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DEVELOPMENT OF A METHODOLOGY FOR 2-D HIGH LIFT TESTING USING A BOUNDARY LAYER CONTROL SYSTEM BY AIR BLOWING

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Abstract. *The present work shows the development of a methodology that corrects the boundary layer effect on 2-D models such as airfoils. The technique of maintaining two-dimensional flow up to maximum lift is based upon energizing the boundary layer along the airfoil. This is accomplished by blowing high-speed air at appropriated test section locations. Here, it is analyzed a formulae (dimensionless parameter, C_μ) that is function of free stream Mach number, model chord, slot thickness and blowing pressure ratio. A dimensionless parameter, namely the momentum ratio is used to determine the blowing pressure ratio required at each attack angle for several Mach number of wind tunnel free flow. The results have shown good agreement between the experimental and theoretical values. Thus, the momentum ratio seems to be an appropriate parameter to estimate blowing pressure ratios.*

Keywords*: Boundary layer control, wind tunnel, blowing slots, airfoils, two-dimensional tests.*

1. Introduction

The present research represents one part of the project supported by FAPESP and EMBRAER for developing new experimental methodologies involving Brazil’s largest subsonic Wind Tunnel located at Centro Técnico Aeroespacial – CTA. To fulfill this objective EMBRAER has decided to work together with the Instituto Tecnológico de Aeronáutica (ITA), the Instituto de Aeronáutica e Espaço, both integrant parts of CTA, the Universidade de São Paulo at São Carlos (EESC-USP) as well as the Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP). The enterprise has two very definite objectives: (i) the development of an experimental apparatus to ensure 2-D flow over high-lift airfoil configuration, and (ii) to develop a data reduction technique to estimate the 3-D wing C_{Lmax} knowing the experimental 2-D result for the wing section. At ITA 2-D flow has been generated by the boundary-layer blowing technique while at EESC-USP boundary layer control has been achieved by sucking.

The investigation of the aerodynamic behavior of a wing section, airfoil, is frequently obtained through wind tunnel testing. These models are so called "two-dimensional", an airfoil of constant cross section, in most cases spanning the entire height or width of the Wind Tunnel test section. Thus, at least ideally, the flow is normal to the body span wise direction. In reality this is not the case because of the interference of the boundary layers growing along the tunnel walls with the one that develops along the airfoil model. During the experiments these ends effects induce premature boundary-layer separation over the model in the region near the tunnel walls. In turn, the ideal 2-D coefficient is degraded. Flow visualization indicates that the flow over the airfoil model is far from being two-dimensional. The greater the angle of attack the more pronounced these 3-D effects become. This departure from the two-dimensional brings about erroneous results and therefore is highly undesirable. In particular, EMBRAER engineers have a very hard time to determine an airfoil parameter, namely, the maximum lift coefficient. Thus, the overall lift coefficient measured is smaller than the true 2-D value. In this context, it may be found in the literature several methodologies to control the boundary layer over the 2-D model and minimize the flow three-dimensionality, (Craven,1960): (i) the use of the end plates; (ii) boundary layer blowing or suction, and (iii) use of vortex generators.

As mentioned previously, at ITA the main objective is to generate results using a blowing technique. Therefore, a methodology for 2-D testing using a boundary layer control system by air blowing into the test section at very specific locations has been developed. The non-dimensional parameter momentum ratio, $C\mu$, has been evaluated for several free stream Mach numbers, model chord, slot thickness and blowing pressure ratio.

2. Non dimensional parameter

In order to make a comparison between the obtained results it’s necessary to work with non-dimensional parameters. The wind tunnel at ITA is an open circuit facility, thus, the atmospheric air admitted in the wind tunnel varies along the day, i.e., in each test it has different ambient conditions such as atmospheric pressure, temperature (density, Mach and Reynolds numbers) and others, that influence directly in the results. In order to generalize the tests using the blowing technique it's important to use a non dimensional parameter that involve the model chord, slot thickness, Mach number and blowing pressure ratio.

