EVALUATION OF A BOUNDARY-LAYER CONTROL SYSTEM BY AIR BLOWING

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Abstract. *The influence of air injectors on the boundary layer along the new low-speed wind tunnel of the Instituto Tecnológico de Aeronáutica is experimentally investigated. It is well-known that boundary-layer control is necessary in order to obtain useful high-lift 2-D results in wind-tunnel tests. Several injector's geometries were tested. Three slot thicknesses were investigated: 1.0 mm, 1.5mm, and 2.0mm, while the air-jet blowing angle was set at 10 or 20 degrees. Boundary-layer measurements were obtained using a pressure rake positioned at eight different stations along the test section floor. The results shown here are for a test-section dynamic pressure of 325 mm*H_2O.

Keywords*: boundary layer, wind tunnel, experimental test, air blowing, pressure rake.*

1. Introduction

In the sixties boundary-layer control was extensively studied at the College of Aeronautics, Cranfield, England. Carven (1960) presented several results on t boundary-layer control by using blowing or suction, for both laminar and turbulent flows. His investigation covered the incompressible regime as well as the compressible one. Another important contribution was made by Stevenson (1963) who developed a wall law for turbulent boundary layers subjected to either blowing or suction.

Boundary layer control, by a secondary blowing jet, has important technological applications in heat, mass and momentum transfer. These include film cooling techniques to protect various components which are exposed to high temperature gases, for instance, in gas turbine it protects the surfaces of the combustion chamber and the turbine blades against the high temperature combustion products. The blown air jet acts as a protective insulating between the wall and the hot gases and, thus, maintain the skin temperature and the thermal gradient within acceptable limits (Hudan(1995)). The effects of slot injection using different slot types, slot thickness and angle of blowing were investigated experimentally by Foster (1975), Jubran and Brown (1985), Quintana et al. (1997) and Aly (2000).

Here, the blowing slots were projected to perform a different, but also very important, task. They will be used to ensure, or at least maximize, 2-D flow over the EMBRAER 170 airfoil at its maximum lift configuration. This particular airfoil is equipped with both leading edge slat and trailing edge flap thus it is a true challenge to keep 2-D flow over the entire model span. In the 2-D tests, without a boundary layer control system, a premature flow separation occurs at both ends of the model. This is due to interaction of the flow over the airfoil with the boundary layer along the tunnel walls, and results in a decrease in airfoil lift. Therefore boundary-layer control is necessary to obtain useful results from two-dimensional high-lift tests in wind tunnels. 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 (1972), de Vos (1973), Vogelaar (1983[a]) (1983[b]) and McGhee et al. (1984).

Before mounting the EMBRAER-170 airfoil model at ITA's new low-speed wind tunnel it was decided to gather information about the boundary-layer behavior along its test section. In this context, three different air-blowing slots ere tested, namely: 1.0, 1.5, and 2.0 mm. The air-jet angle was also varied, being at 10 or 20 degrees. The main objective, of the present experimental effort, is to identify the distance from the slots that boundary-layer thickness reduction occurs and the useful length of such reduction. This is of paramount importance for future tests preparation, in particular for a high-lift configuration airfoil. All results presented here are for a test-section dynamic pressure of q_∞ = 325 mmH_2O.

2. Experimental apparatus and procedure

Figure 1 shows an air injector designed to supply high-speed air into the test section in order to energize the boundary layer. The slot length is 200 mm. By changing the parts numbered form 3 to 8 it is possible to vary the slot width and the jet angle. As observed in Fig. 1, the compressed air enters the blower by a tube installed on the lateral wall. Figure 2 shows the pressure rake and one of the blowers installed on a turntable, at the test section floor. It also shows a 400 psi air-supply system that provides dry compressed air to the blowers. Two small reservoirs supply high-pressure air to the six blowers. In this investigation only one injector is used. The compressed air is stored in a 10m^3 tank. Inside the test-section chamber the air passes through a valve and its pressure is reduced to 250 psi. The air is then divided to the two reservoirs. Before entering in each reservoir the pressure is reduced to 150 psi. Each blower has an individual pressure control system monitored by mercury manometers.

