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# On Boundary Layer Control in Two-Dimensional Transonic Wind Tunnels

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## 1. Introduction

For the successful aerodynamic designing of a new modern aircraft it is necessary to know the accurate aerodynamic characteristics of the whole aircraft, as well as of its individual constituent parts. Since there is no adequate mathematical model of turbulent flows, we cannot solve completely the problem of aerodynamic designing by computer simulation and calculation. We still have to solve many problems related to aerodynamic designing by making tests in wind tunnels. However, wind tunnel simulation is connected with many problems which cause many distortions of flow conditions around the tested models, which finally results in inaccuracy of the measured aerodynamic values. There are many reasons for that, but it is quite understandable that even the best wind tunnels cannot provide conditions for the simulation of the flows around the tested model which would be identical to the flows in the free air. Therefore, the resolving of the problem related to the definition and elimination of the wind tunnel wall interference is a lasting task to be solved through experimental and theoretical research, either during the construction of new wind tunnels or during their exploitation. A special group of problems are related to the simulation of flows around the tested airfoil, i.e. to the provision of two-dimensional flow conditions. Paper presents the algorithm for calculating the suction of air from the working section of the wind tunnel necessary to sustain acceptable boundary layer thickness of the wind tunnel side walls, as regards successful two-dimensional wind tunnel simulation [1-5].

## 2. Numerical and experimental approaches

Some practical examples and results are given for the NACA 0012 airfoil, tested at supercritical flow conditions in perforated wall test sections of the Aeronautical Institute VTI's high Reynolds number trisonic wind tunnel, T-38 (Figure 1). The VTI's trisonic wind tunnel is a blowdown type with a two-dimensional test section, with a cross section dimensions 0.38 x 1.5 *m* with changeable perforation of walls from 0.5 to 6 % (Figures 2 and 3).

The results of this analysis are presented in Figure 4 for NACA 0012 airfoil. They are grouped according to 21 sources of quotation. Many of these results have been achieved by the outstanding and widely known international aerodynamic institutions. For example, an analysis has been made of some old wind tunnel low speed tests made by NACA Institute (symbols 2-4), contemporary results of the NASA (1,5 and 6), the results achieved in the very good industrial facilities (10-12), detailed studies of the NPL and RAE (13-15), the results achieved by AGARD working group 04 DATA BASE (17), the results of ONERA (16-19), of the VTI and the Faculty of Mechanical Engineering (21), etc.

According to this illustration there is a great diversity in the achieved results, as a consequence of the strong influence of the Reynolds numbers effects on the test models and wind tunnels, of inadequate conditions of two-dimensional flows in the test section and the wall interference in the test section of wind tunnel. Wishing to complete this study, the analysis has been extended to the transonic speed range and it has incorporated new tests made by the VTI as well as the calculation of wall corrections made at the Faculty of Mechanical Engineering.

Figure 1. T-38 hall. T-38 is a blowdown-type wind tunnel with 1.5 x 1.5 *m* and 0.38 x 1.5 *m* test sections and trisonic Mach number range (0.2 to 4). It is driven by air stored in 2600 $m^3$ tanks charged to 20 *bars* pressure by a 4 *MW* compressor.

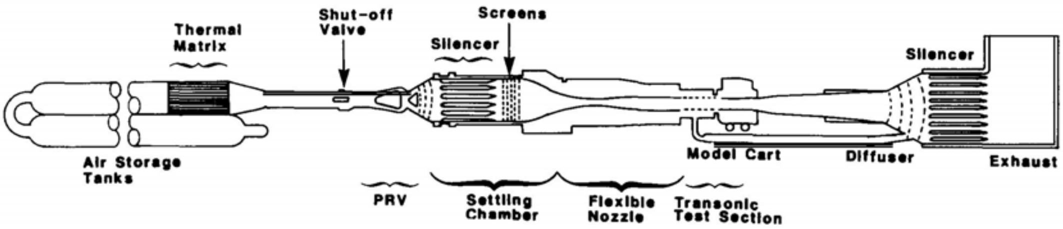


Figure 2. Schematic of the T-38 VTI's wind tunnel (**PRV** - *Pressure Regulating Valve*).

