BOUNDARY-LAYER CONTROL BY BLOWING AT THE TEST-SECTION OF A LOW-SPEED WIND TUNNEL

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Keywords: *wind tunnel, boundary-layer control, boundary-layer blowing, 2-D experiments*

Abstract

This paper presents a few results of an experimental investigation to study the influence of tangential blowing of high pressure air in order to energize the boundary-layer of the wind tunnel of the Instituto Tecnológico de Aeronáutica (ITA). The blowing technique of boundary layer is important in two-dimensional airfoil model tests. Here, results for a test section dynamic pressure of $q_\infty = 76mmH_2O$ are shown. Several injector geometries were tested. Boundary layer measurements were obtained using a rake. It was positioned at eight different stations along the test section.

1 Introduction

Some theories about laminar and turbulent boundary layer blowing or suction were developed in 60's decade in Cranfield (The College of Aeronautics Cranfield). In 1960, Craven[1] presented several results on the laminar and turbulent boundary layer blowing and suction in the incompressible and compressible regime. Stevenson[2] developed a wall law for turbulent boundary layer with blowing and suction.

Boundary layer control by a secondary blowing jet has important technological applications in heat, mass and momentum transfer. For example, film cooling techniques to protect various components which are exposed to high temperature gases. In gas turbine, the air jet acts as a protective insulating between the wall and the hot gases and, thus, maintain the temperature and the thermal gradient within acceptable limits [3]. The effects of air injection using different slot types, thicknesses and angles of blowing were investigated experimentally by Foster [4], Jubran and Brown [5], Quintana et al.[6] and by Aly [7].

Here, the blowing slots were projected to realize other purpose. They will be used in a two-dimensional test using an airfoil in the maximum lift configuration (with slat and flap) at the ITA's wind tunnel. Obtaining a two-dimensional flow over a 2-D model is not an easy task. The tunnel boundary layer interferes with the model generating 3-D effects. In order to minimize such effects a blowing system has been developed. Blowing the boundary layer at the model location energizes it, diminushing its thickness, and consequentlty reduces the 3-D effects over the 2-D model. In order to maximize the 3-D effects the airfoil has both a leading edge slat and a trailing edge flap. Figure 1 displays the boundary-layer control system. Figure 1 (a) is a sketch of the test section showing the 2-D model. While Fig 1 (b) shows the actual blower and the pressure rake mounted on a turn table used to change the airfoil angle of attack. Actually, there are three momentum-injection jets at each turn table. The boundary-layer control system may be moved about its original position. The displacement can be either linear or angular. Therefore, the blowing slots energize the boundary layer, reduce its thickness and insure the two-dimensionality of the flow field on the airfoil. The blowing technique by slots has been used by de Vries [8] de Vos [9] , Vogelaar [10,11] and McGhee et al.[12].

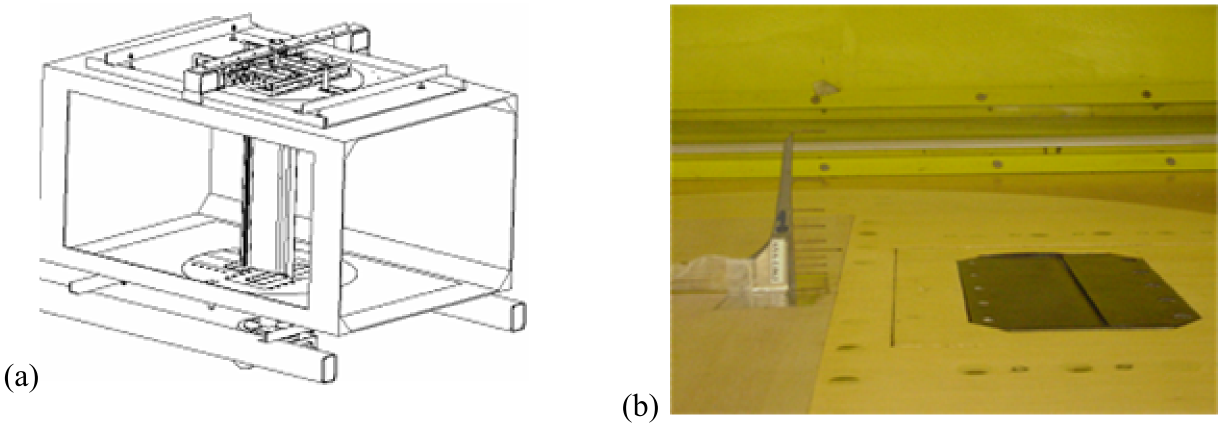


Figure 1: (a) Sketch of 2-D Model Mounted on Turn Table Equipped With a Boundary-layer Blowing Control System. The Flow is From Left to Right. (b) Detail of the Blowing System Installed at The Test Section. Note The Boundary-layer Rack

ITA's new wind tunnel is part of a greater project whose main objective is to increment the productivity and reliability of aerodynamic testing. The IAE-CTA and SP-São Carlos wind tunnels are still used in the developments performed to reach the goal mentioned above, which must solve some problems observed by the EMBRAER personnel in the area of aerodynamic tests.