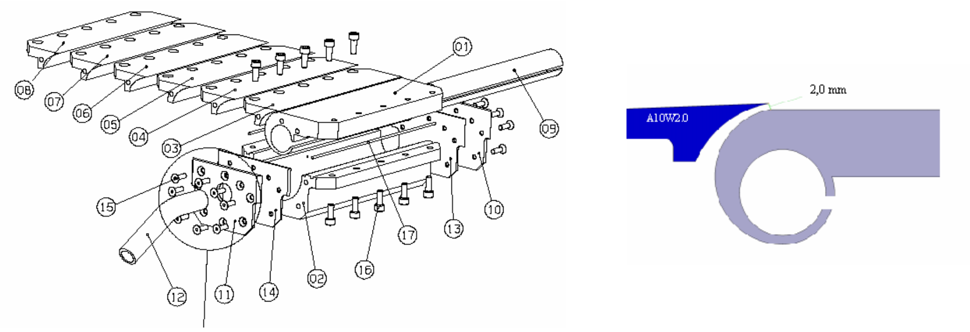


Figure 1. Compressed air blower for boundary layer blowing (slot length of 200 mm).

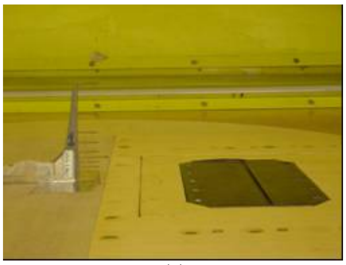
Figure 2. Test section with the compressed air supply and control system, rake and a blower.

Figure 3(a) shows the rake, with eleven pressure tabs, positioned to 160 mm from blowing slot. The taps are located 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. Figure 3 (b) shows the electronic pressure scanners – ESP of 1 psi (704 mmH_2O) with 32 channels. The reference pressure is the tunnel static pressure.

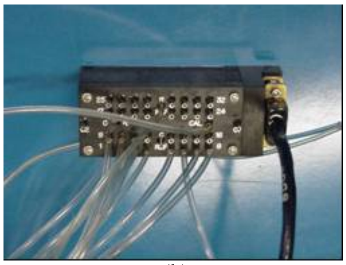
The measurements were obtained positioning the rake at eight stations along the test section. The first one is 100mm form the air slot. The others distance 220 mm, 280 mm, 340 mm, 400 mm 500 mm and 600 mm form it. Data acquisition was done using Labview. The sample rate was SR=10 kHz and a sample number of N=1000 readings. Twenty sweeping were made for each rake position. Then, it was calculated the average pressure for the respective data acquired. The uncertainty is approximately 2%. The software makes the data reduction and calculates the pressure coefficients given by:

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

where, p_t and V is the total pressure and velocity, respectively, obtained by rake, 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.



(a)



(b)

Figure 3. (a) Rake and blower; (b) ESP – Electronic Pressure Scanners.

3. Results

Figure 4 shows the effect of blowing upon the boundary-layer velocity profiles for a free-stream dynamic pressure of q_∞ = 325 mmH_2O. The blowing angle was 10° The boundary layer profiles, with and without blowing, for the positions X_4= 280 mm cm and X_8= 600 mm away from jet exit can be observed. Several velocity profiles with different blower stagnation pressures, h (mmHg), are plotted. It is interesting to notice that for h=280 mmHg and a jet angle of 10 degrees, the pressure coefficient was increased from about 0.5 to 3.0.It is also important to notice that at the position X_8= 600 mm, the C_p values are smaller because the jet lost a good fraction of its kinetic energy to the floor surface and transferred a momentum fraction to the upper layers, energizing them. For the position X_8 it was possible to investigate higher blowing velocities, because 600 mm away from the slot exit, the transducer upper limit was not surpassed. Figure 5 shows the injection effect on the boundary layer for twenty-degree blowers. A close look at the results reveals that for some blowing pressures and rake position it was possible to reduce the boundary layer thickness from 4.5 cm to approximately 2.0 mm.

