



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2604

EXPERIMENTS ON TURBULENT BOUNDARY LAYER SEPARATION USING PARTICLE IMAGE VELOCIMETRY

Leonardo Castellanos Gonzalez

Universidade Federal do Rio de Janeiro, Department of Mechanical Engineering, Rio de Janeiro, Brazil
Leonardo.jose@ufrj.br

Atila Silva Freire

Universidade Federal do Rio de Janeiro, Department of Mechanical Engineering, Rio de Janeiro, Brazil
atilafreire@gmail.com

Juliana Loureiro

Universidade Federal do Rio de Janeiro, Department of Mechanical Engineering, Rio de Janeiro, Brazil
Jbrloureiro@gmail.com

Abstract. *The present work presents experimental results of the study of the separation and reattachment of turbulent boundary layer in Newtonian fluids. Particle image velocimetry (PIV) measurements were carried out over surfaces with 15° and 30° of inclination on a two-dimensional channel of rectangular cross section and 2:1 expansion ratio. Velocity and turbulent kinetic energy profiles for the X-Y plane are presented. Turbulent intensity fields of separated flow appear to be significantly dependent on the Reynolds number. However no marked changes in the position of separation and reattachment point were found for the measured conditions.*

Keywords: *Turbulent boundary layer, Law of the wall, adverse pressure gradient, Separation, Particle image velocimetry, Experimental channel*

1. INTRODUCTION

Flow separation often occurs at regions of sudden changes in the flow geometry. A separated shear layer usually develops close to the surface discontinuity and reattaches shortly after downstream, in most of the cases originating a recirculation bubble. This happens because the flow in the boundary has very low energy (relative to the free stream) and is more easily driven by changes in pressure.

It has a direct influence in the shear stress and the system pressure drop and, depending on the application, it could be favorable or not. This phenomenon is present in most of the fluid engineering applications, since aerodynamics and naval design to heat exchangers and cooling systems.

The asymptotic structure of the attached boundary layer was originally advanced by PRANDTL (1925) and VON KÁRMÁN (1930). They propose that the flow structure can be subdivided into two layers: (i) a wall viscous layer, in which the turbulent and laminar stresses are of comparable magnitude and (ii) a defect layer, in which the velocity profile may be expressed in terms of a small perturbation to the external flow solution. On the other hand the influence of an adverse pressure gradient completely modifies this scenario by changing the behavior of the asymptotic structure as shown by GOLDSTEIN (1948) and STRATFORD (1957).

Many of the investigations and the currently available data have focused on the statistical properties of the flow, obtained from single point measurement techniques such as hot-wires, surface pressure sensors and laser Doppler anemometry (LDA). The physical structures in turbulent flows and their dynamics have been difficult to investigate with single point measurement techniques because of the difficulty involved in obtaining multi-point measurements with high spatial resolution and instantaneously throughout the flow domain. Flow visualization techniques have allowed the flow structure to be investigated, although such images can often be difficult to interpret and only give qualitative information about the flow. On the other hand, quantitative techniques such as Particle Image Velocimetry (PIV) are well suited to the study of instantaneous flow structure and evolving dynamics of turbulent flows.

This technique offers the potential to acquire instantaneous 2D measurements (with a higher spatial resolution than can be achieved with arrays of single point measurement probes) over a relatively large 2D region of the flow.

The aim of the present study is to conduct a detailed experimental study of the structure and behavior especially on the separation and reattachment points of turbulent boundary layer using Particle Image Velocimetry (PIV).

2. FLOW GEOMETRY

A considerable challenge in boundary layer separation is the determination of shear stress at the wall, especially at the separation point. CHARSUDA (1975), KIM J. ET AL (1978) e SEKI E HIRATA (1976) began to use the backward-facing step (BFS) geometry (Fig. 1) to experimentally study the phenomenon of re-circulation and boundary layer re-attachment, becoming a classic case study that despite its simple geometry presents an extremely complex behavior.