After the calibration phase, two research programs will be implemented to reach the following objectives: (i) Experimental methodology development to minimize the three-dimensional flow observed in two-dimensional airfoil models at high angles of attack. This problem occurs due to the interaction between the airfoil extremity and the tunnel wall boundary-layer flow and cause great uncertainty in the measurements of the airfoil Cl_{max}. (ii) Development of a methodology for estimating a wing Cl_{max}, once the airfoil Cl_{max} is known. In order to accomplish this objective a set of experiments will be conducted to understand the separated flow evolution, at the upper surface of a wing, while the angle of attack is incremented up to the wing stall. It is worth to mention that these two research programs were proposed by the EMBRAER personnel to solve important practical problems.

2 Experimental set-up and proceedure

Figure 2 shows the two-dimensional model used an airfoil with high lift devices. The slat is set at 23^o and the flap fixed at 35. For this configuration it has been observed a strong three-dimensional effect on the model due to the influence of the tunnel boundary layer. Blowing will reduce or eliminate the three-dimensionality of the flow. For zero angle of attack the jet forms non null angle with the wind tunnel main flow. For high angles of attack, the blower supplies an air jet approximately aligned to the tunnel flow.

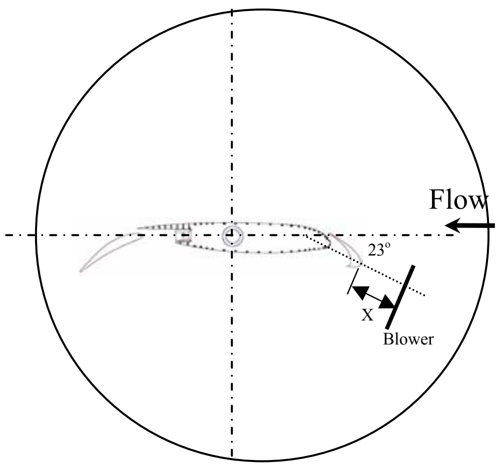


Figure 2: Two-dimensional Model.

Figure 3 shows the injector, designed at ITA. It is capable of supplying jets with slot width of *w=1.0 mm*, *1.5 mm* or *2.0 mm*. The blowing angle may be *10* or *20* degrees. The slot length is of *20* cm. The six different jets are obtained in changing the parts 03-08.

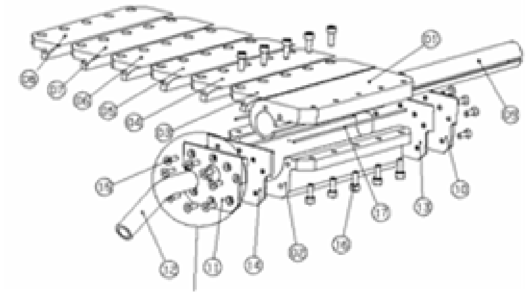


Figure 3: Blower for Boundary-layer Control

Figure 4 shows the pressure rake, the blower installed in a turntable at the test section floor. It also shows a 400-psi air supply system. In present investigation only one injector was used. The compressed air comes from a tank with an air capacity of $10\ m^3$ at *400 psi*. Inside the test-section room the air pressure is reduced to *250 psi*. Then, the air is divided to two reservoirs. Before entering each reservoir the pressure is further reduced to *150 psi*. The air-supply system was designed to regulate separately the pressure for each blower used in the experiment. This is a handy feature for future use.

Figure 4: Air Supply System And The Blower (black spot) Inside The Test Section.

3 Results

The boundary-layer rake, shown in Fig. 1, has eleven total pressure taps. These are located at 1.0, 3.0, 6.0, 9.0, 15.0, 20.0, 30.0, 40.0, 50.0, 70.0 e 100.0 mm from test section floor. Electronic pressure scanners – ESP of 1 psi (704 mmH_2O) with 32 channels are used. The reference pressure is the tunnel static pressure.

The measurements were obtained positioning the rake at eight stations along the test section.: X_1=10 cm, X_2=16 cm, X_3 =22 cm, X_4= 28 cm, X_5= 34 cm, X_6= 40 cm, X_7= 50 cm e X_8= 60 cm from the blower exit Data acquisition was done by Labview®. The sample rate was SR=10 kHz and N=1000 readings were performed for each measurement. Further, twenty sweepings, at each of the eleven rake's taps were conducted. Then, it was calculated the average in Volts. The uncertainty on the data is approximately 2%. The software makes the reduction to pressure values and calculates the pressure coefficients given by:

$$C_p = (p_t - p_{st})/q_\infty = (V/V_\infty)^2 \qquad (1)$$

where, p_t is the total pressure and V is the velocity, p_{st} is the static pressure at the test section walls, q_∞ and V_∞ represent, respectively, the free stream dynamic pressure and velocity at the wind tunnel test section.

The boundary-layer displacement thickness, δ^*, and the boundary-layer momentum thickness, θ, both normalized by slot width, *w*, were also evaluated. Results for all six blowers are shown at the position X_3=22 cm and X_7=50 cm for several blowing pressure ratio, $Bpr=h/p_{st}$. The blowing pressure ratio is defined as the ratio of the jet stagnation pressure, *h*, to the static pressure at the test section walls, p_{st}. These two very important boundary-layer parameters are defined as:

$$\delta^* = \int_0^\delta (1 - V/V_\infty)\,dy \qquad (2)$$

$$\theta = \int_0^\delta (1 - V/V_\infty)(V/V_\infty)\,dy \qquad (3)$$

A very impressive amount of experimental data was generated. The boundary layer was measured for several test section dynamic pressures and at different positions with respect to the jet exit. Due to space limitation just a few graphics are shown here. For the graphics hereafter the test section dynamic pressure is always equal to *76mm* H_20. In figures 5-10 the jet of the blower is aligned with the tunnel flow ($\alpha=0$).