Momentum coefficient

The injected airflow momentum is generally assumed to be the most important parameter governing the effectiveness of the blowing process (De Vries, (1972), Vogelaar, (1983[a]), Vogelaar, (1983[b]), de Vos, (1983) and McGhee et al., (1984)). The idea of the non-dimensional parameter is to keep the ratio between the momentum of the blowing injector and the momentum of the free stream constant in all situations with a fixed angle of attack (jet velocity and temperature are considered less important). At the moment that the applied blowing pressure gives a satisfactory result, the momentum ratio can be calculated using this condition. This momentum ratio can be kept constant in different conditions at the same angle of attack. The momentum ratio is defined as:

$$C_\mu = \frac{\dot{m} v_j}{\frac{1}{2}\rho_\infty V_\infty^2 S_{ref}} , \tag{1}$$

where, $\dot{m}$ is the mass flow through the blowing slot, v_j represents the velocity of the blowing jet, ρ_∞ the density of the free stream , V_∞ is the free stream velocity, and S_{ref} is an arbitrary reference area.

In terms of free stream Mach number, M_∞ :

$$C_\mu = \frac{\dot{m} v_j}{\frac{1}{2}\gamma\, p_\infty M_\infty^2 S_{ref}} , \tag{2}$$

where, γ is the ratio of specific heat, and p_∞ represents the free stream static pressure.

In the work of Vogelaar, (1983[a]) was developed a momentum ratio expression given by:

$$C_\mu = \frac{4}{\gamma - 1}\left[\left(\frac{p_{stg}}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\frac{1}{M_\infty^2}\frac{w_s}{c} \ . \tag{3}$$

In Eq. (3), p_{stg} / p_∞ represents the blowing pressure ratio, *Bpr*, between the stagnation pressure in settling chamber of the injector and the free stream static pressure. The reference area is taken as the airfoil main-element chord length, *c*, times unity in order to keep the non-dimensional momentum ratio. The slot thickness is represented by w_s. It is important to observe that the temperature in the settling chamber does not appear in this equation.

In case the pressure ratio is above the critical value, $p_{stg} / p_\infty > 1.893$, the mass flow is related to the condition in the effective throat, where $M = 1$. Then, the momentum coefficient is written as:

$$C_\mu = \frac{2}{M_\infty^2}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left(\frac{2}{\gamma-1}\right)^{\frac{1}{2}}\frac{p_{stg}}{p_\infty}\left[1-\left(\frac{p_{stg}}{p_\infty}\right)^{-\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}\frac{w_s}{c} \ . \tag{4}$$

Again the reference area is expressed as the chord of the main element of the airfoil times unity.Concluding this analysis the resulting equations can be summarized as follows using $\gamma = 1.4$:

$$\frac{p_{stg}}{p_\infty} < 1.893, \quad C_\mu = \frac{10}{M_\infty^2}\left[\left(\frac{p_{stg}}{p_\infty}\right)^{0.2857} - 1\right]\frac{w_s}{c} \ , \tag{5}$$

$$\frac{p_{stg}}{p_\infty} > 1.893, \quad C_\mu = \frac{2.588}{M_\infty^2}\left[1-\left(\frac{p_{stg}}{p_\infty}\right)^{-0.2857}\right]^{\frac{1}{2}}\frac{p_{stg}}{p_\infty}\frac{w_s}{c} , \tag{6}$$

$$\frac{p_{stg}}{p_\infty} = 1.893 \quad C_\mu = \frac{2}{M_\infty^2}\frac{w_s}{c} \ . \tag{7}$$

If the width and the chord length are considered identical, then the formulae can be written as:

$$\beta_\mu = C_\mu \frac{c}{w_s} . \tag{8}$$

Resulting in:

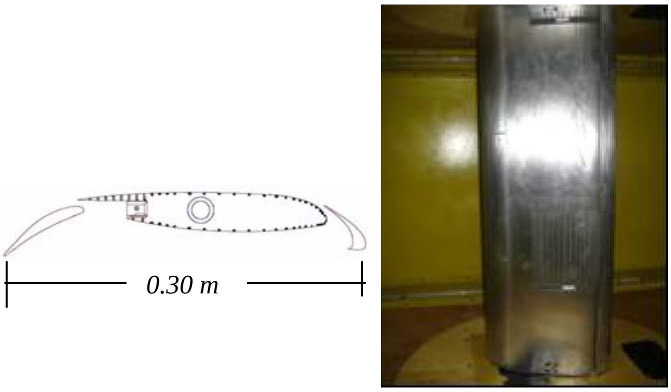
$$\frac{p_{stg}}{p_\infty} < 1.893, \quad \beta_\mu = \frac{10}{M_\infty^2}\left[\left(\frac{p_{stg}}{p_\infty}\right)^{0.2857} - 1\right], \tag{9}$$

$$\frac{p_{stg}}{p_\infty} > 1.893, \quad \beta_\mu = \frac{2.588}{M_\infty^2}\left[1 - \left(\frac{p_{stg}}{p_\infty}\right)^{-0.2857}\right]^{\frac{1}{2}} \frac{p_{stg}}{p_\infty}, \tag{10}$$

$$\frac{p_{stg}}{p_\infty} = 1.893 \quad \beta_\mu = \frac{2}{M_\infty^2} . \tag{11}$$