Figure 6 shows the evolution of interaction of the air jet, emerging from the blower, with the boundary layer along the test section. The blower stagnation pressure, h, is kept constant at 200 mmHg. Looking at Fig. 6 it is easier to notice the decrease of the flow velocity near the floor (the jet diffuses faster in the wall region), and its increase towards the upper layers. It is possible to observe a better efficiency, in energize the boundary layer, using ten-degree blowers.

Figure 7 displays results for the six different blowers studied in the present work. The stagnation pressure is maintained at h= 200 mmHg. The pressure rake was positioned at X_4= 280 mm and X_8= 600 mm away from slot. As it can be observed the 2.0-mm injector set at 10 degrees presented more efficient in energize the tunnel boundary layer. Further, the injector width of 2.0 mm with the air jet set at 20° showed a small advantage in relation to the 1.0 mm one with a jet angle of 10 degrees. The 1.5-mm blowers presented medium efficiency, while the narrowest injector, 1.0 mm, combined with a air-jet angle twenty degrees showed to be the worst of all the blowers. The effect of injection using the blower 2.0 mm and 10° is extended over a longer length of the tunnel floor compared with other blowers. However, the 1.0-mm blower, set at 10, $^\circ$ also proved to be very interesting. It has as primary advantage the smaller mass flow rate. This may come in handy as it maximizes the test duration.

Figure 8 shows the displacement thickness, δ^*, and the momentum thickness, θ, of boundary layer normalized by slot width, w. Results of all six blowers are shown at the position X_8=600 mm for several blowing pressure ratio, Bpr=h/p_{st}. The values of the boundary layer displacement thickness and momentum thickness are defined, respectively, as:

$$\delta^* = \int_0^\delta \left(1 - V/V_\infty\right) dy \,, \tag{2}$$

$$\theta = \int_0^\delta \left(1 - V/V_\infty\right)\left(V/V_\infty\right) dy \,. \tag{3}$$

As pointed out by Aly (2000) negative values of δ^*/w indicate 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 degrees, especially for higher values of Bpr.

Figure 9 shows the distribution of δ^*/w and θ/w along the test section floor using the 1.0-mm blower at 10 degrees. It was observed a small, almost imperceptible, increase of δ^*/w and θ/w along the tunnel floor for lower BPr values. For Bpr=1.578 δ^*/w is constant between X_6= 400 mm and X_8= 600 mm. The same behavior is observed for the momentum thickness distribution, θ/w.

