3D Effects in Nominally 2D Transonic Cascades

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Once the blade aspect ratio of a 2D transonic cascade drops down under a certain value (typically 1.0), 3D effects begin to affect significantly the flow field structure and development. Usually only the displacement effect of the 3D flows is considered and expressed through the so called AVDR factor, regardless of the actual physical phenomena responsible for it.

The AVDR (axial velocity density ratio) is the ratio of the outlet and inlet mass fluxes in the axial direction. In a similar way we can also define the AVDD (axial velocity density distribution along the blade passage) Ω, or, the so called contraction coefficient $x = (\Omega-1)/(\Omega_2-1)$. x is equal to 0 at the inlet, where $\Omega = 1$, and equals 1 at the exit, where $\Omega = \Omega_2$. Outside the transonic region Ω as well as x are monotonous functions of the streamwise coordinate; the pressure distribution, as well as other aerodynamic characteristics of the cascade can be easily corrected for this $\Omega \neq 0$, i.e., for the displacement effect of the viscous and 3D phenomena.

The behaviour of x in the transonic region is different (see e.g., Fig. 1).

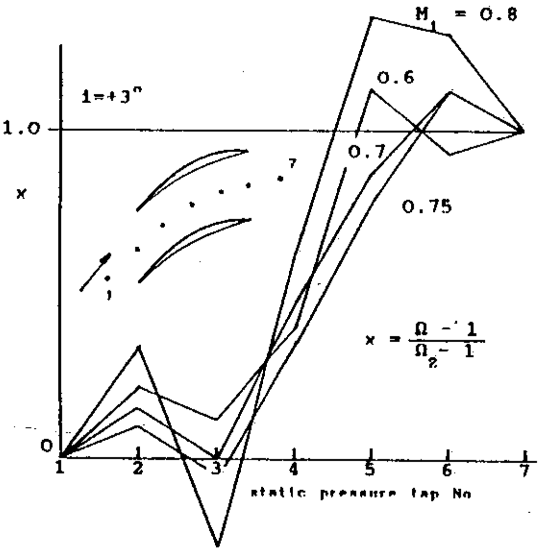

Fig. 1
The AVDR factor in a transonic compressor cascade

The AVDR is usually measured in the exit plane only and it is assumed that this value has been reached from the inlet value following a monotonous curve. This assumption has not been proved by detailed measurements inside the blade passage namely at transonic velocities when there is a sonic cross section inside the passage. The cascade then behaves as a convergent/divergent nozzle with all the consequences for the different development of subsonic or supersonic flow in the cascade.

This measurement also confirms what we have already known from all other measurements in channels and nozzles namely that the boundary layer displacement thickness decreases when approaching the sonic throat, [1]. So far, we do not have sufficient experimental knowledge of the throat effect on the secondary flow development and structure.

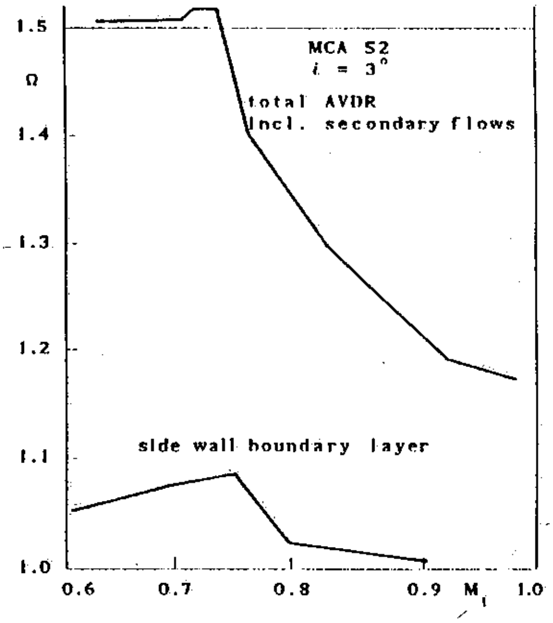

Fig. 2
The AVDR factor for a MCA transonic compressor cascade at incidence + 3°

Fig. 2 presents results of measurements on a MCA compressor cascade at incidence +3° in which the side wall boundary layer was measured to obtain the displacement thickness and the complex secondary flow field (with vortices and separated flows) was measured separately to obtain the remaining displacement effect. The former is hardly only 10% of the total one.