3. Experimental apparatus

ITA has developed a methodology for 2-D testing using a boundary layer control system by air blowing. The equations given above were evaluated and used in the experimental procedure. The airfoil for the EMBRAER 170 was chosen as one capable of producing high lift and, therefore, very representative of the flow pattern the authors wanted to investigate. The model has a basic chord of 0.30 meter and a span of 1 meter, as shown in Fig. 1, and consists of three elements: a slat, the main element and the flap. The airfoil was clamped between the upper and lower turntables of the test section. To produce a two-dimensional flow blowing injectors are installed at the test section upper and lower walls for boundary layer control upstream of the airfoil leading edge, and near the flap, see Fig. 1 (b).



(a)

(b)

Figure 1. (a) airfoil EMBRAER170 with slat and flap, (b) blowing injectors location at lower wall.

The model is connected inside the wind tunnel by a rotating rod. This rod can be rotated freely without rotating the turntable. Because of this independent configuration it is possible to move the position of the blowing slots relative to the model. In the mid-section of the model and near the upper wall pressure tabs holes were drilled in the model.

Figure 2 shows the injector used to control the boundary layer. Three different jet slot width were used, namely: 1.0 mm or 1.5 mm or 2.0 mm. The blowing angle was either 10° or 20°. The different jets are obtained in changing the pieces labeled 03 through 08, see Fig. 2.

The measured pressure in the pressure hole is sent to a transducer, which will convert the pressure measured into an electrical form. To measure pressure the transducers used are the ESP-32 Electronic Pressure Scanners, three 1 psi transducers and a 2.5 psi one. The latter was used to measure the high pressures near the leading edge. The electrical signal was transferred to the software by an interface. Care was taken to minimize signal degradation during the data acquisition process which was done with the aid of the software LABVIEW.

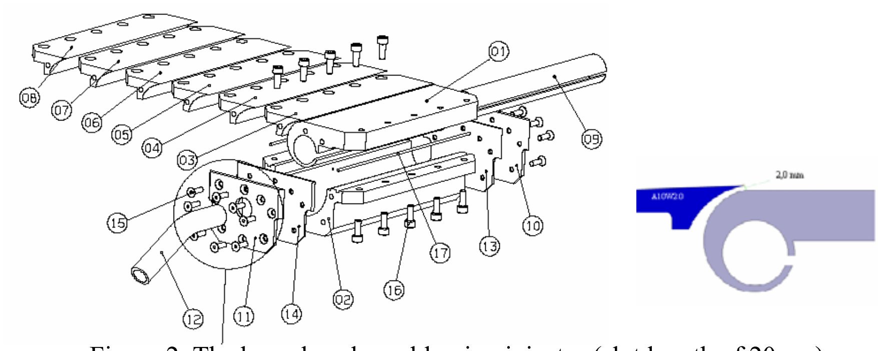


Figure 2. The boundary-layer blowing injector (slot length of 20 cm).

4. Results

In this section a theoretical analysis involving the Eqs. 5-7 or 9-11 is shown. The non-dimensional parameter of interest, namely the momentum ratio is investigated. Its behavior is analyzed as function of several variables such as, model chord, slot thickness, free stream Mach number and blowing pressure ratio. Experimental results also are shown and compared with the theoretical formulas.

4.1. Theoretical results

Figure 3 (a) shows the behavior blowing pressure ratio (*Bpr*), p_{stg} / p_∞, at different free-stream Mach number for constant values of β_μ = 30, 45, 60, 75, 90. It is possible to observe from Fig. 3 that the Bpr is a non-liner function of the Mach number. Further, to get higher values of β_μ it is necessary an increase of the blowing pressure ratio. Figure 3 (b) displays the same variables, however, the Mach number is maintained constant from 0.10 to 0.30. The values for β_μ were calculated using Eq. 5 or Eq. 6 for the pressure ratio smaller or larger than 1.893, respectively. For a fixed Mach number the momentum coefficient, β_μ, is expressed only in function of the pressure ratio. It is noted that for a higher Mach number, for instance, equal to 0.30, one has to increase the *Bpr* up to 3.0 in order to reach a low value for β_μ (approximately 45). While for a Mach number equal to 0.15 using the same pressure ratio (*Bpr=3.0*), one gets β_μ = 179.