Figure 5 displays the boundary layer profiles with and without blowing for the positions X_3= *22 cm* and X_7= *50 cm* from jet exit. The blowing angle is 10°. It can be observed several velocity profiles for several values of *h*. At X_3= *22 cm*, Fig. 5 (a), the air jet energizes the boundary layer, and the pressure coefficient value near the floor was increased from about *0.5* to approximately *2.8* for a stagnation pressure of *h=200 mmHg*. This is for the *2.0 mm* jet blowing at 10°. It is also important to notice that at the position X_7= 50 cm, the C_p values are smaller. This may be explained by the fact that the jet lost a good fraction of its kinetic energy due to friction along floor surface and at the shear layer. It is important to notice also that some momentum is transfered to the upper layers At $X_{7=}$ *50 cm* it was possible to investigate higher blowing velocities because the local pressures did not surpass transducer limit.

Figure 6 shows the injection effect on the boundary layer for a 20-degree jet angle. The same general trend observed on Fig. 5 is repeated.

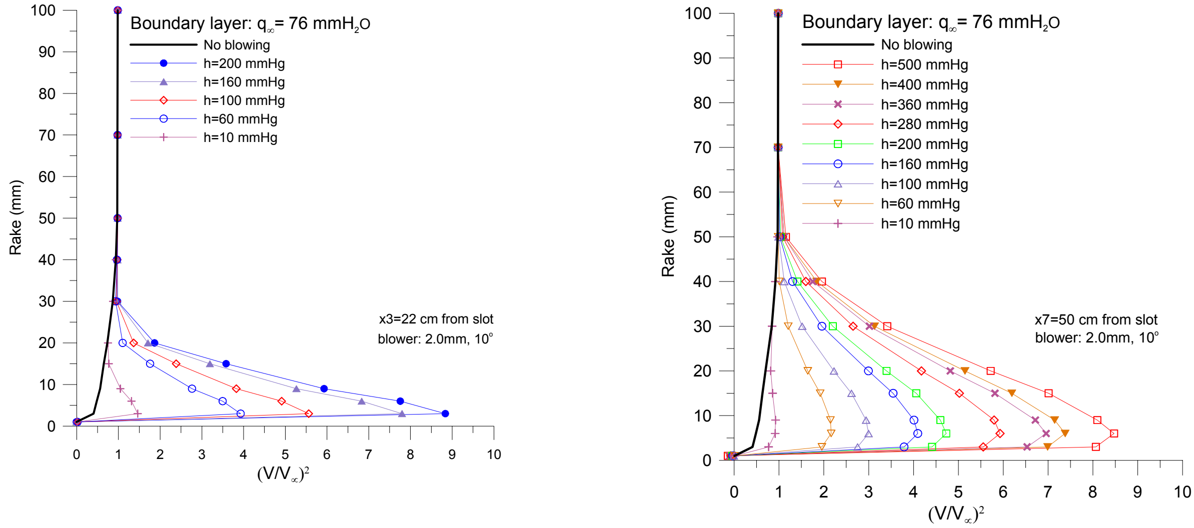
Figure 7 shows the evolution of interaction of the jet with the boundary layer along the test section for a fixed blowing pressure, *h=200mmHg*. From Fig. 7 it is easier to notice the decrease of the flow velocity near the floor (the jet diffuses faster in the wall region), and the increase to the upper layers. It is possible to observe a better efficiency in energizing the boundary layer using the blowers with blowing angle of 10 degrees.

Figure 8 displays the boundary layer measurements for all six different blowers. The results shown here refer to X_3= *22 cm* and X_7= *50 cm* measured from slot exit. In Figs. 8 (a) and (b) stagnation pressure is fixed at *h= 400 mmHg* and *h= 200 mmHg*, respectively. As it can be observed the *2.0mm* injector blowing at 10^{o} is more efficient in energize the tunnel boundary layer. If the angle is changed to 20^{o} the performance is worse but still with a small advantage over the *1.0 mm* blower at 10°. The blowers with width of *1.5 mm* presented medium efficiency among the ones tested, while the injector of *1.0 mm* and 20^{o} showed to be the worst one. Thus, the injection effect using the *2.0 mm* blower set at 10^{o} is extended over a longer length of the floor compared with other blowers. However, the *1.0 mm* blower set at 10^{o} also showed to be very interesting. Mainly, because it needs a smaller mass flow, and hence it permits longer test runs.

