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### DESIGN AND QUALIFICATION OF AN APPARATUS FOR THE EXPERIMENTAL STUDY OF LAMINAR SEPARATION BUBBLES

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**Abstract.** *The present work involves the design, construction and performance test of an apparatus for the investigation of laminar separation bubbles in a flat plate boundary layer. Laminar separation bubbles are relevant for many engineering applications and the dynamic of such bubbles has a strong impact on the performance of aircrafts and turbines. The separated boundary layer reattaches to the surface due to the laminar-turbulent transition in the bubble region. This dynamic process is highly challenging for flow simulation tools used for engineering purposes. Thus, there is a demand for experimental studies that can be used for calibration of models present in simulation tools. To this end, an apparatus was designed and built for the water channel of the Laboratory of Fluid Engineering at PUC-Rio. The boundary layer separation on the flat plate was induced by imposing a constant adverse pressure gradient to the flow. To this end a false wall was built, in order to form a converging-diverging channel with the flat plate. Flow separation on the false wall was avoided using a suction mechanism that was designed to reduce locally the boundary layer thickness. Location of suction and suction flow rates were determined with aid of numerical simulations. In addition, it was designed and built a disturbance source to generate Tollmien-Schlichting waves in the boundary layer of the flat plate. This device was used to trigger the boundary layer transition in a controlled manner. All equipments were tested and their designs were validated against experimental measurements. Laser Doppler anemometry and Particle Image Velocimetry techniques were adopted for assessment of each equipment. Results validate the design and show that separation bubbles can be investigated in detail using this apparatus.*

**Keywords:** *Laminar Separation Bubbles, Hydrodynamic Instability, Laser Doppler Velocimetry, Particle Image Velocimetry.*

## 1. INTRODUCTION

Laminar boundary layer subjected to strong adverse pressure gradients might separate and according to Schlichting (2000), the flow in the separated region is highly unstable. Thus, transition from laminar to turbulent flow is likely to occur in the separated region. This can cause a reattachment of the boundary layer and form a closed region which is known as laminar separation bubble (LSB). LSB can be found in many engineering applications such as aircraft wings, drones, turbine blades, wind generators, and many others. According to Carmichael (1981), Lissaman (1983), Sandham (2008), studies of LSB are of great importance for aeronautical industry because separation bubbles can significantly affect performance of the lift surfaces, radiated noise and vibration.

In next decades, the report from Airbus (2013) predicts an increasing demand for aircraft transportation, especially for countries with emerging economies. According to that work by 2032 there will be around 90 megacities in the world and the demand for new long range aircrafts it is expected to be higher than 29000 units. In addition, around this period it is expected that two-thirds of the population of the emerging economies will make at least one trip per year. Thus, the success of new aircraft designs depends on improvement of aerodynamic performance and reduction of fuel consumption for efficient long range operation. In this context, the design of efficient jet engines is of particular interest. A key component for efficient operation of jet engines, is the low-pressure turbines (LPT), (Airbus, 2013). Works of Hormouziadis et al. (1989) and Sharma (1998) suggest that LPT operating at low Reynolds numbers can exhibit drag counts a few orders of magnitude higher than those observed at high Reynolds numbers. The pressure loss of LPT at low Reynolds numbers is associated with the separation of the laminar boundary layer. Sharma (1998) suggest that at takeoff regime typical Reynolds numbers of LPT are rather high and therefore laminar separation bubble are not usual. However, at cruising regime the Reynolds numbers might be low enough to allow laminar separation bubbles on LPTs.

For mitigation of performance drop due to boundary layer separation several strategies are described in the literature aiming at controlling the phenomenon (Mittal et al., 2001). According to Martinstetter et al. (2010), net gains achieved using these techniques are typically lower than 50%, due to the low efficiency of these devices in generating disturbances that effectively promotes flow reattachment or avoids separation. The development of more efficient control technologies is limited by the lack of understanding of the underlying physics of transition and reattachment processes (He et al., 2017). Studies of Malkiel & Mayle (1996) and of Lou & Hourmouziadis (2000), among others, suggest that in some situations the reattachment is induced, primarily, by two dimensional shear layer instabilities also known as Kelvin Helmholtz instability. In this case, disturbances in the separated layer are amplified to form vortical structures which further downstream can breakdown and induces a reattachment. However, the work of Rodriguez et. al. (2013) suggest that global instability mechanisms can be dominant if the magnitude of reverse velocity, inside the bubble, becomes higher than 10% of the boundary layer edge velocity. This competition between different instability mechanisms reduces accuracy of models and prediction tools used to estimate the behavior LSB. In addition, the structure of disturbances related with the flow transition and reattachment are different for each instability mechanism. In order to shed more light on the physics underlying this problem, it is interesting to describe under different conditions the flow topology near and inside of separation bubbles. It is interesting also to investigate the transient behavior of the flow. The recent work of Michelis et al. (2017) addresses this last topic, by investigating the transient response of a separated boundary layer interacting with an impulsive disturbance. In that work the flow is measured using time resolved particle image velocimetry technique (PIV). The work suggests the presence of closed feedback interactions when disturbances excited upstream the separation region are phase locked with the shear layer breakdown at the bubble end. Due to actual limitations of the measurement technique, sampling frequencies adopted in that study are limited to few kHz. For airflow this is close to the frequency range of the phenomenon.