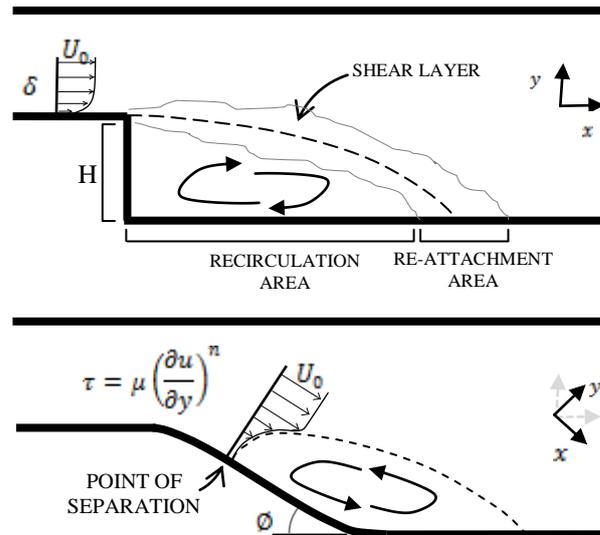


Figure 1. a) General characteristics of backward facing step flow, b) proposed geometry for separation study

According to EATHON AND JHONSTON'S reviews in two-dimensional flows, the separation line is straight and fixed at the corner of the step, and only one recirculation region is observed. Further, the streamlines are substantially parallel to the wall at the separation point; here the so-called shear layer is thin enough to be not affected by the presence of the wall.

However, according to Newton's law of viscosity, the shear stress between two layers of fluid is a linear function of the velocity gradient between them, thus the BFS cannot fully describe this phenomenon.

Hence, the present work uses a different geometry. Rather than using the BFC, a smooth ramp has been adopted, as illustrated in Fig 1.b. This geometry is similar to a diffuser and causes the separation of the boundary layer at one point in the plane of the inclined surface. With this flow configuration it will be possible to measure the velocity gradient perpendicular to the surface and to obtain data for the shear stress and the influence of Reynolds number in the position of the separation point.

3. EXPERIMENTAL SETUP

The experimental system is composed of a 3.3 m long Plexiglas, constant-pressure-driven channel. The test section's height at the inlet is $h = 20$ mm, its width remained constant at $75h$ and the outlet section height D is $2h$. Here the aspect ratio $R = D/d = 2$ is adopted so that for $R > 1.5$ the flow would be symmetrical. The expansion is located at $x/h = 50$ downstream from the inlet to ensure a fully developed flow, whose objective is to force an adverse pressure gradient and boundary layer separation. Here, the flow reaches a Reynolds number up to 40,000 based on the step height ($H = 20$ mm), as is customary in backward-facing step flows (W.J. YANTA, R.A. SMITH, 1978).

A 6.5:1 contraction is used upstream of the test section to further reduce the turbulence intensity by accelerating the mean flow after going through a stabilization chamber. To straighten the flow and remove any mean swirl a honeycomb, a diffuser and some special grids were also used. The channel is part of closed loop in which the fluid is conducted from a reservoir located 3 meters above the floor, controlling the flow by a valve located downstream of the upper tank. A 2 HP centrifugal pump system keeps the reservoir level constant, reaching a maximum variation of 1% of the flow, measured by an electromagnetic flow meter. A filter is placed just after the pump system to avoid possible impurities from disturbing the PIV measurements.



Figure 2. Lay-out of experimental device

The PIV system is composed by a double pulsed Nd:YAG Q-switched Laser, with a wavelength of 532 nm, emitting, each, 130 mJ of energy by pulse, with a maximum frequency of 15 Hz. The beams are combined in a single optical axis of 1 mm width located at the middle of the transversal dimension of the channel as shown in Fig. 2.

A CCD camera with a 1920 x 1200 resolution, 12 bit pixel depth, a minimum interframe time of 1.4 μ s and 1380 fps allows the images acquisition up to 4170 pair of frames. In this configuration is used a lens Nikon AF Micro Nikkor 105mm f/2.8D, it got the best resolution for the measured area. The software Dynamic studio 2015 performs the post-processing of the images. The flow is seeding with Silver coated hollow glass spheres with a mean particle diameter of 20 μ m and a density (particles/water) of about 1.10 ± 0.05 , easily dragged with the water flow velocity without changing it.

4. RESULTS

When using PIV, the points very close to the wall do not give accurate information because of the light reflected by the wall. To avoid this problem and to obtain reliable results near to the wall, an image of the flow without seeding was captured, and then it was subtracted from the acquired images, to get a data set free from noise and laser reflections, as shown in Figure 3.

