity rms profiles at x/h = 4 for PIV, DNS and RSM.

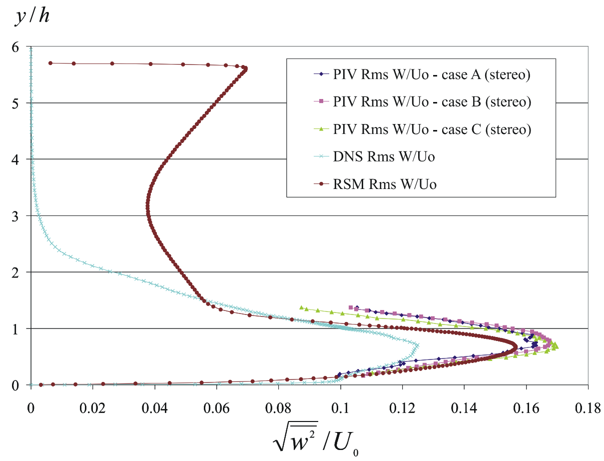

Figure 8. Spanwise velocity rms profiles at x/h = 4 for PIV, DNS and RSM.

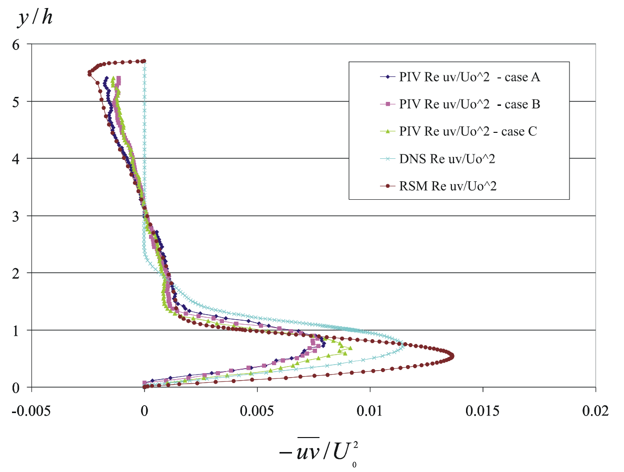

Figure 9. Reynolds shear stress profiles at x/h = 4 for PIV, DNS and RSM.

Spatial sampling resolution and rms error

When the PIV results are compared with CFD, the increased spatial sampling resolution and the measurement rms error are important factors as they have an increasing effect on turbulence intensity. Even in turbulence intensity, the effect is remarkable while in contrast with the velocity gradients the effect of the spatial resolution must be analysed [1]. If the resolution is high, the smaller turbulence scales are included in the estimates and they will be more realistic. However, if the measurement spatial resolution passes the capacity of the PIV system and the number of the particles is too few in a particular interrogation area, it also has an increasing effect in the estimates because of the measurement error. Thus, it is important to prove that the data sets are stationary at least in rms sense [6] and also verify that the measurement rms error do not increase when the spatial resolution increases. This is verified, and the rms error with all the resolutions are about 0.1 pixel for velocity components U and V, and 0.3 pixel for W. These are estimated by zero-flow tests [7] provided for each one of the resolutions of the following spatial sampling resolutions and for the resolution used with the measurements of the previous page. One kind of estimate for the uncertainty is if these rms errors are divided by rms maxima. In location x/h=4 these maxima are about 1.4 pixels, 1.4 pixels and 2.3 pixels for streamwise, vertical, and spanwise velocity rms estimates, leading to uncertainty error of 7%, 7%, and 13%, respectively. In practice, the rms error increases urbulence rms. However, this uncertainty estimate is rather the maximum than the average because velocities are much higher on non-shear regions, typically between 2 – 10 pixels. The effect of the spatial resolution is plotted in Figures 10 and 11 for streamwise velocity rms and Reynolds shear stress.According to this test, the effect of the spatial sampling resolution is about 5-10% for streamwise velocity rms depending on the case, and about 5% for Reynolds shear stress $\overline{uv}$ when the resolution increases from Δy= 0.05h to Δy = 0.0125h.

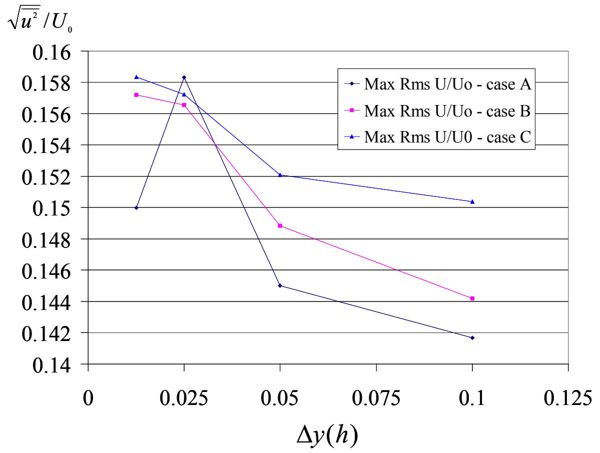

Figure 10. Streamwise velocity rms maxima at x/h = 4 with 2D/2C PIV test data sets of different spatial sampling resolutions.

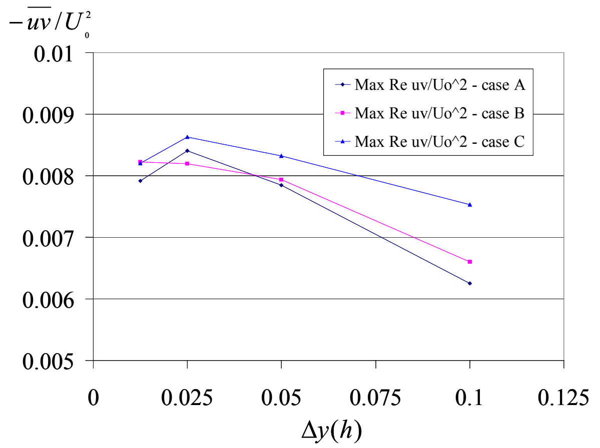

Figure 11. Reynolds shear stress maxima at x/h =4 with 2D/2C PIV test data sets of different spatial sampling resolutions.

As was mentioned, this resolution Δy=0.05h is used with 2D/2C and 2D/3C measurements in the results of the previous Section. This increased spatial resolution will take the PIV results a bit closer with the CFD results.

Conclusions

Turbulent backward-facing step flow of a square-channel is measured by conventional PIV system and stereo PIV system at three Reynolds numbers of about 12000 (Case A), 21000 (Case B), and 55000 (Case C), based on the step height h and the inlet streamwise maximum mean velocity U_0. The inlet flow before the step is fully developed and the expansion rate of the step is ER = 1.2. The turbulence intensity profiles are almost identical between the experimental cases at different Reynolds numbers. The PIV results are compared with DNS and RSM for infinite width of the channel that have similar Reynolds number with the Case A. The shapes of the profiles agree well with each other in the separated shear layer part y/h = 0 – 1.5. The most remarkable difference is the spanwise velocity rms maximum, which probably depends more on the sidewalls than the other turbulence intensities. In addition, the re-attachment length with PIV Case A is 5.3h whereas with DNS, it is 6.3h and with RSM, it is 4.5h. The effect of the PIV spatial sampling resolution is analysed with the four test data sets. When this effect is taken account, the quantities between PIV and DNS are almost the same. However, it can be assumed that some difference exists between PIV and CFD results when the effect of the sidewalls will be analysed by three-dimensional RSM computations.

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