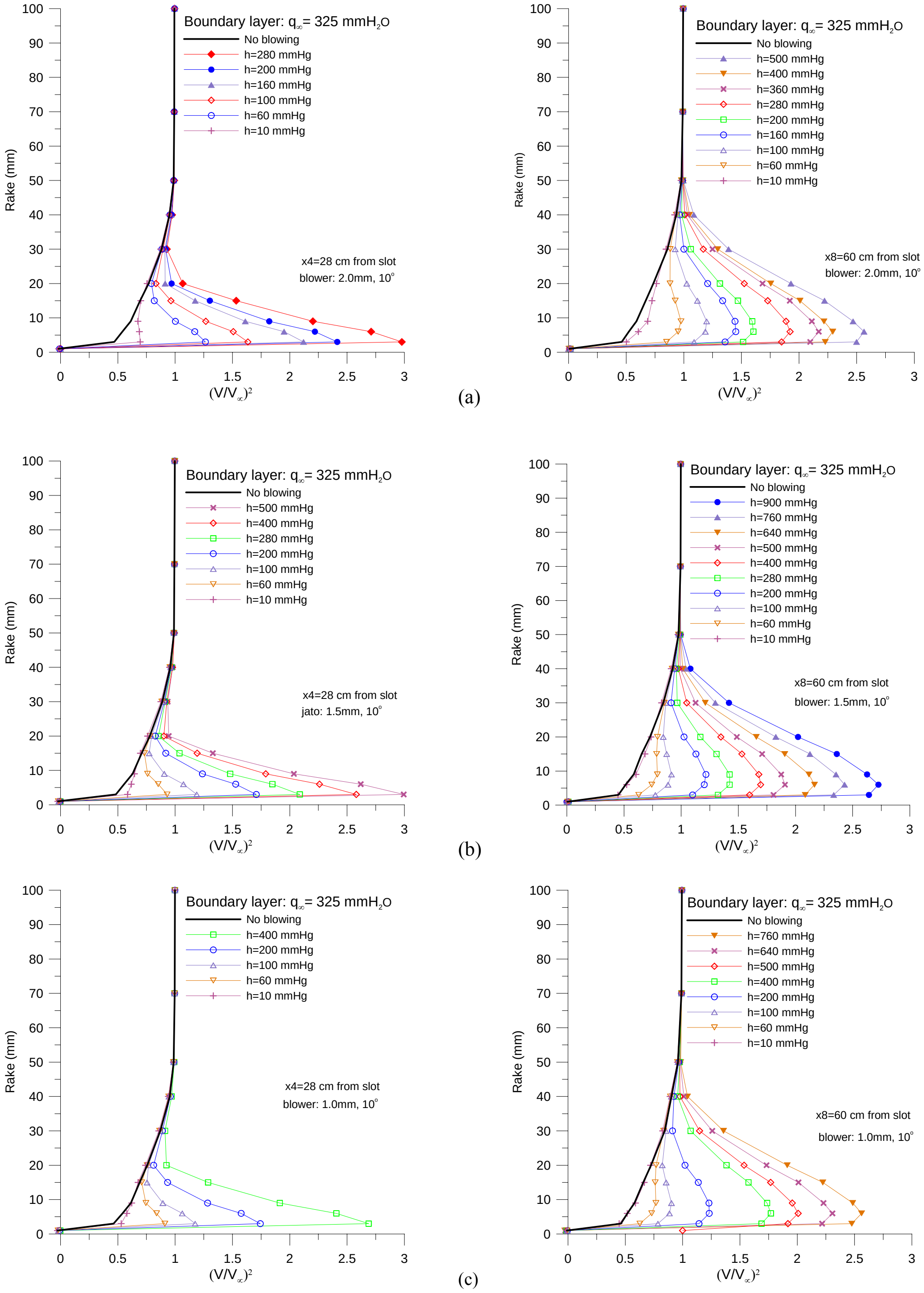


Figure 4. Effect of blowing on boundary layer profiles on floor of the test section for the positions X_4= 28 cm and X_8= 60 cm and several stagnation pressures: (a) blower: 2.0 mm 10°; (b) blower: 1.5 mm 10° ; (c) blower: 1.0 mm 10°.