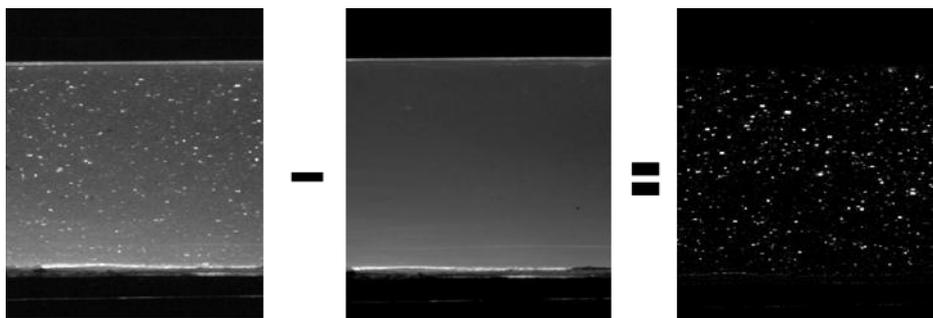


Figure 3. Image subtraction on PIV processing

The test configurations used in the present work are listed in Table 1. The backward-facing step is an ideal test case for the development and validation of turbulent models, while the ramps allow the characterization of the separation point.

The Reynolds numbers that can be simulated in the horizontal channel assure a fully turbulent flow in all investigated experimental conditions.

Figure 4 shows the streamlines and mean velocity field for the 15° degree inclination ramp (R15). According to BARLOW, J. et al [1] and others, geometries with inclination angle higher than 10 degrees should produce an adverse

pressure gradient and separation. However, for the present experiments, no boundary layer detachment from the wall has been observed. On the contrary, the flow seems to be uniform, with just a small perturbation in the bottom edge.

Table 1. Experimental geometries used for PIV measures

Geometry	Re	
Backward Facing Step	18.000	36.000
Rampa 15° (R15)	18.000	36.000
Rampa 30° (R30)	18.000	36.000

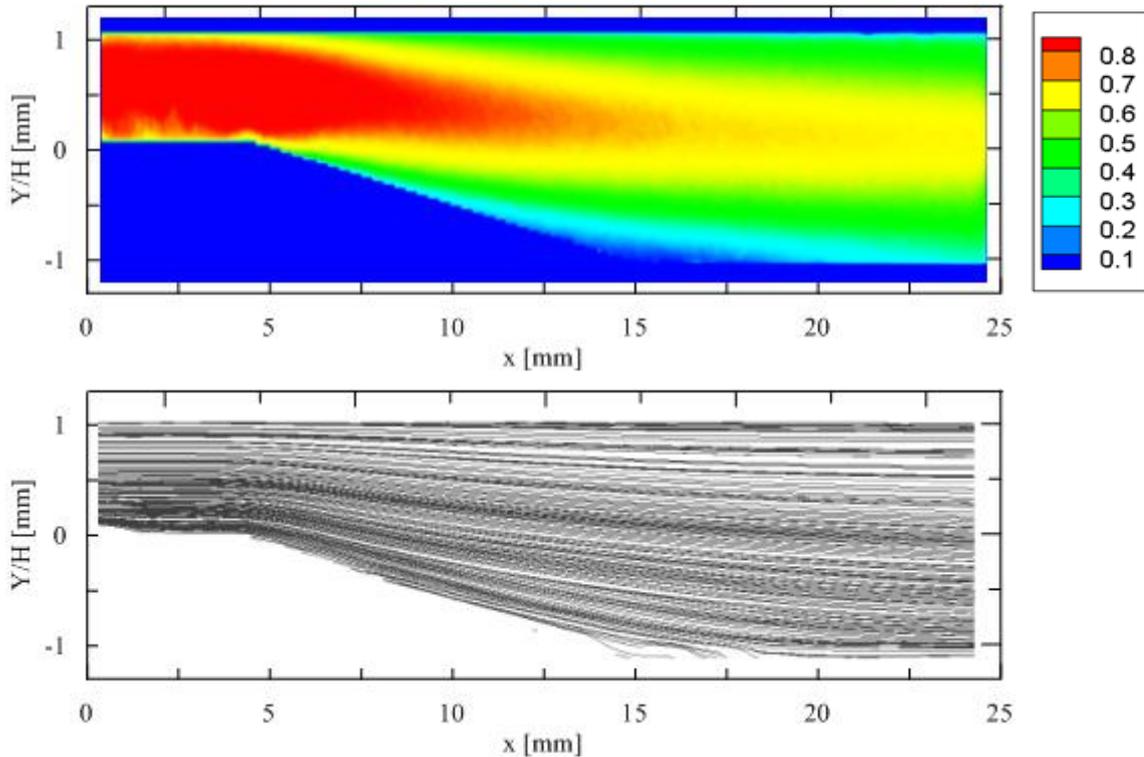


Figure 4. Mean velocity field and streamlines for the 15° degree inclination ramp (R15), $Re = 18,000$