In present work an experimental apparatus is built and tested to allow the study of LSB in a water channel. In this case, the frequencies involved are considerably lower than those observed in wind tunnels. Therefore, very detailed measurements of transient processes can be performed by using available PIV systems. This might contribute for new insights about the mechanisms involved in the formation of separation bubbles. In this work the separation bubble was investigated on the surface of a flat plate. The pressure gradient, required for generation of separation bubbles, was set by using adjustable upper walls on the test section of the water channel. To ensure the formation of the bubble, only on the surface of the flat plate, boundary layer suction was applied at the divergent upper wall. In order to study of the response of the separated shear layer to perturbations, a blowing and suction device was designed and tested.

The present paper describes the design and the qualification tests of the apparatus. To this end, Laser Doppler Velocimetry measurements were employed to characterize the boundary layer development on the flat plate without pressure gradient. Flow visualization with dye injection was used to examine the general characteristics of the bubble. Velocity fields measured with time resolved PIV technique were applied to evaluate effectiveness of the boundary layer suction mechanism and to characterize the separation bubble generated on the flat plate.

## 2. PRELIMINARY TESTS AN DESIGN OF APPARATUS

This work focuses on the LSB formed by the imposition of an adverse pressure gradient. In this work an experimental apparatus was designed to reproduce the behavior of the flow along airfoils, where typically there is a region with acceleration of the flow followed by a region with adverse pressure gradient. To reproduce this pressure distribution in a simpler geometry than an airfoil, a flat-walled conduit with a constriction was designed, as shown in Figure 2. The base is formed by a flat plate on which the boundary layer is developed. The imposition of an adverse pressure gradient was achieved through a convergent-divergent wall

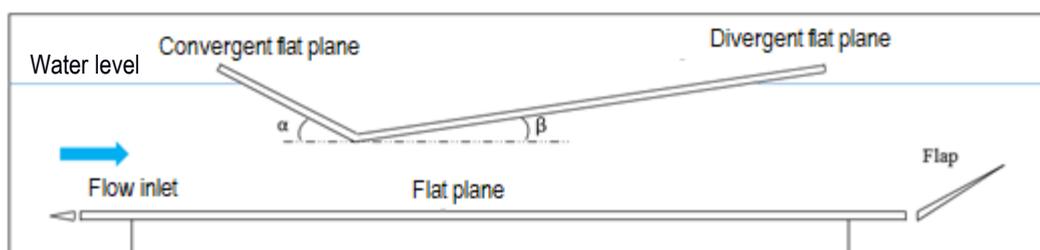


Figure 2. Schematic of the Apparatus for the Study of Laminar Separation Bubbles. Where  $\alpha$  is the angle of convergence and  $\beta$  the angle of divergence

To avoid the problem of coupling between the flow in the divergent plate and the flat plate, a suction system has been designed through slots on the divergent plate. The criteria proposed by Stratford (1957), is used to estimate the location of the separation point for different flow conditions. Based on this location, we tried to put a suction point a little upstream to avoid the detachment of the boundary layer. However, once the suction is made, the boundary layer will continue to develop further downstream and we will find a new separation point for which a new suction point corresponds and so on, until it covers the total surface length. Figure 3 shows the positions of the suction points on the divergent plate for different values of  $\beta$ . Each marker symbol represents a separation point. For the case of  $\beta = 7^\circ$  a numbering was used to identify the points, which is shown above the markers

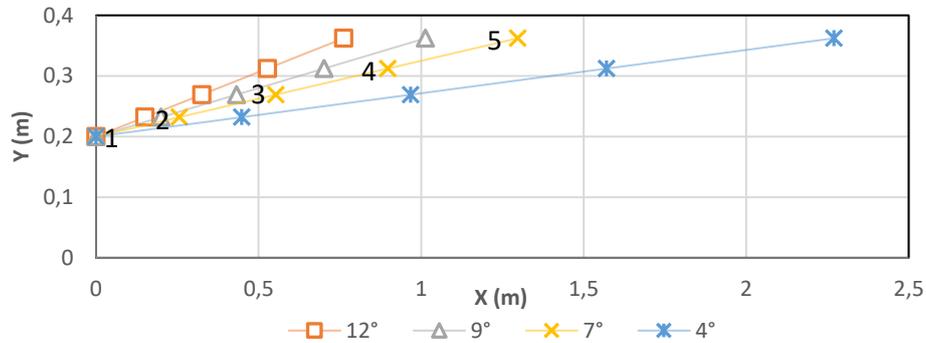


Figure 3. Location of the suction points along the divergent plate

Analyzing the interaction between the divergent plate and the flow, we found that values of  $\beta$  greater than  $12^\circ$  are impractical for the study of bubbles, because of the strong adverse gradient, which makes it difficult to reattach the bubble. At the other extreme, angles smaller than  $4^\circ$  are also not interesting, as the weak adverse gradient favors the flow transition without the occurrence of separation. Thus, in the design of the apparatus, the range of angles of divergence ( $\beta$ ) between  $4^\circ$  and  $12^\circ$  was restricted. With this, it was possible to estimate the suction points based on the most critical condition.