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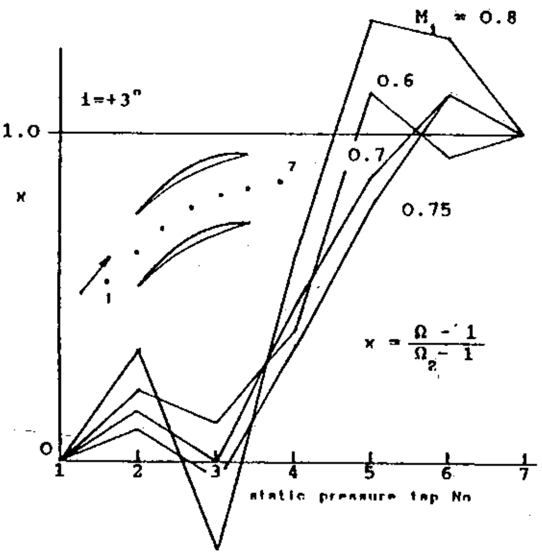

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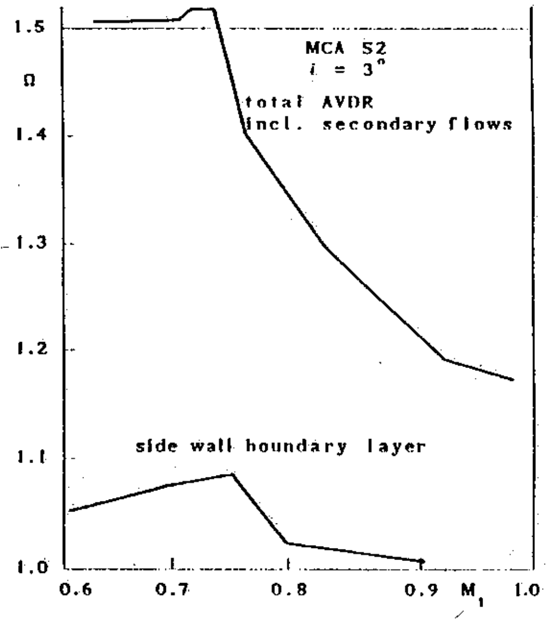

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We can easily understand the next Fig.3, giving a M_{21s} relation with Ω as a parameter for a typical turbine cascade. Ω does obviously reflect the cascade aerodynamics and it varies significantly according to the operational conditions.

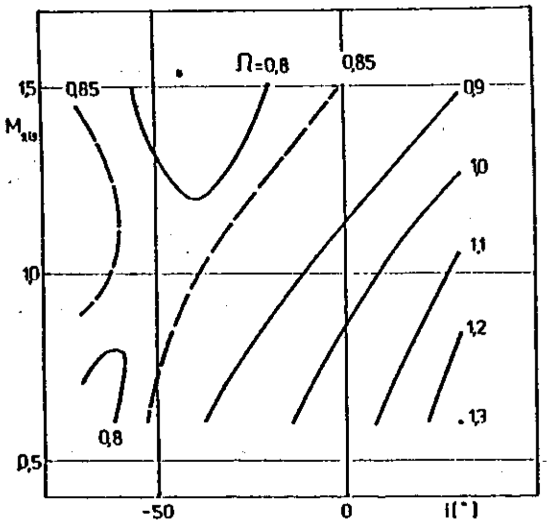


Fig.3
The AVDR in a turbine cascade for various M_{2is} and incidences

If more than the integral aerodynamic characteristics is demanded, the only AVDR is of no help, and it is necessary to take a more fundamental view of the characteristic phenomena in the cascade.

Out of these the pressure distribution is one of the most important ones.

The following results were obtained during measurements on a very simple cascade composed from symmetric double-circular arc airfoils, 8% relative thickness, stagger angle 45°, pitch/chord ratio 1,0. The cascade was measured at aspect ratios ranging from 0.4 to 1.6, to study the effect of channel width on the development and structure of the transonic flow field.