On the other hand, for the R30 ramp a well-defined flow separation region appears in the middle of the inclined surface, as shown in Fig 4. It is shown that the point of separation remains almost in the same location for the two Reynolds numbers investigated. Similar observation applies for the reattached point. However, for the lower Reynolds number, the region of separation seems to be longer.

Many of the turbulence measurements found in literature for separated flows were done with x-wire hot-wire probes, which are inadequate for highly turbulent flows. However, the non-intrusive characteristic of PIV allows the measurement of near wall accurate data. Figure 5(c,d) shows the turbulent intensity field of the R30 ramp. Here it is observed a region with high turbulence levels in the shear layer formed in the neighborhood of recirculation bubble. It is also noticed that in middle of the recirculating bubble the levels of turbulence are low. The re-attached point presents higher turbulent intensity levels as compared to the detached region for $Re = 36,000$, which implies that there is also a higher production of turbulent kinetic energy there. For lower Reynolds numbers, when the recirculation bubble is smaller, the region of separation appears to be longer, as well as the turbulent intensity is higher in comparison to the reattachment zone for this condition.

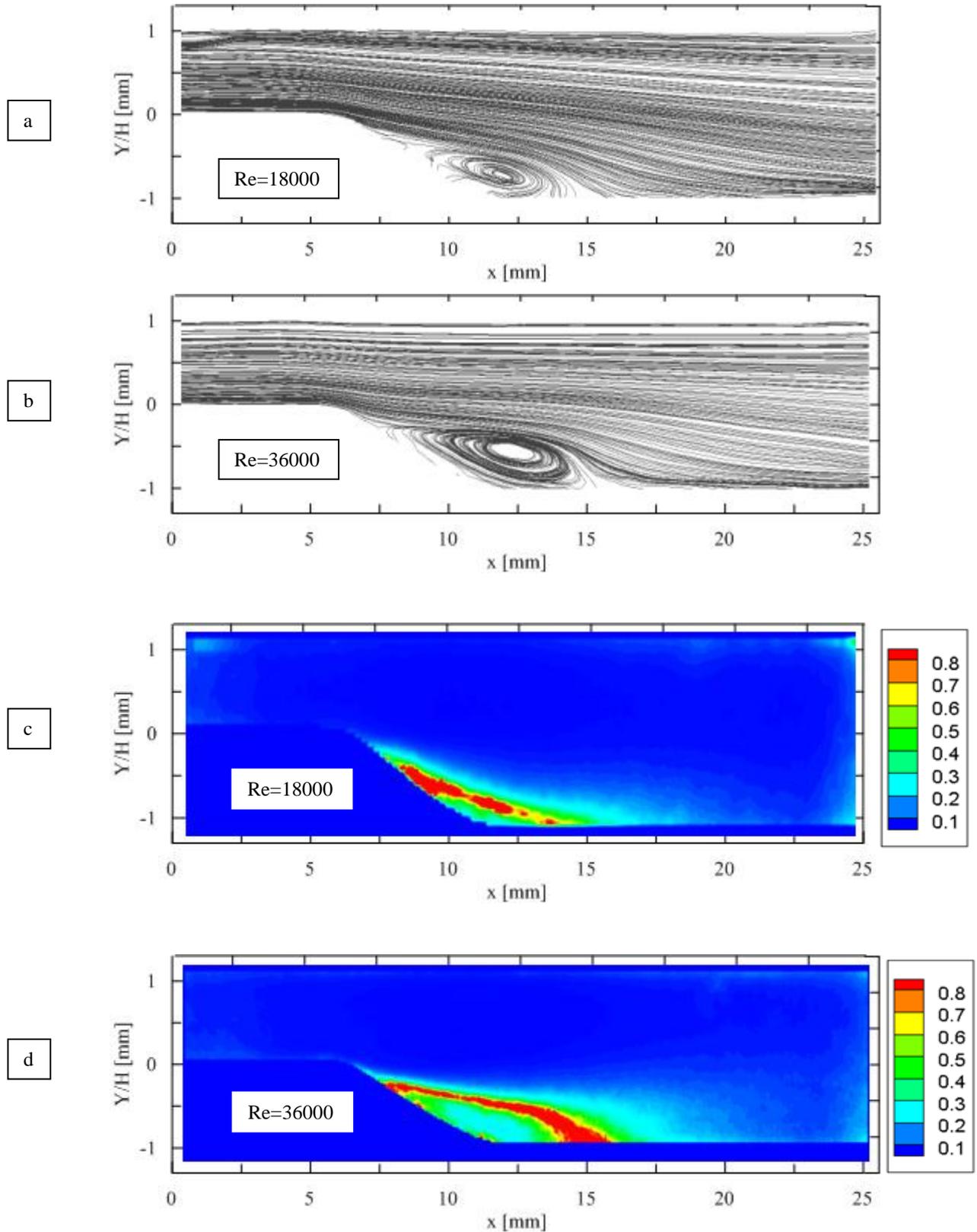


Figure 5. Flow over the 30° degree inclination ramp (R30): a) streamlines for $Re = 18,000$ and b) streamlines for $Re = 36,000$, c) turbulent kinetic energy for $Re = 18,000$ and d) turbulent kinetic energy for $Re = 36,000$

Velocity profiles at point of separation and on the re-attachment region for $Re = 36,000$ are shown on Fig. 6.