Another important parameter is the suction flow rate. An initial estimate was calculated from the difference between the static pressure of the flow flowing through the channel created by the plates and the atmospheric pressure. If we consider the flow of an ideal flow, without load loss, we find that the acceleration and deceleration process cause a difference between the static pressure of the flow and the atmospheric pressure over the entire surface, in particular over each suction point on the divergent surface. This surface is divided into sections and delimited through plates so regions with similar pressures can be obtained.

Under steady-state conditions, in each section we find a decrease in the water level that would remain constant, which we named  $\Delta h$ , this value is proportional to the local pressure loss  $\Delta P$ . In this condition the fluid inside the sections remains at rest, but we can break this balance by imposing a pressure deficit, this can be done by extracting a volume equivalent to decrease in water level equal to  $\Delta h$ , i.e. causing a deficit  $\Delta P = \rho g \Delta h$ . With this value the equilibrium is broken and the pressure of the hydrostatic column is less than the static pressure of the flow inside the channel, therefore an upward flow is generated that attempts compensate this deficit with a velocity equal to  $V_{suction} = \sqrt{2g\Delta h}$  or  $V_{suction} = \sqrt{(2(\Delta P)/\rho)}$ . In summary, table 1 shows the suction positions and the suction flow rates.

Table 1 shows the location of the suction points and estimated suction flow rates

	Suction points				
	1	2	3	4	5
X (m)	0	0,150	0,325	0,527	0,762
V (m/s)	0,3	0,259	0,223	0,192	0,166
$\Delta P$ (Pa)	-33,8	-22,2	-13,6	-7,2	-2,5
$ \Delta P $ (mmwc)	3,4	2,3	1,4	0,7	0,3
Q (L/h)	3805	1044	720	448	224
$V_{sucção}$ (m/s)	0,425	0,115	0,081	0,050	0,025

In this work a RANS simulation was used to help in the verification of the suction flow rates, this simulation was implemented in commercial software FLUENT, which uses a finite volume method of discretization, the mesh parameters used in this simulation were 253074 number of nodes, normal wall expansion rate 1.05, first layer height 0.05mm, minimum orthogonal quality 0.25 and maximum aspect ratio 21. In this simulation different suction velocities were tested, until finding the minimum necessary, on the other hand, different angles of divergence cause different pressure gradients, the suction velocities were optimized for the most critical case corresponding to an angle of divergence of 12 °. the optimized results of the simulations are shown in the figures 4. which indicates that the suction velocities are adequate since the streamlines do not manifest sink effects.

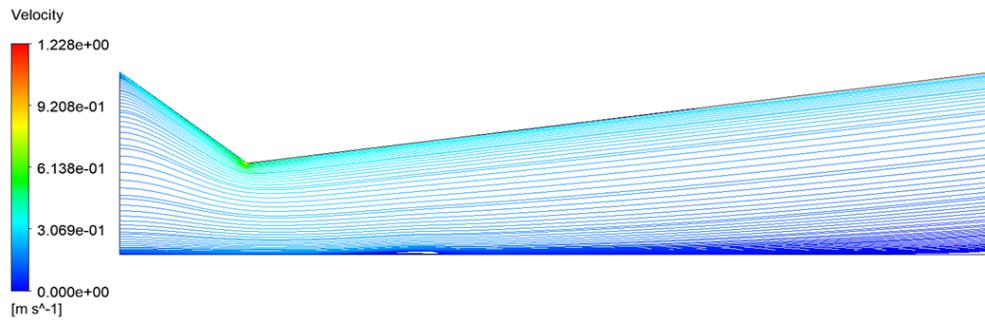


Figure 4. Streamlines with active suction

After performing the preliminary tests, the devices and elements of the apparatus were manufactured.

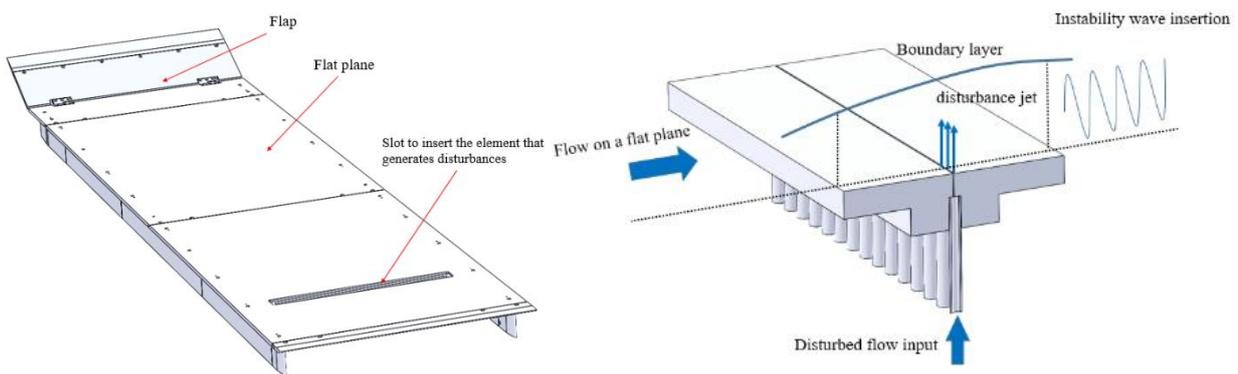


Figure 5. Flat plane and disturbance generator

The dynamics of the insertion of instability waves consists of the formation of an artificial jet through a slot of 0.3mm wide that interacts with the boundary layer. If the flow exceeds the critical Reynolds number and the injection of the disturbance occurs at an unstable frequency, the disturbance growth process will be triggered.