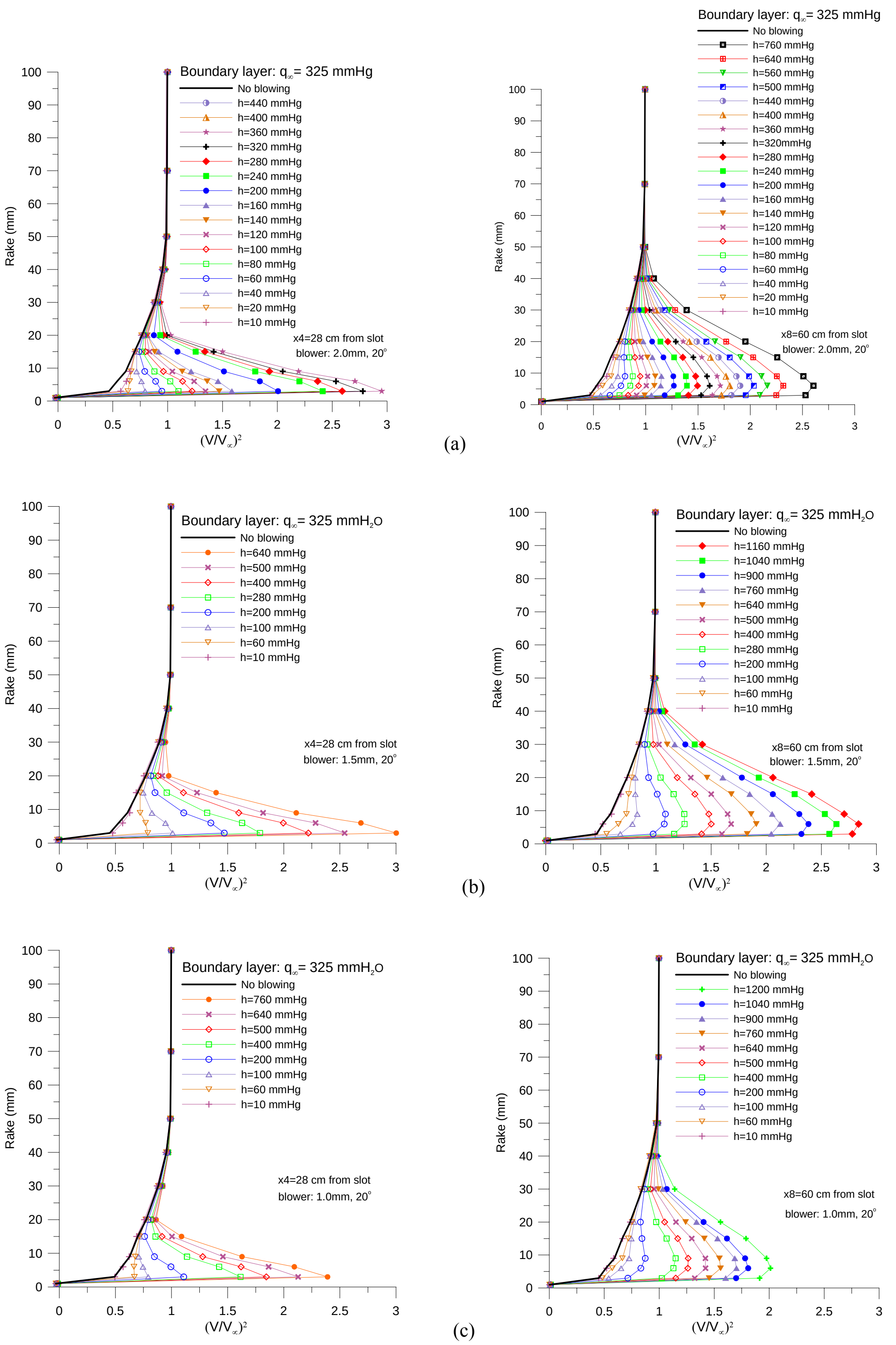


Figure 5. Effect of blowing on boundary layer profiles on floor of the test section for the positions X_4= 28 cm and X_8= 60 cm and several stagnation pressures : (a) blower: 2.0 mm 20°; (b) blower: 1.5 mm 20° ; (c) blower: 1.0 mm 20°.

