INFLUENCE OF AIR COOLING AND AIR-JET VORTEX GENERATOR ON FLOW STRUCTURE IN TURBINE PASSAGE

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Abstract: The paper concerns the experimental investigations and numerical simulations of a high loaded model of a turbine blade. An increase in the blade load leads to enlargement of a local supersonic zone terminated by a shock wave on the suction side. The Mach number upstream of the shock reaches up to 1.6. The interaction of the shock wave with a boundary layer at such a high Mach number leads to a strong separation. Streamwise vortices generated by air-jets were used for the interaction control. The work presents the experimental and numerical results of the application of an air-jets vortex generator on the suction side of cooled turbine blades. Very interesting results were obtained in the context of the air cooling and air-jet vortex generator influence on the flow structure in the turbine passage.

Keywords: shock wave, separation control, air-jet vortex generator, blade cooling

1. Introduction

Nowadays a lot of efforts have been made to reduce the mass and size of newly designed aircraft engines. It is achieved by the reduction of the number of blades in specific turbine cascades. This leads to an increase in the blade load, and as a consequence, to the appearance of a local supersonic region terminated by a shock wave in the blade passages. The Mach number on the suction side of a blade upstream of the shock reaches up to 1.6. The interaction of the shock wave with a boundary layer at such a high Mach number leads to a strong separation. The process of separation usually becomes unsteady and is connected with buffeting at airfoils and shock oscillations in the internal flows. Shock oscillation causes the pulsation of pressure, and thus, the fluctuation of the blade load.

Application of streamwise vortices for shock induced separation control appears to be very effective. Vane type vortex generators (VG) with different shapes are very well known and often used especially on airfoils, mounted in adequate regions of the profile flow. The advantage of this VG type is the reliability and easiness of installation and maintenance. They have not been used in the turbomachinery because of the danger of the VG vane element detachment from the blade. For internal flows more suited are streamwise vortices generated by air-jets (AJVG). In the previous century, it was shown that the effectiveness of AJVGs was comparable with classical vane type VGs [1]. The earlier research of the author [2–4] has proven the effectiveness of AJVGs for the separation control. In our approach the method is treated as passive, meaning that the stagnation parameters of the jets are equal to the stagnation parameters of the main stream. Therefore, air can be supplied from the leading edge and there is no need to install any additional devices. In the case of internal flows, as in cooled gas turbines, injection of coolant through holes is used. In such a case introduction of flow control in the form of AJVGs is fully acceptable.

During these investigations we also had a possibility to check the influence of cooled air itself on the flow structure in the turbine passage. This issue usually is not raised in research as the present turbine technology does not allow using uncooled blades at first turbine stages due to that the gas temperature at the first stages of the turbine is extremely high and can cause metal melting. Maybe in the future the development of materials used in blade production will allow such solutions.

2. Experimental Setup

The test section layout which was used in the experiment is shown in Figure 1. The test section of the rectilinear wind tunnel was designed in such a way as to obtain a flow structure corresponding to a turbine profile on the suction side, marked in Figure 1 by the dotted line. As shown in [5] the key factor to obtain an appropriate flow pattern was the introduction of the "auxiliary blade" wake indicated in Figure 1. The test blade is of the same shape as the reference profile from the location of the vortex generator (VG) to the trailing edge.

The shock system and the location of cooling holes and flow control devices (AJVG) are shown in Figure 2. The numbers on this figure mean the location in the X/Cax coordinate (Cax-blade cord projection on X axis). The shock system location is depicted by the location of the main shock wave above the λ-foot. The cooling row of holes of diameter $d = 1.8$ mm was located at $X/Cax = 0.01$. The pitch of cooling holes was equal to 5.4 mm, which was threefold of the hole diameter. The cooling air was introduced in a streamwise direction with a small angle to the blade surface. The cooling holes geometry was prescribed by the blade manufacturer. The objective was to minimise the disturbance by the coolant injection. At the coolant injection location the flow Mach number was $\mathrm{Ma} = 0.7$. The blowing ratio of cooling to the main stream was equal to 0.8‰ (per mille).