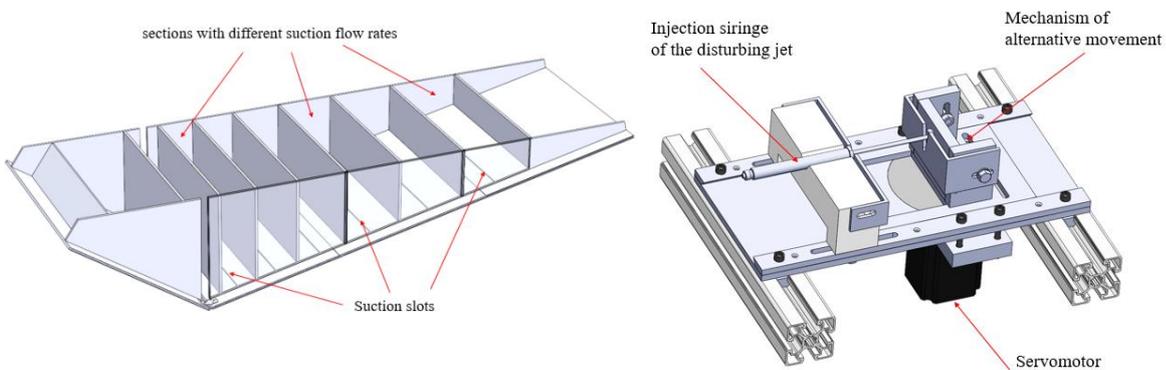


Figure 6. Convergent-divergent plate and perturbation injection mechanism

### 3. METHODOLOGY

The experimental tests of the present work were carried out in the water channel of the Laboratory of Fluid Engineering of PUC-Rio. The channel has an open test section of 4x0.86x0.64m (length x width x height) and an average turbulence level of 0.5% in the 0.1 to 10 Hz range of the motor frequency.

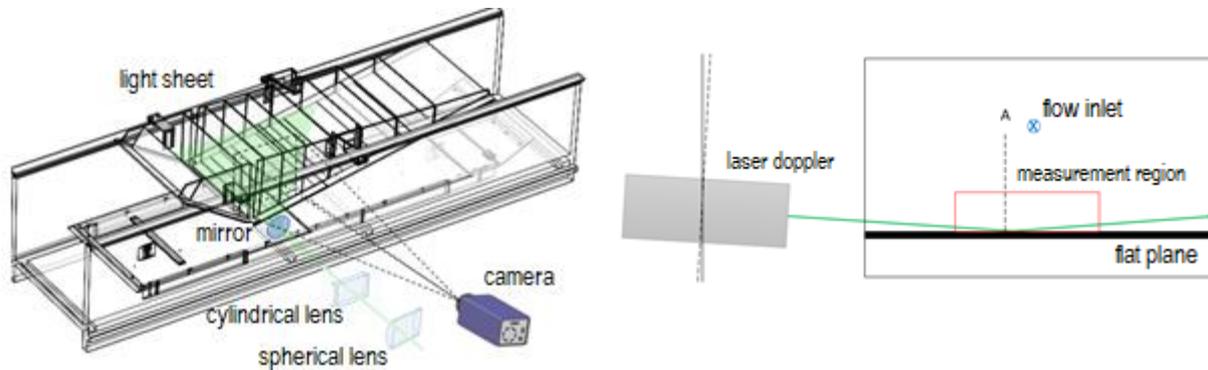


Figure 7. experimental arrangement, left: PIV technique, right: LDV technique.

An LDY-300 series laser system was used as the light source. The use of two independent controlled and pulsed resonators allows the generation of a double pulse output with minimum pulse separation times of just under ten nanoseconds. MotionPro X3Plus high-speed camera was used to record the images. This camera has a resolution of 1280x1024pixels at a sampling rate of up to 2000 frames per second. The camera has a dual capture mode, especially for PIV, with 100 nano seconds of frame switching interval. In the tests of this work the measurements were made with a sampling rate of 250Hz and a time of exposure of the first frame of 2800  $\mu$ s. This frequency corresponds to the minimum firing rate of the laser. Below this frequency the laser power is severely reduced. In the validation tests of the suction mechanism a Nikkor lens with f2.8 aperture was used. This allowed for capturing images in a large area on the divergent board. In the case of measurements in the boundary layer with the separation bubble, a 105 mm Nikkor lens was used for a better visualization of the flow.