Experimental tests have been made in the wind tunnel T-38 with transonic two-dimensional working section. Aerodynamic coefficients have been calculated by measuring the distribution of the static pressure in 80 equally distributed tested points along the upper and lower side of NACA 0012 model with a chord of 0.254 *m*. For this measuring, the complete most modern equipment for aerodynamic measuring has been used. An additional experimental study has included the Mach test number from 0.25 to 0.8 and the Reynolds model numbers from 2 to 35 *MRe* (Reynolds number in millions - $10^6$, see Figure 4).

In order to create correct two dimensional flow conditions and uniform spanwise loading of the airfoil model, it is necessary to apply side-wall suction, i.e. the control over the boundary layer along the side walls of the wind tunnel. In the case that the control of boundary layer along the side walls is not ensured, this will certainly result in a loss of lift (and difference in drag) caused by the two basic effects of the complex flow. First, the loss of lift is caused by the decreased speed near the wall. This effect can be significantly diminished if the side-wall boundary layer is reduced to the value which is very small in comparison with the spanwise of the model. Second, the influence of the airfoil pressure range will cause nonuniform increase of boundary layer along the side walls, which will result in the creation of some tree-dimension effects in the flow around the airfoil. The separation along the side walls is also quite normal. For example, it usually occurs near a rounded leading edge (in the vicinity stagnation point), approaching the trailing edge and during the subcritical and supercritical flow, as well as in the zone of the maximum local value of pressure.

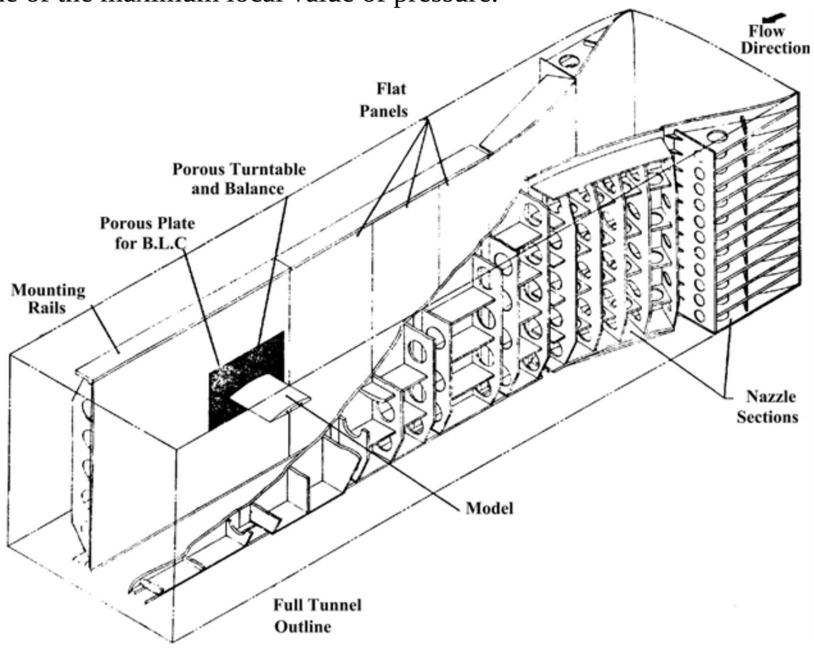


Figure 3. Two-dimensional working section.