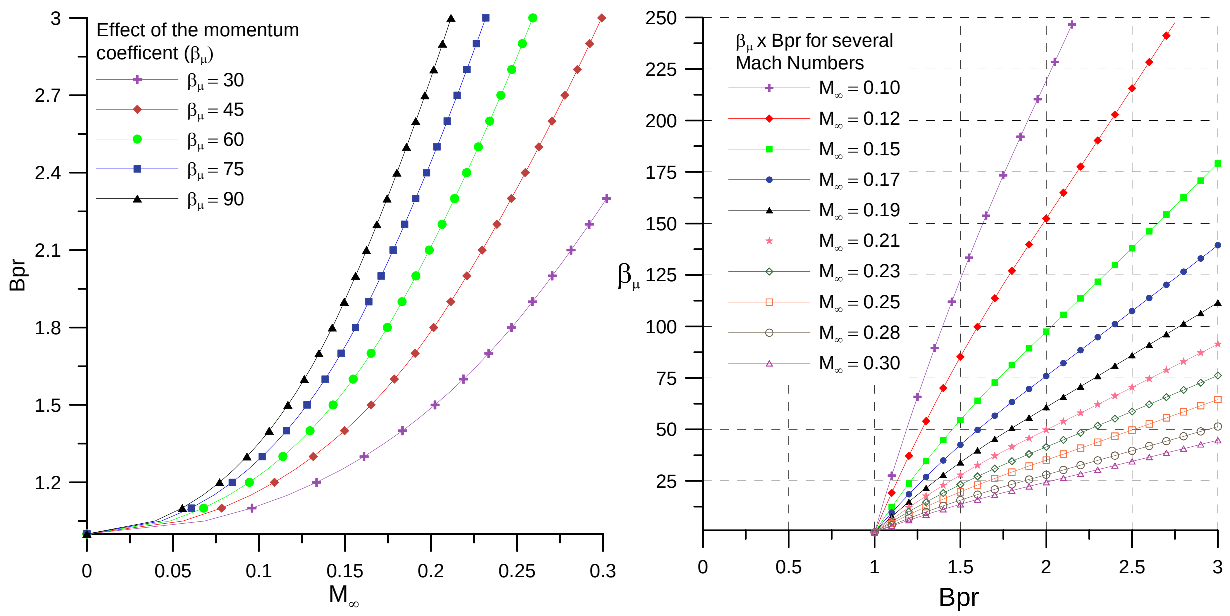


Figure 3. Analysis of the blowing pressure ratio (Bpr) required in tests. (a) Effect of the momentum coefficient; (b) Effect of the Mach number.

Figure 4 displays the influence of the model chord, as it ranges from 0.10 m to 0.90 m, on the blowing pressure ratio. Four different cases were studied: (a) C_μ = 0.20 and w_s = 1.0 mm; (b) C_μ = 0.30 and w_s =1.0 mm; (c) C_μ = 0.20 and w_s = 2.0 mm; (d) C_μ = 0.30 and w_s =2.0 mm. It can observe that as the model chord increases it is necessary a higher blowing pressure ratio. It is also seen that when the momentum coefficient varies from 0.20 to 0.30 it is noted an increase in the pressure ratio values. However, as the slot width is increased from 1.0 mm to 2.0 mm the blowing pressure ratio decreases.