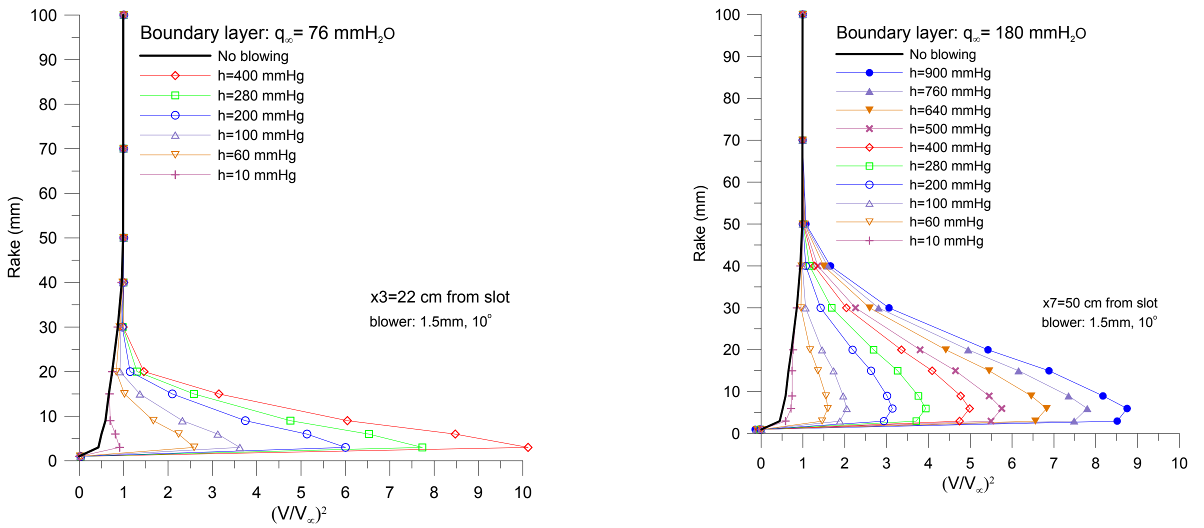
Figure 9 shows the displacement thickness, δ^*, and the momentum thickness, θ, of boundary layer normalized by slot width, *w*. Results of all the six blowers are shown at the position X_3=*22 cm* and X_7=*50 cm* for several blowing pressure ratio, $Bpr=h/p_{st}$. As commented by Aly [7] the negative value of δ^*/w indicates that the jet brought more fluid to the wall vicinity compared with the free main stream. It becomes more negative by increasing *Bpr* and it is more significant for the *1.0 mm* blower set at 10°, especially for higher *Bpr* values.

Figure 10 shows the distribution of δ^*/w and θ/w along the test section floor using the *1.0mm* blower set at 10^{o}. It has been observed a small (almost imperceptible) increase of δ^*/w and θ/w along the *X*-axis for lower *Bpr* values. For *Bpr=1.578*, δ^*/w remains constant between X_6= *40 cm* and X_8= *60 cm*. The same behavior is observed for the momentum thickness distribution, θ/w.

(a)



(b)



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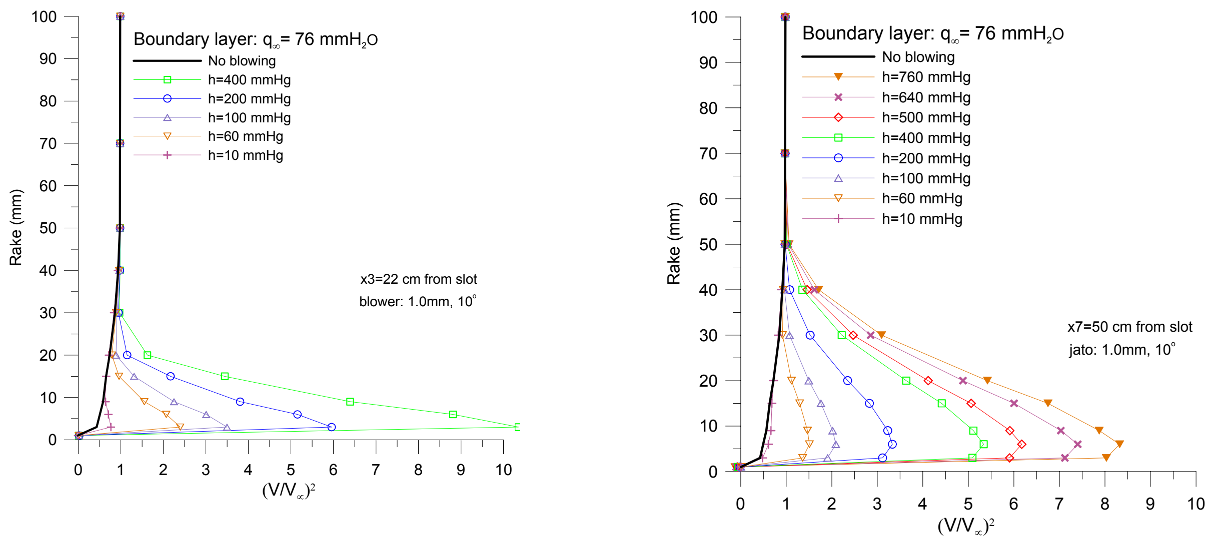

Figure 5 - Effect of Blowing on Boundary-layer Profiles on the Test-section Floor for X_3= *22 cm* and X_7= *50 cm* and several stagnation pressures: (a) blower: 2.*0 mm 10*$^{\circ}$; (b) blower: *1.5 mm 10*$^{\circ}$, (c) blower: *1.0 mm 10*$^{\circ}$**.**