Measurements with Doppler laser anemometry were performed with a TSI PowerSight system. There are two main modules for this system, the PowerSight Laser Velocimeter module, and the PowerSight Controller module. The PowerSight Laser Velocimeter module has been mounted on a traverse that can travel on three axes. The axes normal to the lower channel wall and transverse were equipped with servo motor for automatic displacement. The control of the motors was done with micro controllers Arduino Uno and drivers of power tb6600, for motors of up to 4.5A. The system control interface was created in the LabView environment. The shift in the vertical direction of the PowerSight Laser Velocimeter module is of special importance because the spacing between two consecutive points defines the spacing between the points of the velocity profile acquired. This spacing within the boundary layer was chosen variably, being 0.5mm in the region closest to the wall, 1mm in the intermediate region and 2mm until reaching the free flow velocity. The number of points for each profile depends on the height of the boundary layer, changing from 20 to 35 points. According to the size and flow regime of the boundary layer. Figure 7 shows the experimental arrangement used in this work.

### 4. RESULTS

The characterization of the flow on the flat plate without pressure gradient was performed by measuring the mean velocity profiles of the boundary layer with the Doppler laser anemometry technique. Profiles were measured at different positions along the plate. The purpose of these measurements was to check the quality of the base flow on the flat plate. Figure 8 shows some profiles along the flat plate.

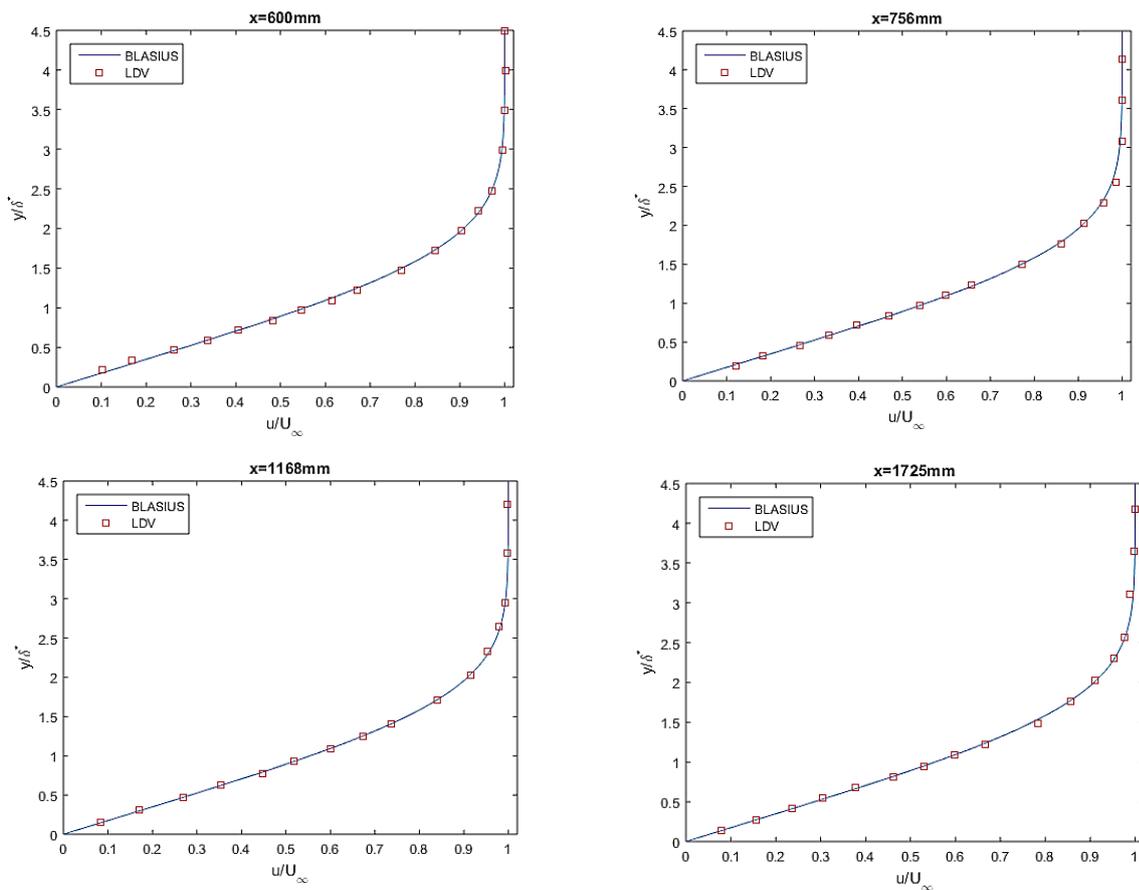


Figure 8. Some profiles along the flat plate, for different streamwise positions

The calculation of the integral of the displacement thickness and the momentum thickness was performed using the trapezoid method, the relation between them provided the value of the shape factor for each of the profiles. The results obtained are presented in the Figure 9a. According to Blasius (see Schlichting and Gersten, 2000), laminar boundary layers on plates without pressure gradients should exhibit a shape factor around 2.6. Several experimental results prove Blasius' theory, for example the experiments of Schubauer and Klebanoff, (1955). This indicates that the boundary layer developed on the flat plate, can cross the entire measurement region being laminar.