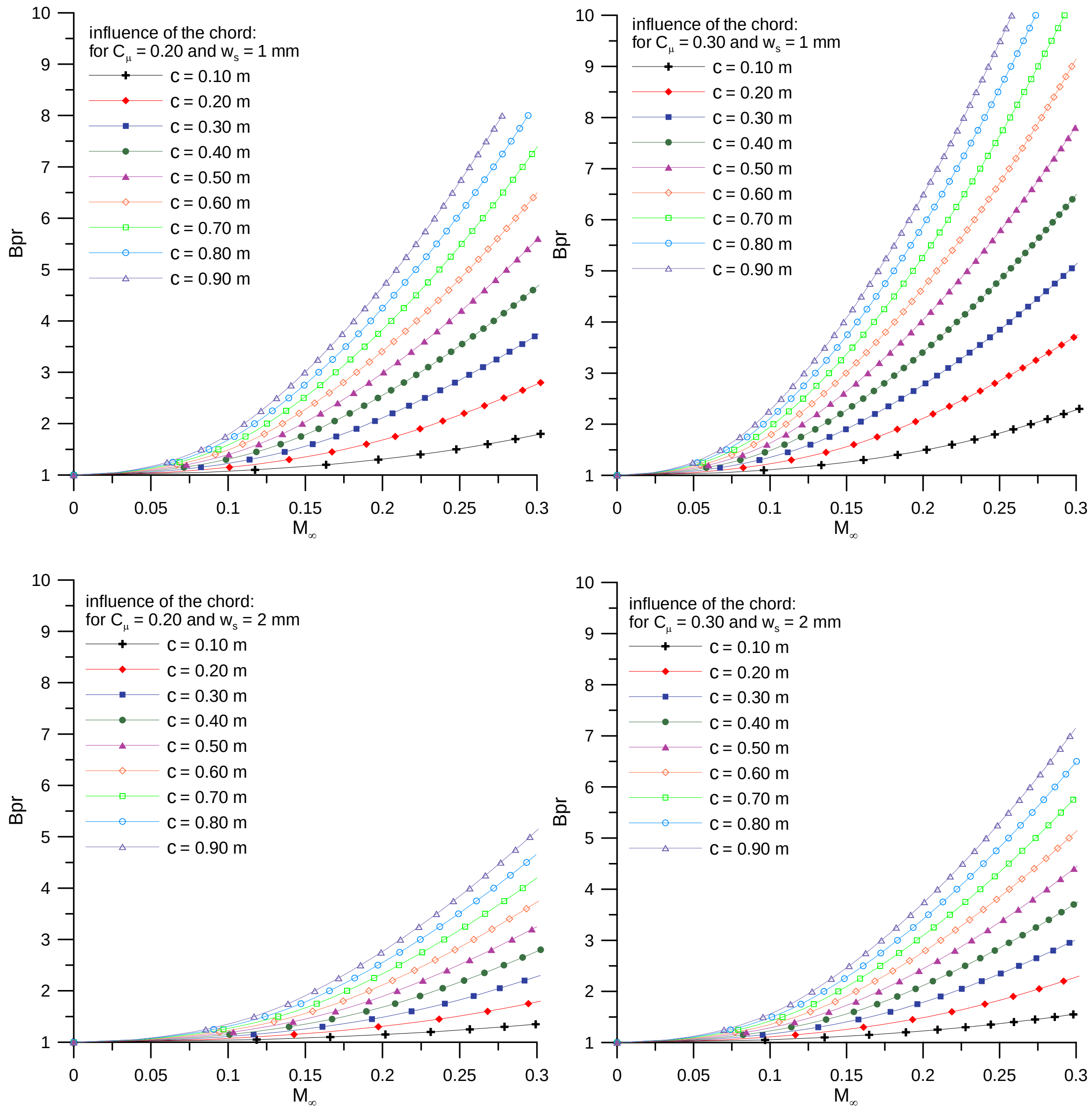


Figure 4. Analysis of the blowing pressure ratio (*Bpr*) required for several model chord. (a) For C_μ = 0.20 and w_s = 1.0 mm; (b) For C_μ = 0.30 and w_s =1.0 mm; (c) For C_μ = 0.20 and w_s = 2.0 mm; (d) For C_μ = 0.30 and w_s =2.0 mm.

4.2. Experimental results

All results were obtained using an "in-house" experimental procedure developed to ensure reliable data. The interested reader is urged to refer to Girardi et al (2005).

In order to achieve a good approximation of true two-dimensional flow over an airfoil model with high lift devices, it has been applied boundary layer control system by compressed air blowing. Figure 5 (a) shows the chord-wise pressure coefficient distribution without and with air blowing system for an angle of attack, α, equal to18°, dynamic pressure of $q_\infty = 226 mmH_2O$ and Reynolds number equal to $Re = 1.14x10^6$ based on the model chord. The free stream velocity is of approximately equal to *60 m/s*. The pressure coefficient is given by:

$$C_p = \left(p - p_{st}\right) / q_\infty = (V / V_\infty)^2 , \qquad (12)$$

where, p is the pressure along the airfoil, p_{st} and q_∞ represent, respectively, the static and dynamic pressure of the flow in the test section and V_∞ is the free stream velocity.