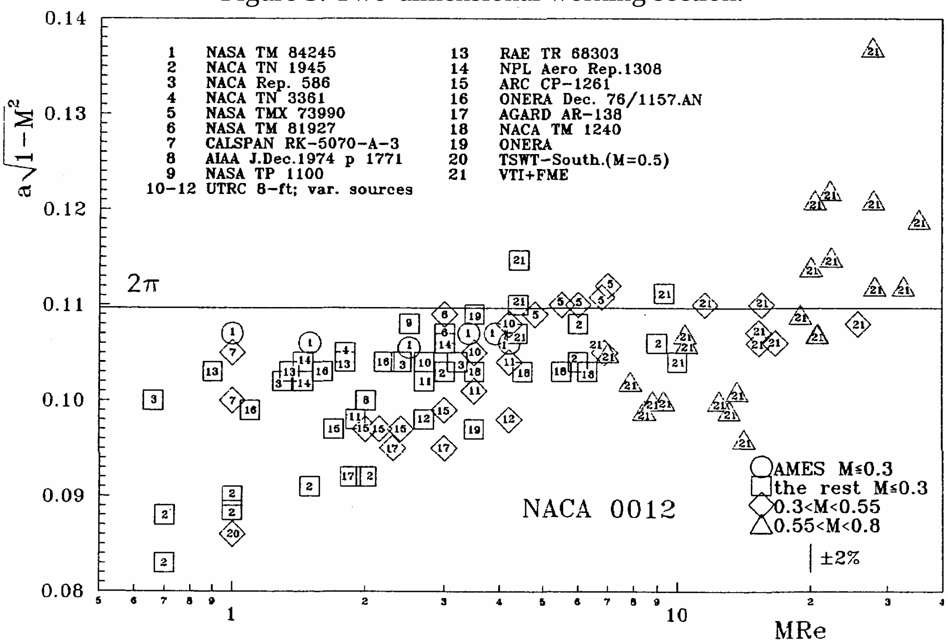


Figure 4. Lift-curve slope in function of the Reynolds number.

It is desirable that the quantity of the removed volume of the air through porous side walls of the wind tunnel is minimal as required for creating satisfactory conditions for two-dimensional flow. If the too much quantity of air is removed from the working section this will cause an extensive axial gradient of pressure in the wind tunnel, which will result in (buoyancy) defect in drag and in the Mach number.

The importance of the correct definition of the quantity of the removed air is evident from the ONERA tests presented in Figure 4 for its results given under point 19. The lower point is the case with inadequate suction and the upper point with right quantity of the removed air. Most frequently the removed quantity of air is expressed through the ratio of normal component of flow velocity through the wall, to the velocity of undisturbed flow (far upstream from the model) $V_n/V_\infty$. In all tests made by the VTI which are presented in Figure 4, the velocity ratio has been within the limits $V_n/V_\infty$=0.0050-0.0054 [6-10].

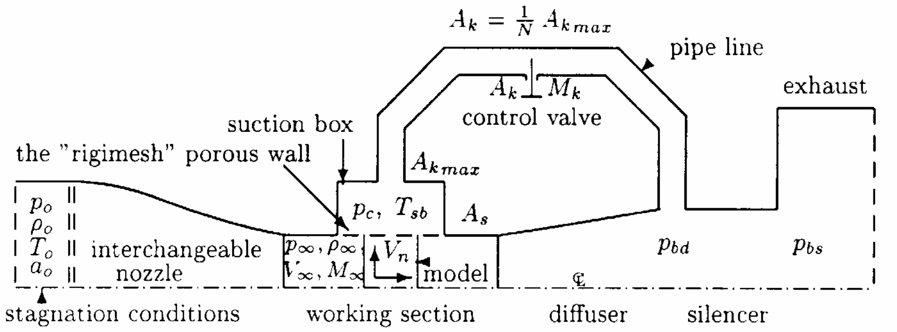


Figure 5. Two-dimensional working section.

Control of the sidewall boundary layer in the vicinity of the model is provided for by suction. The arrangement is shown in Figures 3 and 5. An area 685.88 x 156.65 *mm* for the trisonic wind tunnel T-38 is covered by compression welded multilayer woven wire sheet (stainless steel, so call "Rigimesh").

The following approximate analysis serves to calculate conditions in the system; using the usual isentropic relationships, the transonic wind tunnel working section conditions can be calculated for a stagnation values of pressure, density, and free stream Mach number ($p_o$, $\rho_o$, $M_\infty$). Ignoring any sidewall suction outflow and any in or outflow through the top and bottom walls, the working section mass flow is

$$m_\infty = A_\infty \rho_\infty V_\infty \qquad (1)$$

where $A_\infty$ is working section area.

The sidewall suction mass flow per side is

$$m_s = A_s \rho_\infty V_n \qquad (2)$$

where $V_n$ suction velocity (normal to the wall), and $A_s$ is suction area per sidewall

$$A_s = K_p ab \qquad (3)$$

where $K_p$ is the ratio of the open to total wall area, $a$ and $b$ are the sides of the porous plates for suction.

The discharge orifice area is

$$A_k = \frac{1}{N} A_{k\max} \qquad (4)$$

where $N$ is the fractional opening of discharge orifices ($1/N$, $N=1,2,4,8,16$, etc.), and $A_{kmax}$ the maximum discharge orifice area.