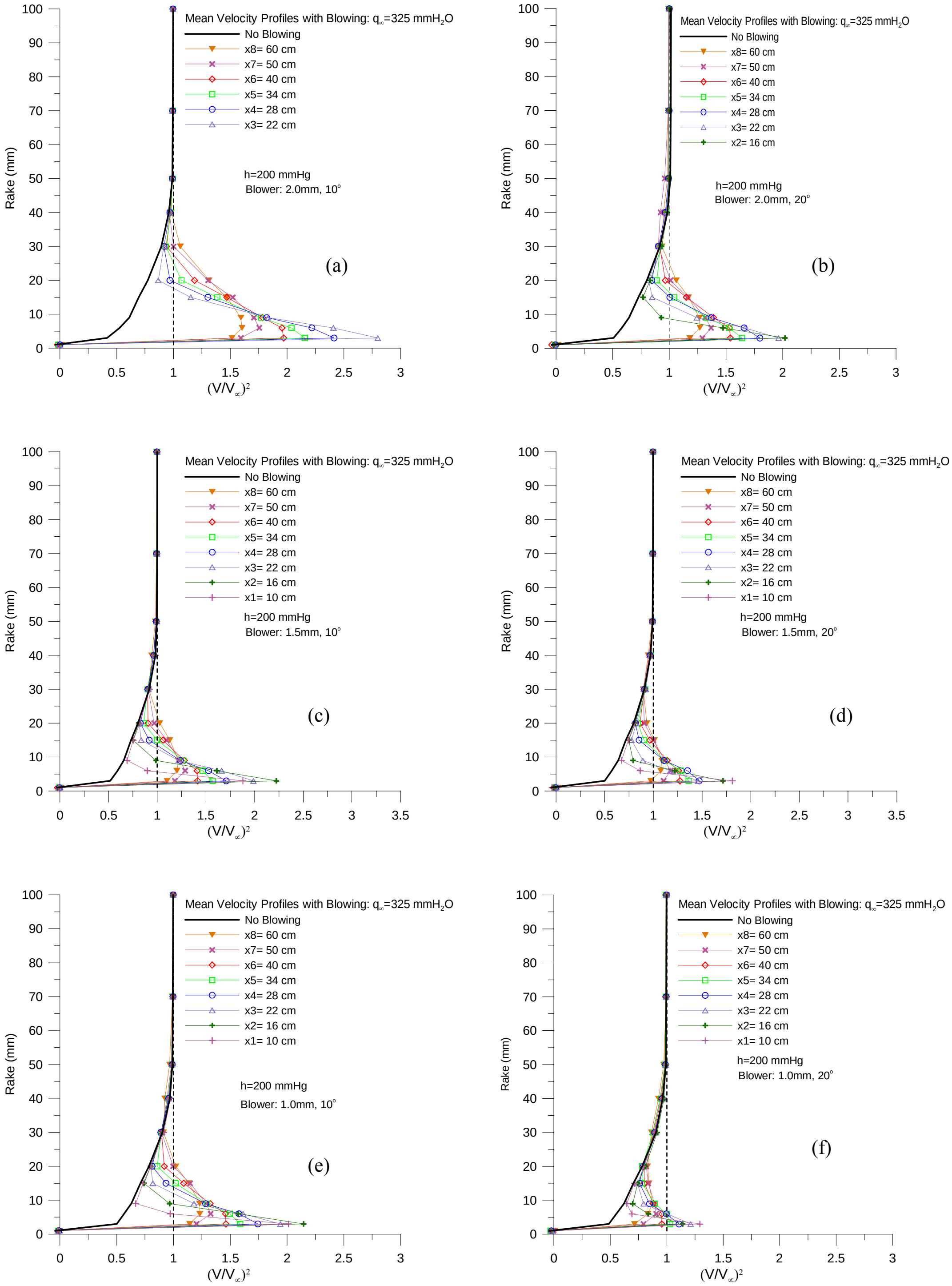


Figure 6. Behavior of blowing on boundary layer profiles along the test section floor for h= 200 mmHg: (a) 2.0 mm 10°; (b) 2.0 mm 20° ; (c) 1.5 mm 10°, (d) 1.5 mm 20°; (e) 1.0 mm 10° ; (f) 1.0 mm 20°.

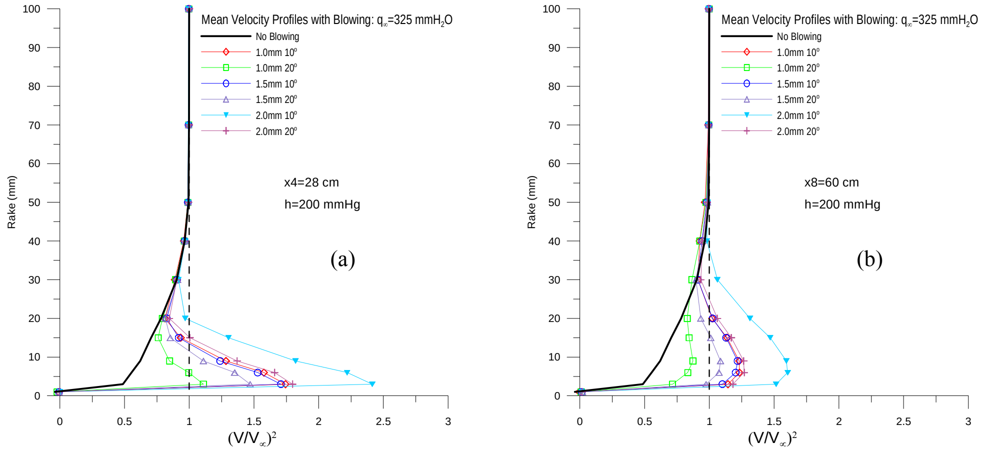


Figure 7. Analysis of six injectors for h= 200 mmHg at the positions: (a) X_4=28 cm, and (b) X_8=60 cm.