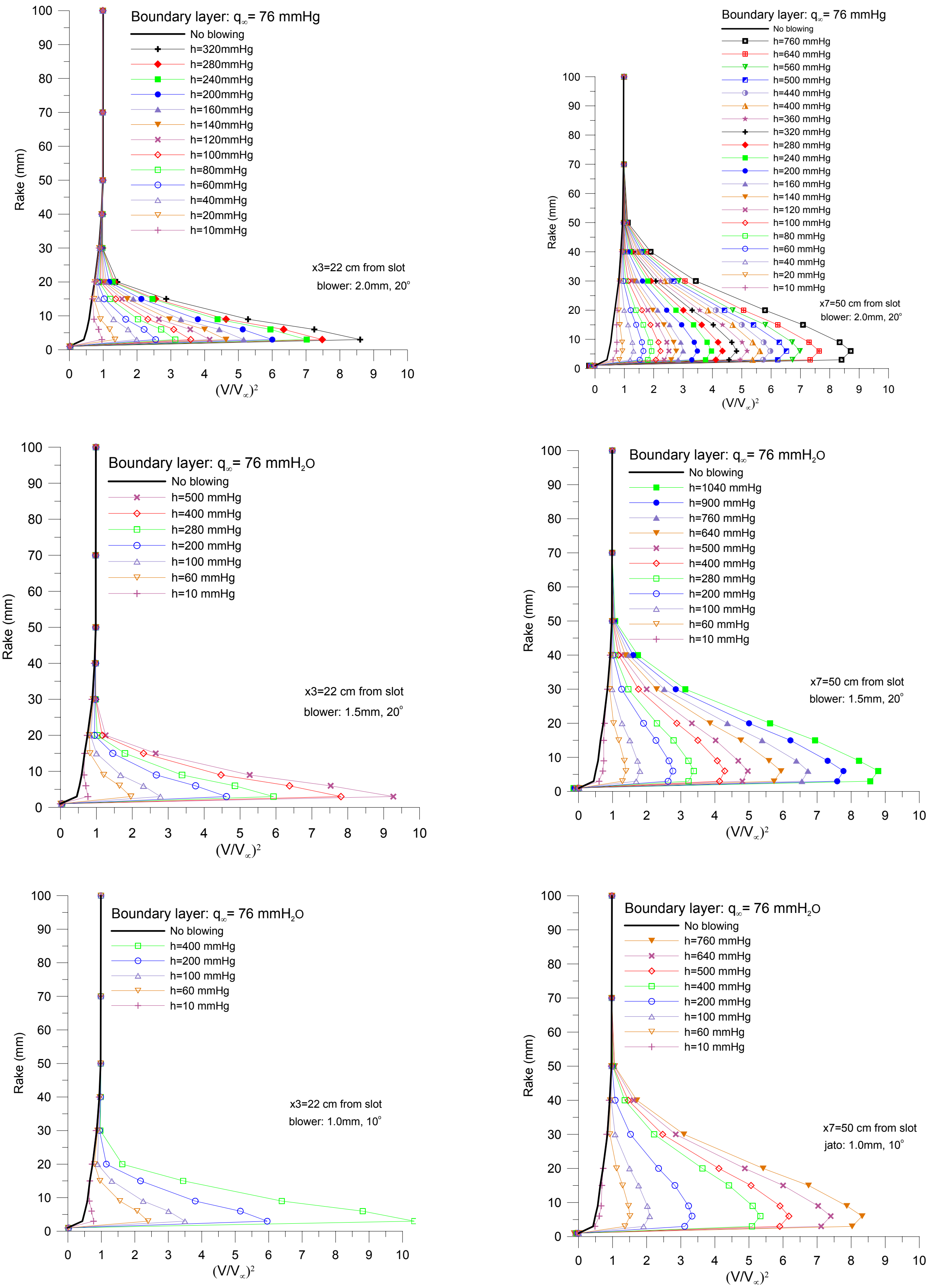

Figure 6- Effect of Blowing on Boundary-layer Profiles on the Test Section Floor at X_3= *22 cm* and X_7= *50 cm* and Several Stagnation pressures : (a) blower*: 2.0 mm 20°*; (b) blower: *1.5 mm 20°*; (c) blower: *1.0 mm 20°*