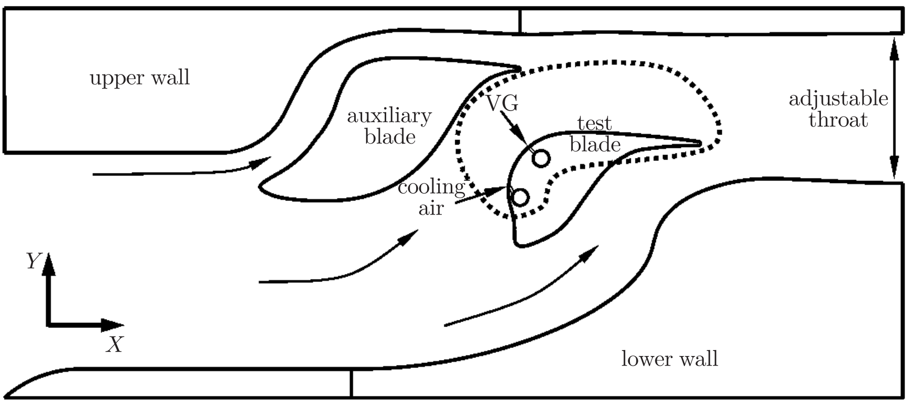

Figure 1. Test section layout

The AJVGs in the test blade were introduced as a row of holes located along the span of the blade at $X/Cax = 0.12$. The jets were blown trough these holes in the transverse direction to the main flow at the location where $\mathrm{Ma} = 1.3$, hence the air was chocked in the holes due to the adequate pressure difference between the jet and the flow. Such pressure difference is the reason why there is critical flow (sonic line) in the jets holes of the vortex generator. The jet penetration through a strong velocity gradient layer close to a wall caused the flow to swirl around the jet, creating a streamwise vortex, carried away further downstream.

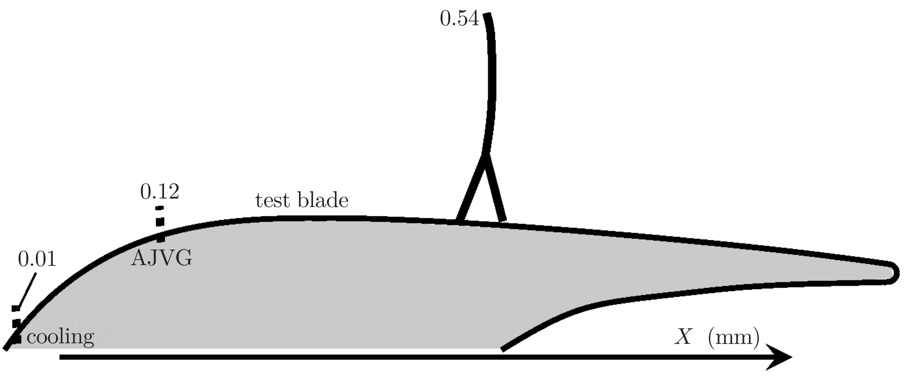

Figure 2. Measurement setup

The jets have to be given in an appropriate angle of injection in relation to the main stream. The jet configuration angles were optimised with respect to the obtained streamwise vortex intensity [6]. The optimization process was carried out for VG of 0.5 mm diameter. The goal function during the optimization was the maximum vorticity in a chosen distance from the VG injection hole. The definition of the jet angles is shown in Figure 3. The optimised VG configuration, based on the numerical optimisation for a supersonic flow, yields the injection angle $\varphi = 30°$ and the skew angle $\theta = 65°$ and this configuration was used in the investigations.

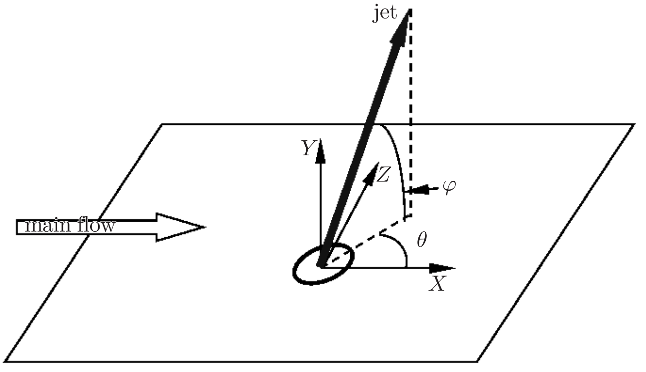

Figure 3. Configuration of angles in VG

The diameter of the VG holes was $d = 0.5$ mm. The pitch to AJVG diameter ratio was $s = 10$. The blowing ratio of 0.5 mm AJVGs to the main stream was equal to 0.15‰ (per mille). The jets direction of all VGs was the same what means that the obtained vortices were corotating. All jets in the test section were injected in the direction of the further side wall.

The results are presented in the form of plots obtained from the measured data and photographs from the schlieren and oil visualization. For every flow case the following measurements were carried out:

- schlieren visualization of the flow structure in the passage
- oil flow visualization on the test wall to display the separation size and structure
- static pressure distribution along the centre line of the lower wall.

3. Experimental Results

3.1. Schlieren visualization

The examples of schlieren visualization are presented in Figures 4 and 5. The case for the flow without a cooling and vortex generator (VG) is presented in Figure 4. In this picture one can see that the λ-foot of the shock is rather small. The size of the λ-foot is small due to the small boundary layer thickness, which is expected to be laminar. In the left upper corner one can also notice the wake of an auxiliary blade.

When the cooling air is introduced into the boundary layer the λ-foot increases significantly, Figure 5a. The cooling air causes an increase in the boundary layer (BL) thickness, and in consequence, the size of the λ-foot increases considerably. The height of the λ-foot is strongly correlated to the boundary layer thickness. Besides, the coolant introduction may produce a low momentum boundary layer close to the wall, which additionally can support enlargement of the λ-foot size.