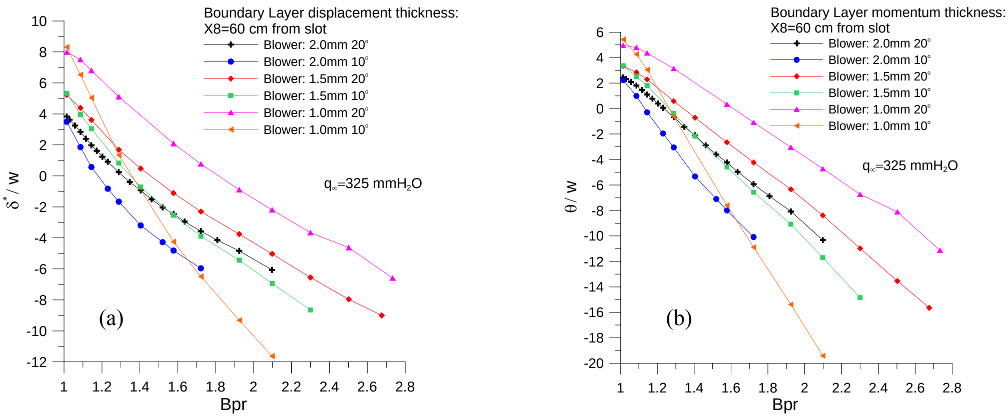


Figure 8. Boundary layer displacement thickness (a), and momentum thickness (b) for several blowing pressure ratios at the position X_8=60 cm.

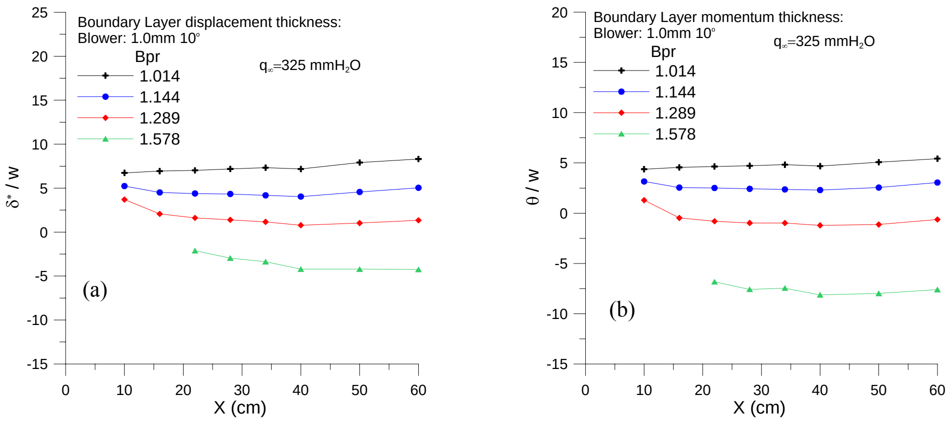


Figure 9. Boundary layer displacement thickness (a), and momentum thickness (b) along the test section floor for several blowing pressure ratios and blower of 1.0 mm 10°.

4. Conclusion

This work reported some experimental results obtained in the evaluation of the boundary-layer control system of ITA's low-speed wind tunnel. Six different configurations were tested. The slot width was set at 1.0mm, 1.5mm or 2.0mm and air-jet blowing angle was fixed at 10 or 20 degrees. A pressure rake was positioned at eight stations along the test section floor in order to evaluate the effect of the blowing system upon the boundary- layer along the test-section longitudinal axis. The free stream dynamic pressure was q_{∞} = 325 mmH_2O. Several blowing velocities were used. 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 set-up, blowing pressure ratio (Bpr), and rake position. The injectors with blowing angles of 10° showed a better efficiency than 20-degree ones, for the same blowing pressure. A previous work on calibration process of the blowers, the authors measured a higher blowing velocity using the slots of 10° for a same blowing pressure. Then, the blowers of 10° present better efficiency for the same slot width. It was concluded that the 2.0-mm injector, at 10°, is more efficient in energize the boundary layer. The 2.0-mm injector, at 20°, showed a small advantage over the 1.0-mm blower set at 10°. The blowers of width equal to 1.5 mm presented medium efficiency, while the 1.0-mm injector of 1.0 mm, at 20°, showed to be the worst one