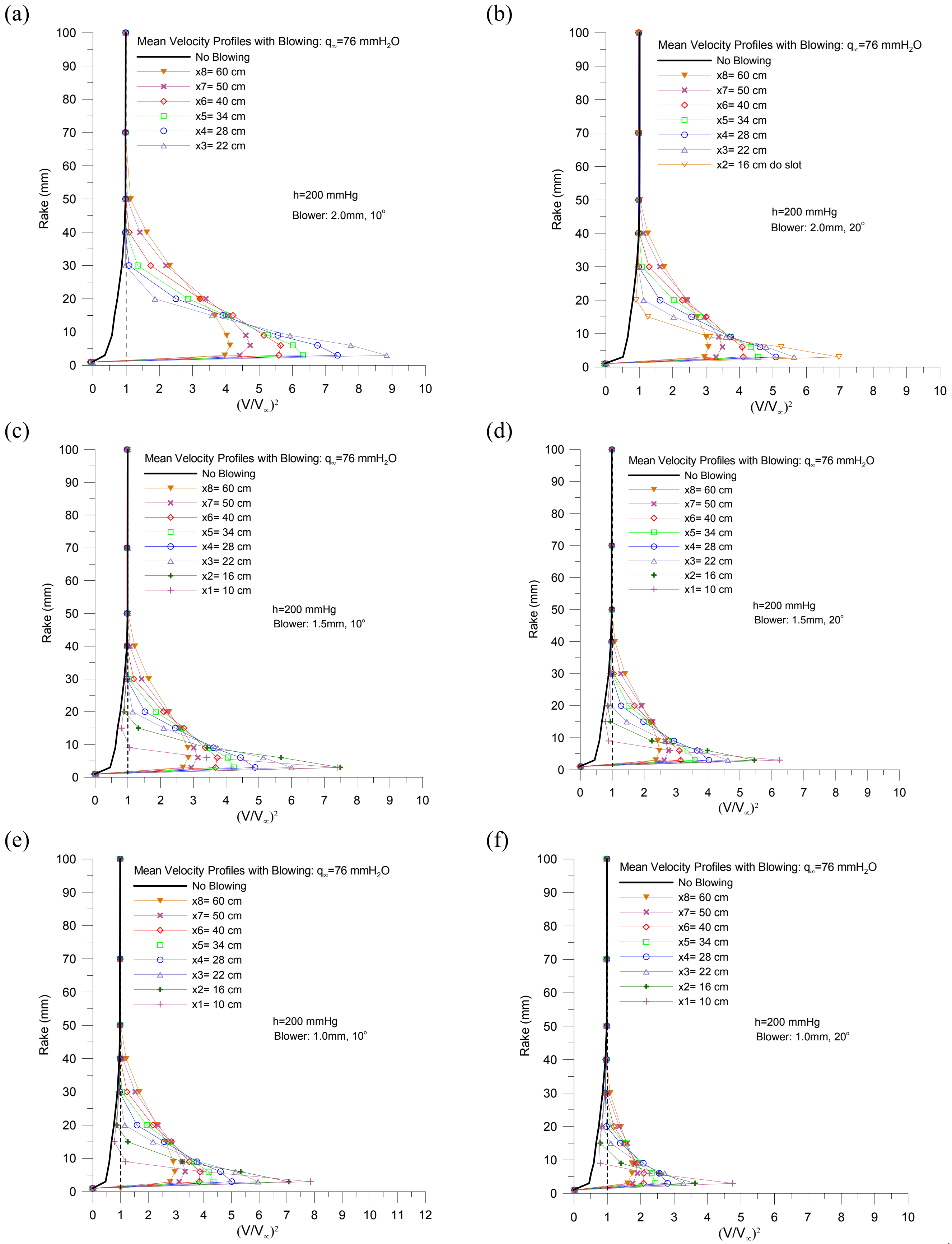

Figure 7- Behavior of Blowing on Boundary-layer Profiles Along the Test Section Floor for *h= 200 mmHg*: (a) *2.0 mm 10°*; (b) *2.0 mm 20°* ; (c) *1.5 mm 10°*, (d) *1.5 mm 20°*; (e) *1.0 mm 10°* ; (f) *1.0 mm 20°***.**