Under steady flow conditions $m_s$ is equal to the mass flow through the discharge orifice

$$m_s = m_k = \frac{1}{N}\rho_k V_k A_{k\max} \tag{5}$$

where $\rho_k$ is density $V_k$ velocity at the discharge orifice area $A_k$ (Figure 5). After involving some isentropic relation we can write the mass flow through discharge orifice

$$m_k = \frac{\frac{1}{N}\kappa p_c M_k A_{k\max}}{a_0\left(1+\frac{M_k^2}{5}\right)^3} = A_s \rho_\infty V_n \tag{6}$$

where $p_c$ is test chamber pressure and $M_k$ the discharge orifice Mach number.

Because

$$M_k = 1 \qquad \text{for} \qquad \frac{p_c}{p_{bd}} \geq 1.892$$

$$M_k = \left\{5\left[\left(\frac{p_c}{p_{bd}}\right)^{2/7} - 1\right]\right\}^{0.5} \qquad \text{for} \qquad \frac{p_c}{p_{bd}} < 1.892 \tag{7}$$

The pressure behind diffuser $p_{bd}$ we my find from the analysis of losses in the wind tunnel [10]

$$p_{bd} = p_{bs}\frac{p_{bde}}{p_0} \tag{8}$$

where $p_{bs}$ is the pressure behind silencer, and $p_{bde}$ pressure behind diffuser at the end of the wind tunnel ran. That pressure depend on the losses in the wind tunnel and the Mach number in the working section

$$\frac{p_{bd_e}}{p_0} = 1 - \frac{\kappa K_0 M_\infty^2}{2\left(1+\frac{\kappa-1}{2}M_\infty^2\right)^{3.5}} \tag{9}$$

where $K_0$ is the losses coefficient in the wind tunnel

$$K_0 = \sum_1^n \xi_n \tag{10}$$

where $\xi_n$ are the losses of the all parts of the wind tunnel (working section, flow screens, nozzle, dryer, diffuser, valve, silencer etc.).

The remaining equation to close the above system represents the pressure drop across the "Rigimesh" porous plates. This can be expressed as

$$\Delta p_c = p_\infty - p_c = \frac{1}{2}K_1 \rho_\infty V_n^2 \tag{11}$$

where $K_1$ is the losses coefficient by the cross-flow through porous walls. The values of this coefficient we can find by experiment [10].

By combining previous equations we obtain fractional opening of discharge orifices

$$N = \frac{\kappa A_{k\max}}{abK_p}\left(\frac{K_1}{2}\right)^{0.5}\frac{p_c}{\left(p_\infty - p_c\right)^{0.5}}\frac{M_k}{\rho_\infty^{0.5} a_0\left(1+\dfrac{M_k^2}{5}\right)^3} \tag{12}$$

This equation gives a functional links between the fractional opening of discharge orifices, the difference between the static pressures (in the working section and the suction box - test chamber) and the Mach number at the discharge orifice area (the critical section of the pipe line). This equation is possible to solve altogether with the system of equations (7), (8) and (9) by the iterative procedure and by assuming the test chamber pressure is approximately equal

$$p_c = \frac{p_\infty + p_{bd}}{n} \tag{13}$$

with the step the of iteration $n=2,3,4,...$ . The iterative procedure is necessary to perform for the all values of the pressure ratio $p_c/p_{bd}$.. This iterative procedure is very convenient for the calculation of the global cross-flow parameters $m_s/m_\infty$ and $V_n/V_\infty$ in a function of the valve fractional opening $N$ and the pressure ratio $p_c/p_{bd}$ and for the known stagnation conditions and the Mach number in the working section.

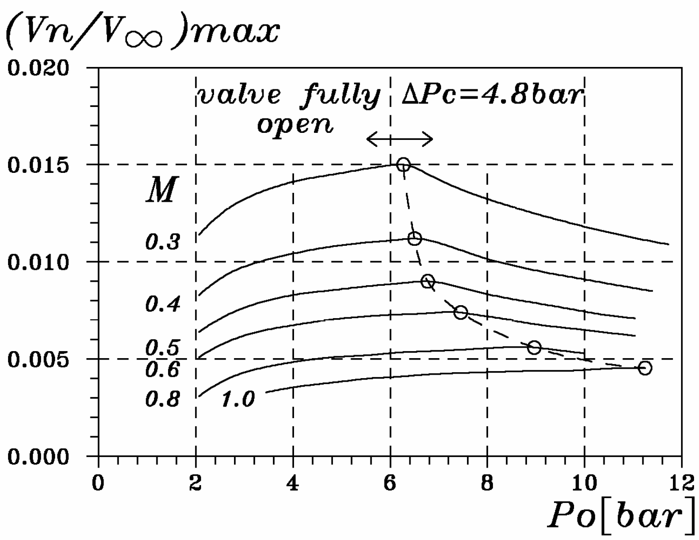


Figure 6. Maximum suction velocity versus test section total head (stagnation pressure in working section) and Mach number for the Aeronautical Institute VTI's T-38 high Reynolds number trisonic wind tunnel.