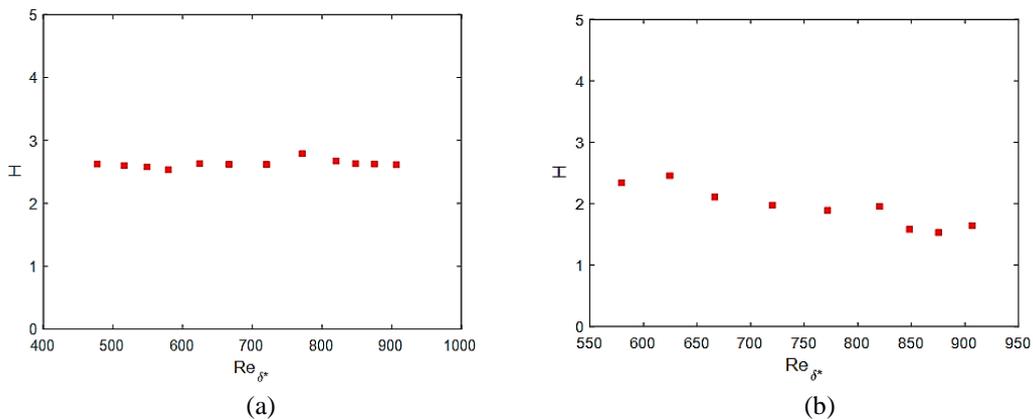


Figure 9. Shape factor evolution, (a) undisturbed, (b) with suction and blowing oscillatory

In the tests with disturbances an alternative movement mechanism was used to perform oscillatory suction and blowing. The frequency chosen for disturbance excitation was 0.3 Hz. This corresponds to a dimensionless frequency of TS waves of approximately  $70E-6$ , in this frequency range the TS waves become unstable at a Reynolds number of approximately 720. The transition process was evaluated by examining the shape factor of the velocity profiles. The evolution of the form factor is shown in Figure 9b. It can be verified that the form factor has a tendency of reduction

along the direction of the flow. According to Schubauer and Klebanoff (1955), turbulent boundary layers exhibit a shape factor of 1.4. Notice a trend of the values towards this value.

The PIV pattern technique was used to evaluate the suction of the boundary layer in divergent plate. The field of view of the cameras with the lenses selected for the tests was limited in an area of 160x80mm. As the divergent plate extends over a region much larger than this area, it was necessary to move the measuring region in both the longitudinal and vertical directions. In the results presented in this section, the window refers to the vertex of the diverging convergent plate. The previously estimated suction flows rate, which provided good results for the simulations were taken as reference values. In a similar way to the methodology used in the simulations, it was tried to identify in the experiments the minimum suction flow rates to avoid the vortex detachment. the results obtained showed that the suction rates provided by simulations were overestimated, however, it was possible to find the optimal suction rates. Figures 10, 11 and 12 shows the region of the vertex between the plates.

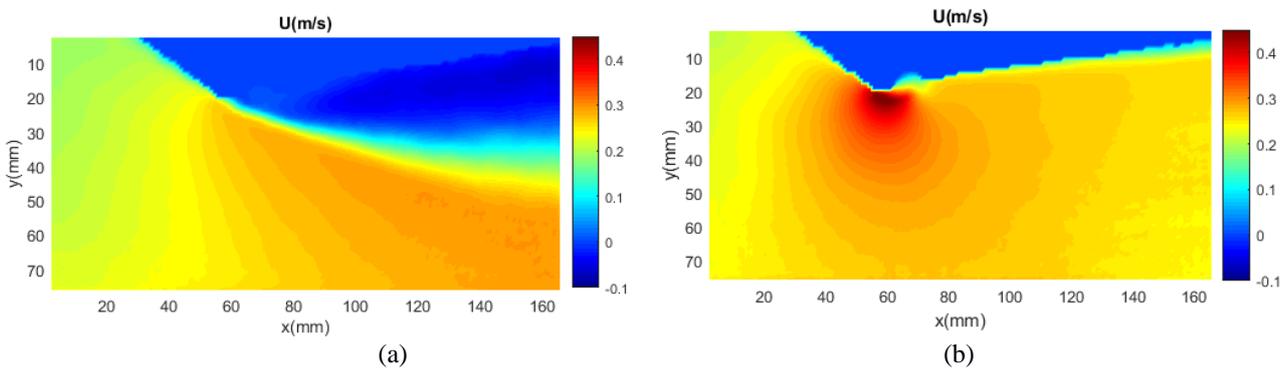


Figure 10. Contour of velocity, (a) without suction, (b) with suction,  $Q_{suction}=1708L/h$

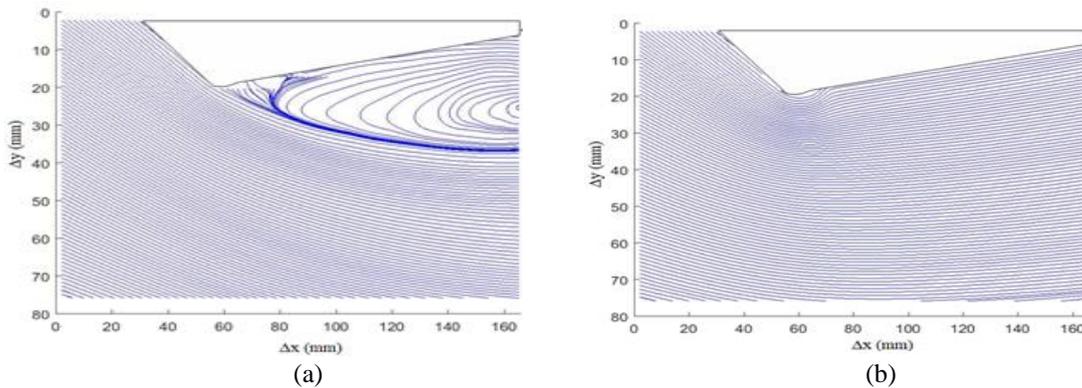


Figure 11. Streamlines, (a) without suction, (b) with suction,  $Q_{suction}=1708L/h$