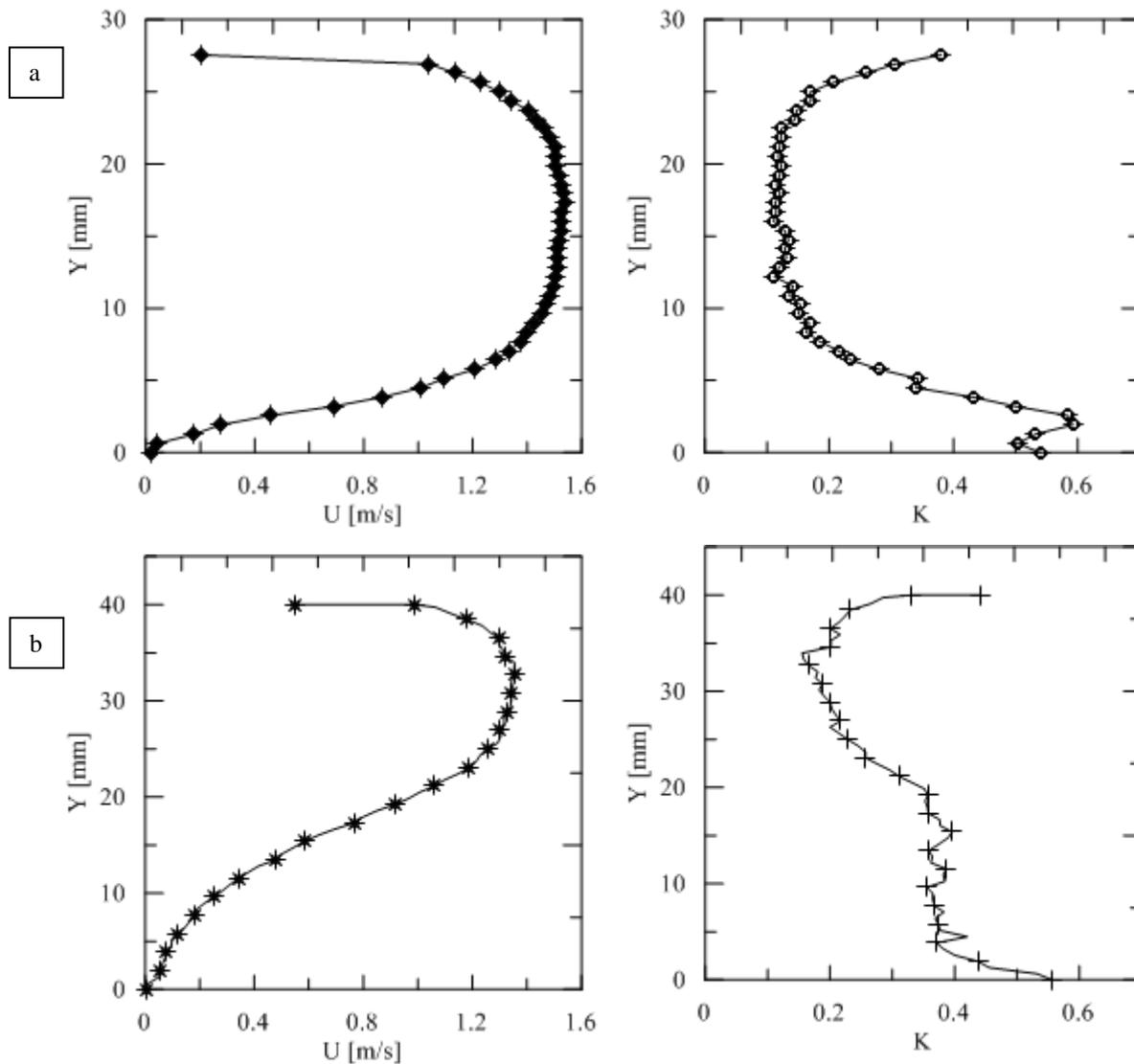


Figure 6. a) Mean velocity and TKE profile at separation point, b) velocity and TKE profile at reattachment point

As shown in Fig 6(a,c), close to the wall the velocity decay due to the adverse pressure gradient. It is also observed that the turbulent kinetic energy at the wall is equal for both separation and reattachment point, but there is a peak of 0.6 on the separated region. On the other hand, the minimum value of K is located far from the wall, where the flow reaches the maximum velocity.

5. CONCLUSIONS

PIV measurements were performed on a two surfaces of 15 a 30 degrees of inclination, at a Reynolds number of $Re=18\ 000$ and $36\ 000$. No boundary layer separation occurs for the R15 geometry.

Vortex interactions were found to occur often at the locations where both the turbulent stresses and the turbulent Kinetic energy production peak, located principally at the so-called shear layer formed between the recirculation area and the maximum flow velocity.

For the R30 geometry the point of separation remains almost in the same location for the two Reynolds numbers investigated. On the other hand the turbulent intensity was higher at separation point for $Re=36000$ while for $Re=18\ 000$ the point of highest turbulent was located on the reattached point.

The PIV technique shows a very good results for recirculation areas but it is important to apply a image subtraction in order to improve the results.

6. REFERENCES

- BARLOW, J., RAE, W., POPE, A., \Low-speed wind tunnel testing, 1999", Jhon Wiley & Sons, Canada.