In the case, that the Mach number $M_\infty$ and the stagnation pressure $P_0$ are known and it is required to remove $t$ times the sidewall boundary layer deficit mass flow, i.e.

$$m_s = t m_{\delta*} = t\rho_\infty V_\infty \delta^* b \tag{14}$$

where $b$ is the height of the suction area, and $\delta^*$ the boundary layer displacement thickness.

Analysis of Preston tube measurements taken just upstream of the porous sidewall plates has shown that for most test conditions the displacement thickness of the approaching boundary layer is $\delta^*= 4 \pm 0.75$ *mm* [10], and hence

$$t = \frac{m_s}{m_{\delta *}} = \frac{A_s V_n}{\rho_\infty \delta * b V_\infty} \tag{15}$$

the proportion of boundary layer deficit mass flow removal by suction, $0.6 < t < 1$ is typically.

## 3. Results and Discussion

The maximum suction quantities that are available at any given test condition is limited by either one of two factors; the strength limitations of the side structure supporting the porous panels and the pressure difference available with the discharge orifices fully open. It is considered unsafe to exceed a pressure drop across the porous panels of $\Delta p_c$=4.8 *bar*. For the VTI's trisonic wind tunnel T-38, the maximum suction quantities for the load limit and with the discharge orifices fully open ($N$=100%) are given in Figure 6. The dashed line separate the region of valve fully open and the region of the maximal pressure drop across the porous panels of $\Delta p_c$=4.8 *bar* for a maximum available suction. The maximum discharge orifice openings and suction quantities available at this maximum wall loading are given in Figure 7.

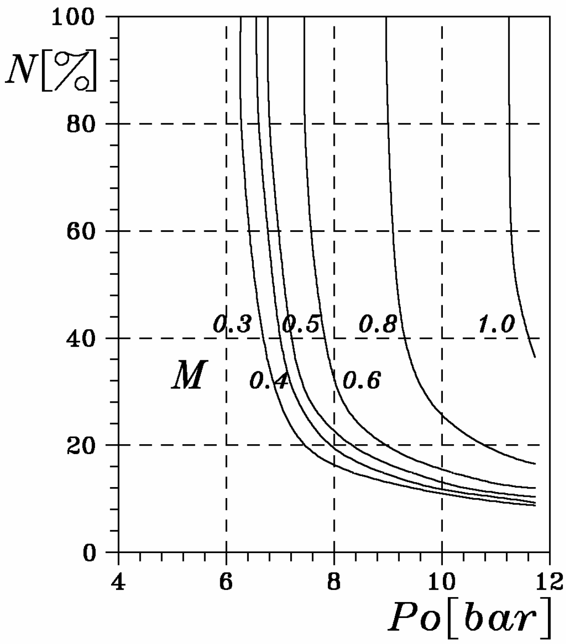


Figure 7. Suction valve maximum opening for safe operation for the Aeronautical Institute VTI's T-38 high Reynolds number trisonic wind tunnel.

## 4. Conclusion

The establishment of exact two-dimensional conditions of flow in wind tunnels is a very difficult problem. This is evident for wind tunnels of all types and scales. In order to create correct two dimensional flow conditions and uniform spanwise loading of the tested airfoil model, it is necessary to apply side-wall suction, i.e. the control over the boundary layer along the side walls of the wind tunnel.

In this paper the model problem that is treated involves a flat plate airfoil in a transonic wind tunnel with a suction sidewall porous panel shaped to permit an analytic solution. This solution shows that the lift coefficient for airfoil depends explicitly on the porosity parameter (or the losses coefficient) of the suction porous panel, the fractional opening of discharge orifices and implicitly on the suction pressure differential (between the working section pressure and the suction box pressure). For a given sidewall displacement thickness, the lift coefficient for airfoil increases as the suction-porous panel porosity decreases.

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