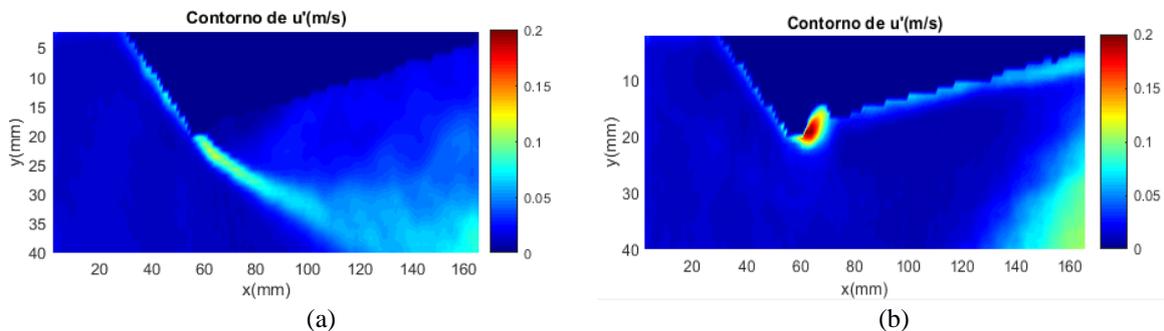


Figure 12. velocity fluctuation,  $u'$  component, (a) without suction, (b) with suction,  $Q_{suction}=1708L/h$

Through the technique of flow visualization by dye injection and using an LED light source, the formation of the phenomenon was verified. The dye used was whole milk with food paint. A little ethanol was added to the milk to reduce miscibility of the mixture in the water. The dye was deposited on the surface of the flat plate with a thin tube and a syringe. The tube and syringe were removed and the dye was gradually released from the surface of the plate. Thus, the tracer continued in the flow, but the disturbances created by the syringe and the tube were no longer present. Thus, it was

possible to visualize the flow without the induction of turbulence by the dye injector. A color camera was used to film the flow. The result is shown at the top of Figure 13. Two distinct views were included to illustrate the behavior of the bubble. For reference purposes, a smoke visualization taken from the work of Braun and Kluwick (2005), was added in the Figure from a bubble formed on an Eppler profile 387

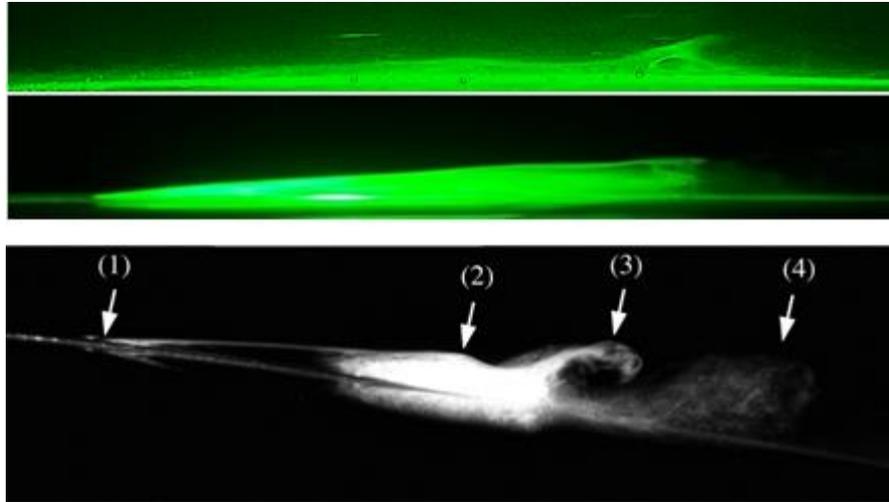


Figure 13. Comparison of results, images above in green: Flow visualization in the PUC-Rio water channel. Black-and-white image: Smoke visualization of a laminar separation bubble on an airfoil Eppler 387, Retrieved from Braun, S. & Kluwick, A. (2005)

In order to evaluate the characteristics of the bubble, measurements were made with the high temporal resolution planar PIV technique. As the bubble length was larger than the viewing region it was necessary to shift the plane in two positions. In each region 3000 pairs of images with a sampling rate of 200Hz were collected. So the total acquisition time was 6 seconds. Figure 14a shows the combined of the velocity fields. A dashed line corresponding to the mean velocity iso-contour in the direction of flow equal to 0. This line divides regions with positive velocity component  $U$  and regions with negative velocity  $U$  was added. In order to evaluate the quality of the velocity profiles, the profiles measured with the hyperbolic tangent profile were compared. This is important if one wishes to use the measured profiles in simulations and stability analyzes. as shown in the figure 14b.