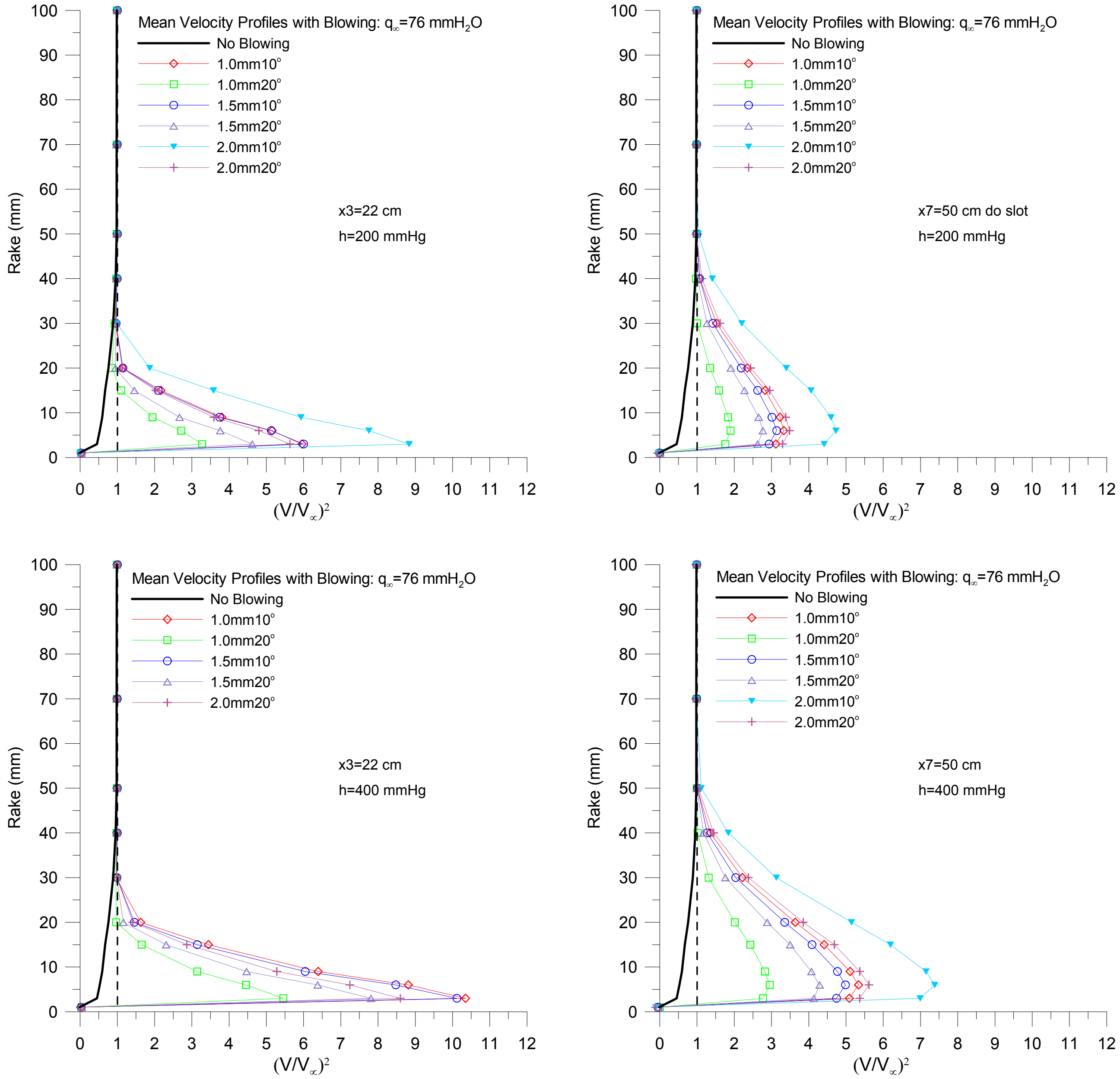

Figure 8 - Analysis All Six Injectors at X_3=*22 cm* and X_7=*50 cm* (a) *h= 200 mmHg* and (b) *h= 400 mmHg*.

(a)

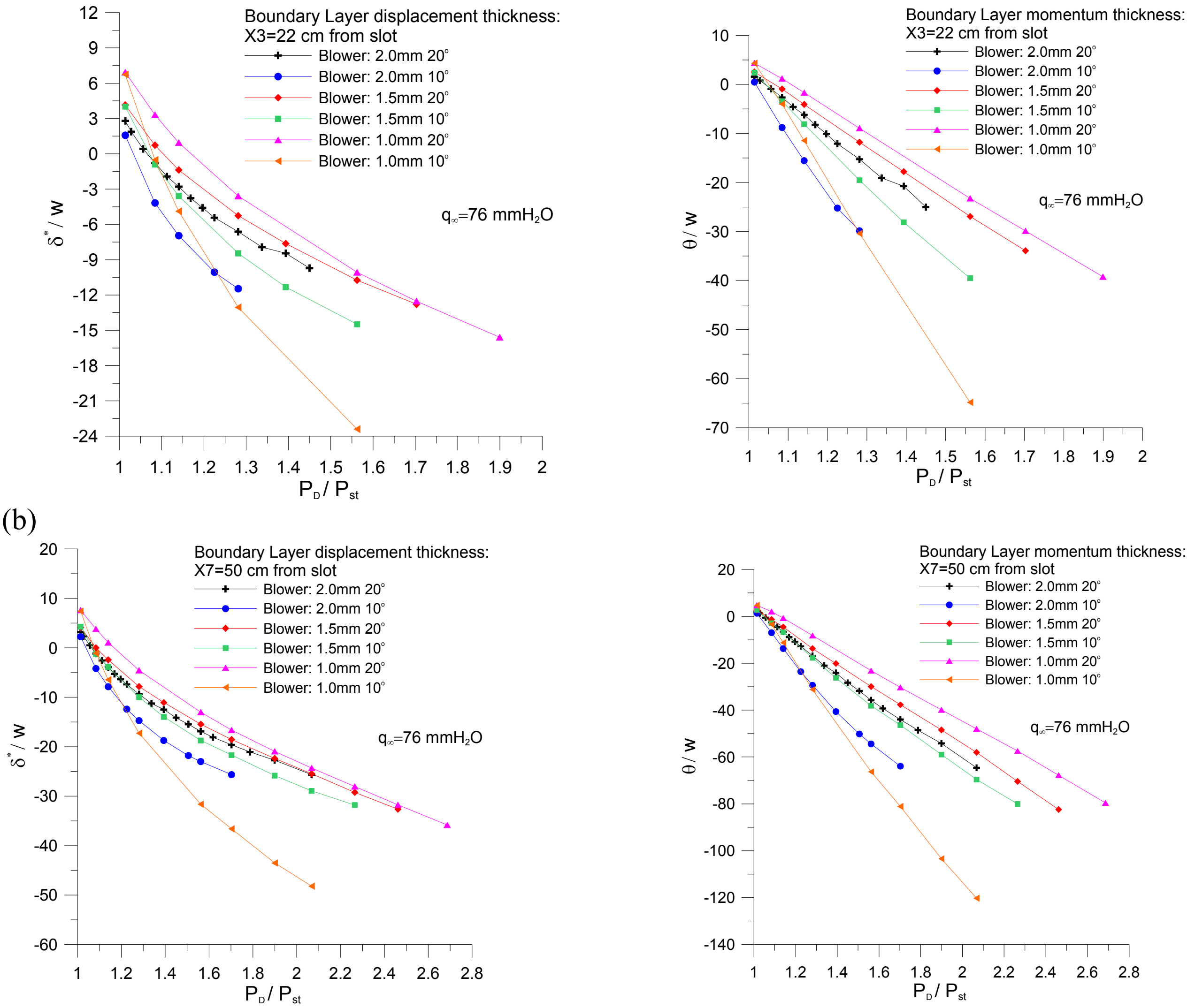

Figure 9: Boundary-layer Displacement, *δ/w*, and Momentum Thickness, *Θ/w*, for Several Blowing Pressure Ratios at (a) X_3=22 *cm* and (b) X_7=50 *cm*.