To obtain the same "2D flow pattern" even in the narrower channels, it was necessary to adjust the inlet Mach number. This, however, lead to a corresponding change in the critical Mach number, so that the only possible way how to assess the effect of the channel width was to assume a certain configuration of the flow field (for instance at transonic velocities characterized by the position of the terminal shock wave) and register the changes in other flow parameters.

Fig.4 shows the pressure distribution (as measured pneumatically using pressure taps) in the channel axis for three aspect ratios (three different channel widths).

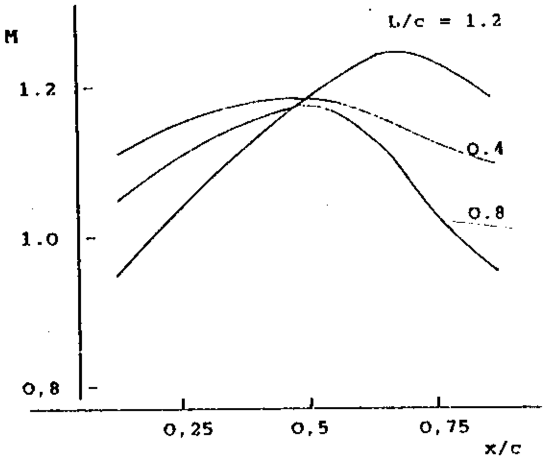


Fig.4
Pressure distribution in the midsection of the cascade of symmetric double-circular arc airfoils $\gamma = 45^0$, $s/c = 1.0$, $t/c = 0.08$ for 3 aspect ratio

The next figure (Fig.5) shows the pressure distribution at various distances from the side wall. As apparent from both these figures the changes in the pressure distribution are not only quantitative but even qualitative. As the nonuniformity affects even the flow along the sidewalls, the corresponding changes in the corners are very pronounced.

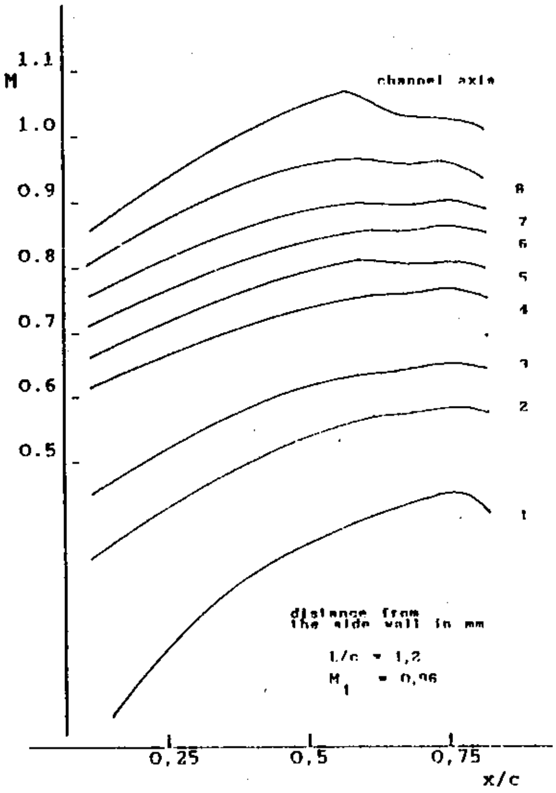


Fig.5
Pressure distribution for the same cascade as in Fig.4 at various distances from the side wall

Most serious effects in 2D transonic cascades have been encountered in connection with research of flow separation due to the shock wave boundary layer interaction. To study these flows we have extensively used surface streamline visualization.