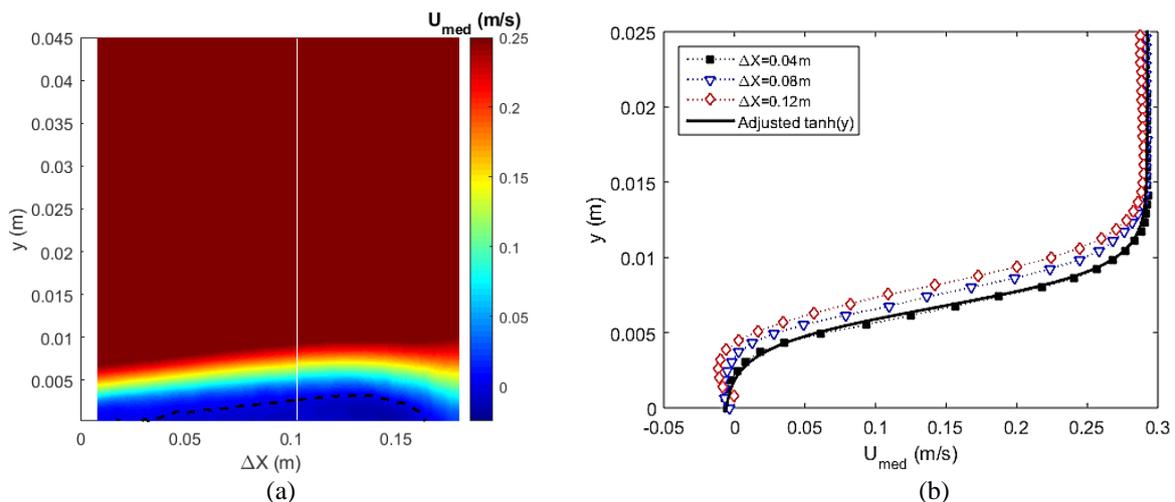


Figure 14. (a) laminar separation bubble, (b) velocity profiles inside the laminar separation bubble

In order to analyze the dynamic behavior of the flow in the reattachment region, was used the time series of the velocity fields. A very useful tool in the study of jets is the normal modes decomposition ou Proper Orthogonal Decomposition (POD). The technique is a correlation tool that decomposes a series of empirical achievements into an optimal orthogonal basis. The method is able to identify patterns in a data series. A review of the technique is presented in the paper by (Berkooz, et al., 1993).

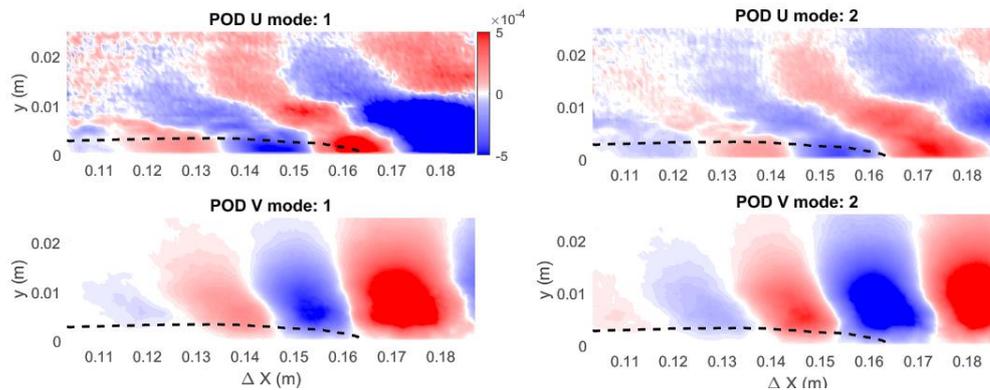


Figure 15. POD Modes 1 and 2 of streamwise (U) and wall normal (V) velocity fluctuations

The analysis is done only in the region of reattachment bubble. The relative energy of the first four modes shown in the Figure is less than 20% of the total energy of the fluctuations. The first two modes represent the same type of structure and show rapid growth of perturbations. These structures are often associated with Kelvin-Helmholtz instability (Lengani et al, 2014)

## 5. CONCLUSIONS

This work corresponds to the initial stage of the project developed in the fluids engineering laboratory of PUC-Rio, whose general objective is the study of the formation and evolution phenomena of laminar separation bubbles. Several devices were built and evaluated with this objective. The arrangement designed to suction the boundary layer on the divergent flat plate was verified successfully as well as the mechanism of injection of disturbances.

The analysis of the results showed that in the case of undisturbed flow, the boundary layer remains laminar along all the measuring stations. The measured profiles presented excellent agreement with the Blasius profile. The results obtained with the perturbation generator indicate that as it moves along the plate the velocity profile tends to be expected for a turbulent flow. Using the PIV technique the formation of the bubble was verified on the surface of the flat plate. The velocity field was measured in the bubble region, and it was possible to identify that a bubble 150 mm long, 8 mm high, was formed on the plate. The velocity profiles within the bubble were measured and compared with a hyperbolic tangent profile, this function is much used to model the base flow in the bubble region. The results suggest that the flow inside the bubble was well captured. The analysis of the flow structures in the region of bubble recovery also showed to be compatible with what is reported in the literature. Therefore, consequently can be concluded that the design of the apparatus for the study of laminar separation bubbles has been successfully completed

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