(a) (b)

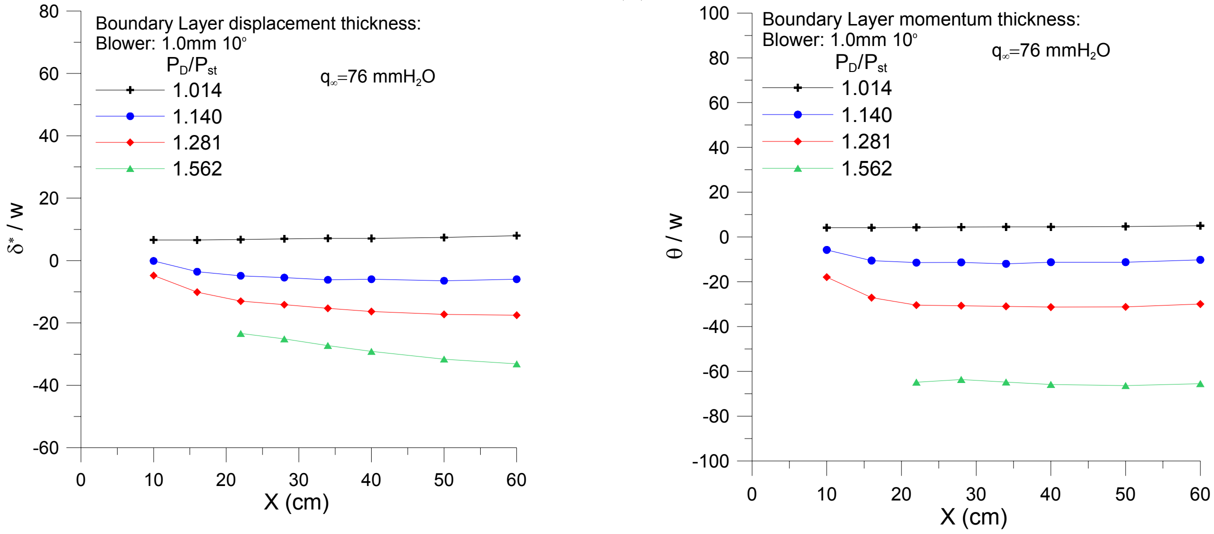

Figure 10 – Boundary-layer Parameters Along the Test Section Floor for Several Blowing Pressure Ratios. *1.0mm* blower set at 10°: (a)Displacement Thickness and (b) Momentum Thickness.

4 Conclusion

This work reported part of an extensive experimental study performed at the test section of ITA's wind tunnel in order to evaluate a boundary layer control system. For this task a air-jet blower was designed and constructed. The air injection into the tunnel test section used three different slots widths. These were: 1.0 *mm* or 1.5*mm* or 2.0*mm*. The blowing angle was also varied. The chosen values were 10 and 20 degrees in relation to the tunnel lower wall. Thus a total of six different blower geometries were investigated. To measure the boundary-layer velocity profile, a pressure rake was used. It was placed at eight different stations along the test section floor. Although several values of free stream dynamic pressure, q_∞ , were used during this work, the results reported herein are for $q_\infty=76\ mmH_2O$ only. The jet velocity was also varied and some results are reported herein. It was observed a reduction of the boundary layer thickness from *4.5 cm* to approximately *2.0 cm*. This reduction occurs in function of the blower used, blowing pressure ratio (*Bpr*), and distance from the slot. The injectors with blowing angles of 10° showed a better efficiency than the *20*-degree ones, for the same blowing pressure. It was concluded that the injector of 2.0 *mm* and 10° presented more efficient in energize the boundary layer. In second, the injector 2.0 *mm* and 20° showed a small advantage in relation to the 1.0 *mm* and 10°. The blowers of width 1.5 *mm* presented medium efficiency, while the injector of 1.0 *mm* and 20° showed to be the worst. This may be explained by a previous work, on calibration process of the blowers, Assato et al. [13]. On that occasion, it was found a higher blowing velocity for the 10-degree jet as compared to the 20-degree one, keeping the blowing pressure constant. On the one hand, the 2.0 *mm* 10-degree blower presented, as its main advantage, an effect on the boundary layer that extended over a longer length, along the tunnel floor. On the other hand, the 1.0 *mm*, 10-degree blower showed a very interesting characteristic. It provides a good boundary- layer energization using, obviously, a smaller air mass flow and thus allowing for more running time. Furthermore, if the results are normalized by the slot width, the *1.0 mm* blower set at 10 degrees showed better performance than the 2.0 *mm* one with the same jet angle. Finally, it should be mentioned that the results obtained in the present effort, of which only a small portion was reported herein, proved to be very useful in obtained a 2-D flow over a high-lift configuration airfoil.

Acknowledgements

The authors would like to thank FAPESP (www.fapesp.br) and EMBRAER (www.embraer.com.br), Brazil, by their financial support during the obtaining of these results. We also like to thank the engineers and technicians of the Prof. K.W. Feng Aeronautical Engineering Laboratory for their support in assembling the experimental apparatus.

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