The 2.0-mm blower, set at 10°, presented as main advantage the fact that its effect that extended over a longer length of the floor than that of the other blowers. The1.0-mm blower, at 10°, is very interesting because it energizes the boundary layer, obviously, using a smaller amount of compressed air and thus allowing for longer 2-D tests. Besides, when the values are normalized by slot width, the 1.0-mm blower, at 10°, showed better performance than the blower of 2.0 mm and 10°, as observed in Fig. 8.This work has important information that it will help in decision of the best distance of the slots in relation to the airfoil as well as what blower should be used in the two-dimensional test.

5. Acknowledgements

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6. References

Aly, S.E., 2000, "Injection Effect on Two Dimensional Boundary Layer", Energy Conversion & Management (41), pp. 539-550.

Craven, A. H., 1960, "Boundary Layers with Suction and Injection", CoA REPORT AERO No. 136, The College of Aeronautics Cranfield, September, 1960.

Comentário: Craven (1960)

de Vos, D.M., 1973, "Low Speed WindTunnel Measurements on a Two-Dimensional Flapped Wind Model Using Tunnel Wall Boundary Layer Control at the Wing-Wall Junctions", National Aerospace Laboratory NLR, Originator's Ref.: NLR TR 70050 U, Amsterdam, The Netherlands, pp 1-26.

Comentário: de Vos (1973)

de Vries, O., 1972, "Comments on the Methods Developed at NLR for Conducting Two-Dimensional Research on High-Lift Devices", NLR the Netherlands.

Huda Z., 1995, "Development of Design Principles for a Creep Limited Alloy for Turbine Blades", J. Materials Engng. Performance 1995;4(1), pp. 48-53.

Foster R. and Haji-Sheikh, A., 1975, "An Experimental Investigation of Boundary Layer and Heat Transfer in the Region of Separated Flow Downstream of Normal Injection Slots", J. Heat Transfer, Trans ASME, pp. 260-266.

Jubran B. and Brown A., 1985, "Film Cooling from Two Rows of Holes Inclined to the Stream Wise and Spanwise Directions", J. Engng. Gas Turbines Power, 107, pp. 84 - 91.

McGhee, R.J., Beasley, W.D. and Foster, J. M., 1984, "Recent Modifications and Calibration of the Langley Low-Turbulence Pressure Tunnel", NASA Technical Paper 2328, pp. 1-63.

Comentário: McGhee et al. (1984)

Quintana D., Amitay M., Ortega A. and Wygnanski I., 1997, "Heat Transfer in the Forced Laminar Wall Jet", J. Heat Transfer, Trans ASME, 119, pp. 451-459.

Stevenson, T.N., 1963, "A Law of the Wall for Turbulent Boundary Layers with Suction or Injection", CoA REPORT AERO No. 166, The College of Aeronautics Cranfield, July, 1963.

Comentário: Stevenson (1963[a])

Vogelaar, H.L.J., 1983[a], "Wall Blowing Requirements for 2-D High-Lift Testing in Pressurized WindTunnels", National Aerospace Laboratory NLR, Memorandum AI-83-005 U, Amsterdam, The Netherlands.

Comentário: Vogelaar (1983[a])

Vogelaar, H.L.J., 1983[b], "Description and Validation of the Two-Dimensional Test Setup for Multiple Airfoils in the Pressurized Wind Tunnel HST", National Aerospace Laboratory NLR, Originator's Ref.: NLR TR 83031U, Amsterdam, The Netherlands, pp 1-34.

Comentário: Vogelaar (1983[b])

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