- CHANDRSUDA, C., "A Reattaching Turbulent Shear Layer in Incompressible Flow," Ph.D. thesis, Dept. of Aeronautics, Imperial College of Science and Technology, 1975. [4] J.K. EATON, J.P. JOHNSTON, A review of research on subsonic turbulent flow reattachment, AIAA J. 19 (1981) 1093.
- GOLDSTEIN, S., 1948, "On laminar boundary-layer ow near a position of separation", The Quarterly Journal of Mechanics and Applied Mathematics, v1 pp. 43-69.
- KIM, J., KLINE, S. J., AND JOHNSTON, J. P., "Investigation of Separation and Reattachment of a Turbulent Shear Layer: Flow over a Backward-Facing Step," Thermosciences Div., Dept. of Mechanical Engineering, Stanford Univ., Rept. MD-37, 1978
- PRANDTL, L., 1925, "Bericht uber Untersuchungen zur ausgebildeten Turbulenz", Z. Angew. Math. Mech, v. 5, n. 2, pp. 136-139.
- SEKI, N. AND HIRATA, T., "Turbulent Fluctuations and Heat Transfer for Separated Flow Associated with a Double Step at Entrance to an Enlarged Flat Duct," Transactions of the ASME, Journal of Heat Transfer, Vol. 98, Nov. 1976, pp. 588-593
- STRATFORD, B., 1959, "The prediction of separation of the turbulent boundary Layer", Journal of fluid mechanics, v. 5, n. 01, pp. 1-16.
- VON KARMAN, T., 1930, "Mechanische anlichkeit und turbulenz", Nachrichten Von der Gesellschaft der Wissenschaften zu Gottingen, Mathematisch- Physikalische Klasse, v. 1930, pp. 58-76
- W.J. YANTA, R.A. SMITH, Measurements of turbulence-transport properties with a laser-Doppler velocimeter, in: Proceedings of the 11th Aerospace Science Meeting, Washington, AIAA paper 73, 1978, p. 169.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.