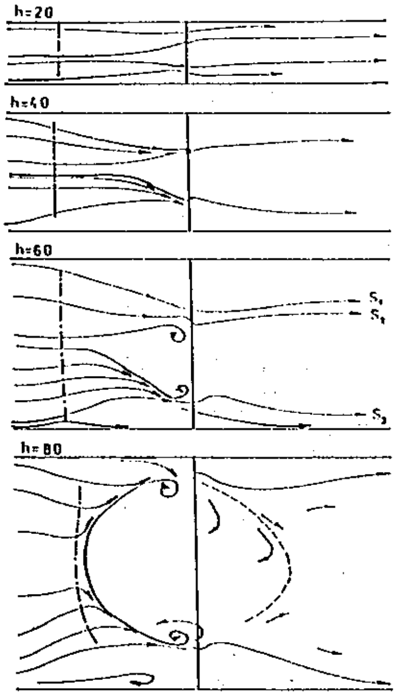
Shock wave boundary layer interaction with flow separation in low aspect ratio cascades or in relatively narrow channels is a problem of itself and cannot be discussed at this Symposium.

Nevertheless, it may be useful to mention here how sensitive the development of transonic flow and the flow structure are to minor changes in the initial flow conditions. We have video-recorded both the visualized surface streamlines and, using the laser knife, we have visualized even the complicated 3D structures. (The viewgraphs presented at the Symposium have been redrawn by the computer from the video film. They are not presented here).

To make detailed measurements easier, the following measurements were made on a wind-tunnel wall shaped in such a way that a 4° wedge of the length L=156.88 mmwas ended by a circular arc segment of the length 0,825 L with a radius of 2.69 L. All results were qualitatively in very good agreement with those obtained on similarly shaped cascades. In Fig 6 are the surface streamlines for four different channel widths. All are symmetric, however, at a certain Mach number there has always been a loss of stability of these patterns leading to an asymmetric case, as apparent, for instance, in Fig.8. In this case the wall curvature is low, corresponding to a slightly curved thin compressor cascade. The supersonic region is terminated here by a shock wave leading to boundary layer separation and generating vortices near and at the side wall. These vortices disappear in the narrower channels where the flow has a shear flow character. In the meridional plane the flow is symmetric with a nice reversed flow from the "trailing edge".

Fig. 7 corresponds to the same velocity as Fig. 6, however, the surface curvature is much higher and even the boundary layer initial thickness is higher. This figure has been reprinted from the paper by Doerffer and Dallmann [4], who made a similar kind of measurements as above, only in a different wind tunnel arrangement. There is no clear separation line and the vortices near to the wall move in the opposite direction.

A slight increase of M_1 leads first to an asymmetry in the flow pattern and ultimately to a collapse of the flow structure into a complete asymmetry with one vortex in the central part of the channel (Fig. 8). Even if this happens, it is possible to make routine measurements (in the meridional plane) of the losses and the outlet angle.The whole flow is quite steady, though it may not reflect any situation we may encounter in an actual cascade.



Shock wave position (as observed visually) ------

Fig.6
Surface streamline pattern for the same transonic flow pattern at various channel widths

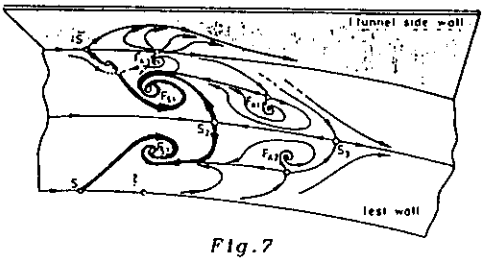


Fig.7
Surface streamline pattern for transonic flow over a wind tunnel bump of much higher surface curvature than in Fig.6 Fig.taken from a paper by Doerffer and Dallmann [4])

Fig.8
Asymmetric surface streamlines for an unstable regime

Conclusion

If more than integral aerodynamic characteristics of a transonic cascade have to be investigated, special care has to be given to 3D effects, namely, if the blade aspect ratio is less than 1.0.

At smaller aspect ratios even these characteristics can be influenced by the channel width.

The complex 3D structures are mainly due to shock wave boundary layer and secondary flow interaction. They are heavily facility-dependent and become important especially when results from various facilities have to be compared, or when detailed aerodynamic research is carried out. They may be well reproduced (unless corresponding to an unstable regime) and the error in the measured data (if the real transonic flow structure is not taken into account) cannot be eliminated by using a more sophisticated measuring technique.

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