Two sections with pressure measuring holes, at the mid-span section and close to the upper tunnel wall (0.04 m from the wall) were investigated. Without blowing the flow at the tunnel wall-model junction separates early, while at mid-span the flow still attached. With boundary-layer blowing the pressure distributions at both sections are almost equal using a blowing pressure ratio of *Bpr=1.5157*. Figure 5 (b) confirms the correction to the two-dimensionality of the flow measured along the model span using only a blower with slot of 2.0 mm and jet angle of 20° positioned to 16 cm in front of airfoil slat (as shown in Fig. 1). It can also be noticed from Fig. 6 an increase in the C_p values using the blowing technique.

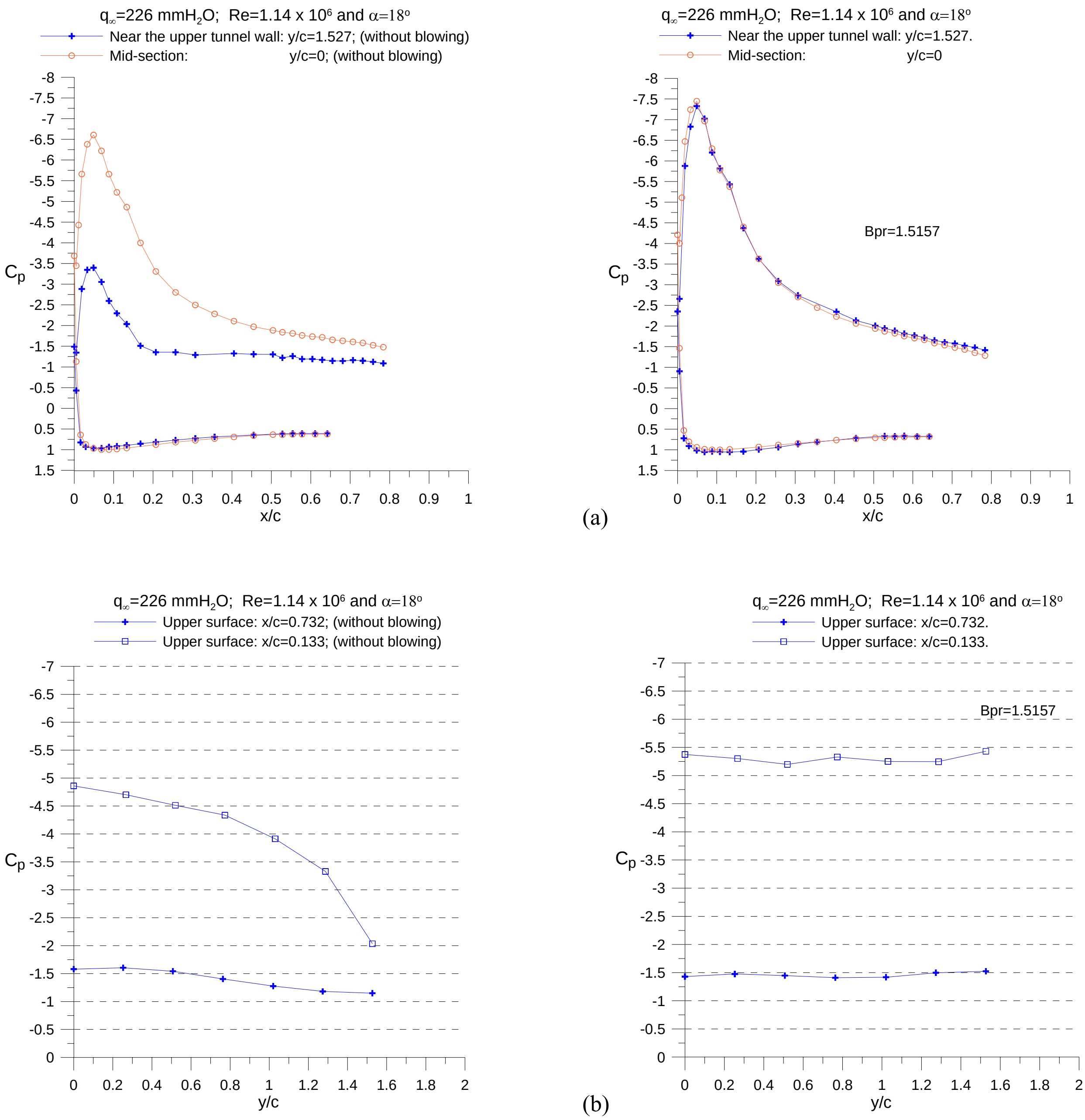


Figure 5 Distribution of C_p on the model for α=18° without and with boundary layer blowing system. (a) measurements – chordwise; (b) measurements – spanwise.

Results appearing in Fig. 6 make it clear that an increase in angle of attack produces, in general, an increase in the momentum coefficient, C_μ. For each AOA investigated several blowing pressure ratio were tried, and thus, it was found the one that produces a better flow two-dimensionality. Unfortunately, the non dimensional parameter, C_μ, doesn't involve the angle of attack. However, there are other variables in two-dimensional test that also is not included, such as: the boundary layer thickness, information on slat and flap, blowing angle of injectors, etc.

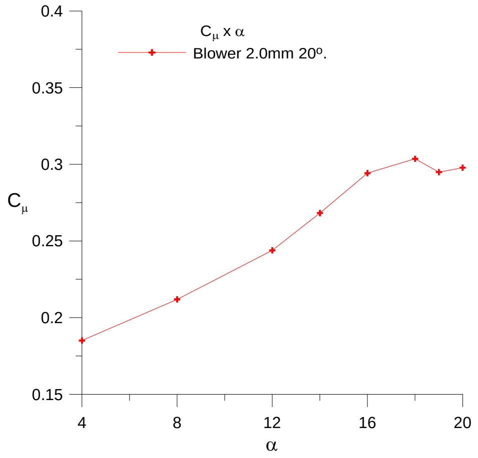


Figure 6. Behavior of the momentum coefficient, C_μ, with the increase of the angle of attack.

Figures 7 and 8 show a comparison between the theoretical and experimental results obtained in the present work. In experimental tests (on the airfoil of chord c=0.30 m) measurements for five different dynamic pressures were made. The free stream velocities investigated were V_∞ = 60, 45, 35, 25 and 15 m/s. Firstly, it was made the measurement for the V_∞ = 60 m/s using the blowing system and was found the better momentum coefficient (C_μ), which it was kept constant to estimate the blowing pressure in the injector for the other velocities of the wind tunnel. Figure 7 (a) displays a good agreement between the theoretical and experimental results for AOA of 19° and C_μ=0.265 using the injector 2.0 mm and 20° positioned at 159 cm in front of the slat. Good agreement also were found for other angles of attack 12° and 20°, blowers and positions them in relation to model slat, as shown in Figs 7(b), 8(a) and 8(b). Therefore, it was observed that experimental tests using the momentum coefficient follow the theoretical behavior, i.e., the non-linear behavior of the Mach number to the blowing pressure ratio. From these figures it is possible to note that at lower Mach numbers the values are more deviating from the theoretical values. The explanation for this is that the range of momentum coefficient at which good results are obtained is much larger at low Mach numbers, but the measuring at these low numbers is very difficult. A low blowing pressure, for example, 1.0 mmHg can give a large variation in the momentum coefficient. At higher Mach numbers the 'bucket' of momentum coefficients which generate 2-D results is much smaller and hence the measurements are more accurate.

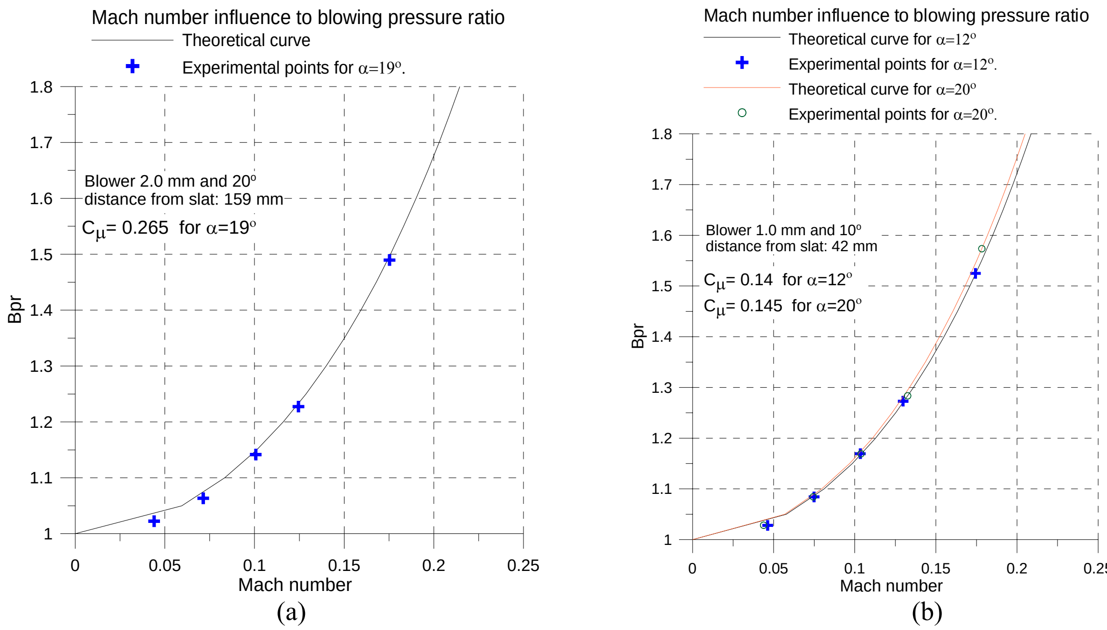
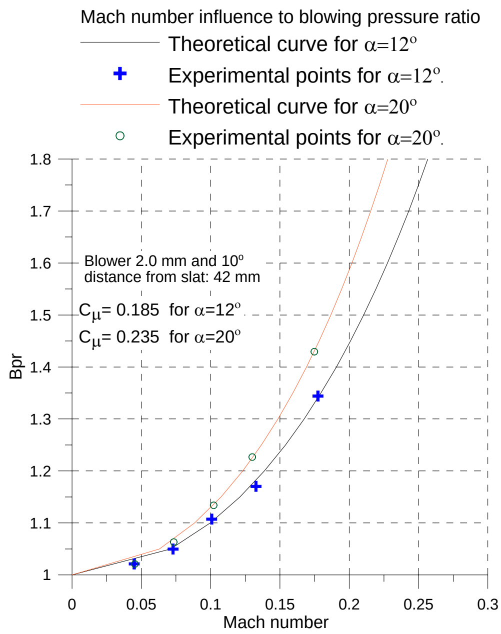
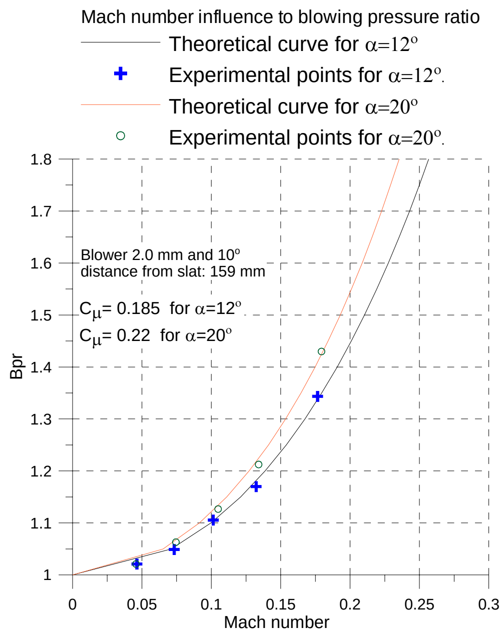


Figure 7. Comparison between the theoretical and experimental results using the momentum coefficient, C_μ: (a) for α=19°, blower of 2.0mm and 20°, distance from slat of 159mm; (b) for α=12° and α=20°, blower of 1.0mm and 10°, distance from slat of 42 mm.



(a)



(b)

Figure 8. Comparison between the theoretical and experimental results using the momentum coefficient, C_μ: (a) for $\alpha=12^\circ$ and $\alpha=20^\circ$, blower of 2.0mm and 10°, distance from slat of 42mm; (b) for $\alpha=12^\circ$ and $\alpha=20^\circ$, blower of 2.0mm and 10°, distance from slat of 159 mm.

5. Conclusion

At ITA it has been studied the use of a boundary layer control system, that blows high-pressure air into the test section, in order to obtain a good approximation of the true two-dimensional flow over an airfoil model with high lift devices (slat and flap). Good two-dimensionality of the flow has been insured by blowers located upstream of the airfoil. The blowing system has proven to supply two-dimensionality of the flow up to high angle of attack, as can be seen in Fig. 5, premature flow separation has been avoided at the critical near-wall regions. Consequently, the C_p distribution it has been corrected to near 2-D values and hence the overall lift coefficient.

The used momentum coefficient in two-dimensional tests showed to be a good non-dimensional parameter to determine the blowing pressure ratios required in different cases (in different angles of attack or free stream Mach numbers). It was noted that for each angle of attack is necessary to use a momentum coefficient (see Fig. 6). Figures 7 and 8 have shown good agreement between the experimental and theoretical values, checking the theoretical equations, and confirming the non linear behavior of the Mach number to the blowing pressure ratio.

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5. Responsibility notice

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