The effect of AJVG application is shown in Figure 5b. The height of the λ-foot in this case is about 10% lower in relation to the flow without a VG (Figure 5a). This is due to changes in the boundary layer upstream of the shock.

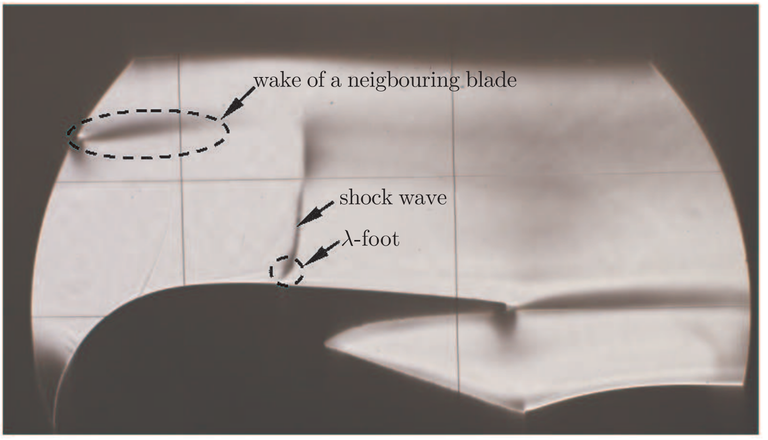

Figure 4. Schlieren picture for flow with cooling off and AJVG off

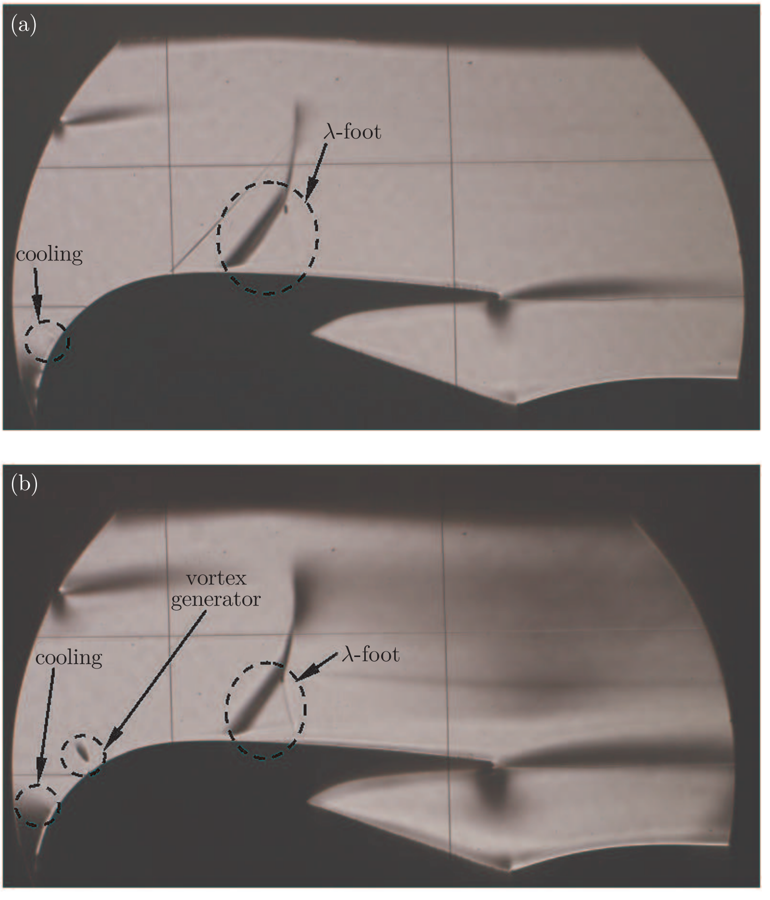

Figure 5. Schlieren picture for flow, (a) reference case, (b) cooling on and AJVG on

As a result of the action of AJVGs the boundary layer increases the momentum and the separation size is reduced. These effects help to reduce the height of the λ-foot.

3.2. Oil visualization

Additional information about the flow structure on the wall surface is provided by the oil visualization presented in Figueres 6 and 7. This is a view onto the blade suction side through a side wall window. The flow is from left to right. The beginning of the shock wave boundary layer interaction is marked by a dashed line drawn transverse to the flow direction. The thicker oil layer was created due to reduced skin friction induced by the shock. The separation zone is displayed by the oil streaks downstream of the interaction start line, indicating a low momentum and a reverse flow area before reaching the dotted line indicating reattachment. The case of the flow without cooling and a VG is shown in Figure 6. The reference case is shown in Figure 7a (*e.g.* the flow with active cooling and without VG) where one can see a large separation zone with a distinct 3-D reattachment line. Cooling (Figure 7a) causes significant enlargement (almost double) of the separation region. The influence of the AJVG on the separation region is shown in Figure 7b.

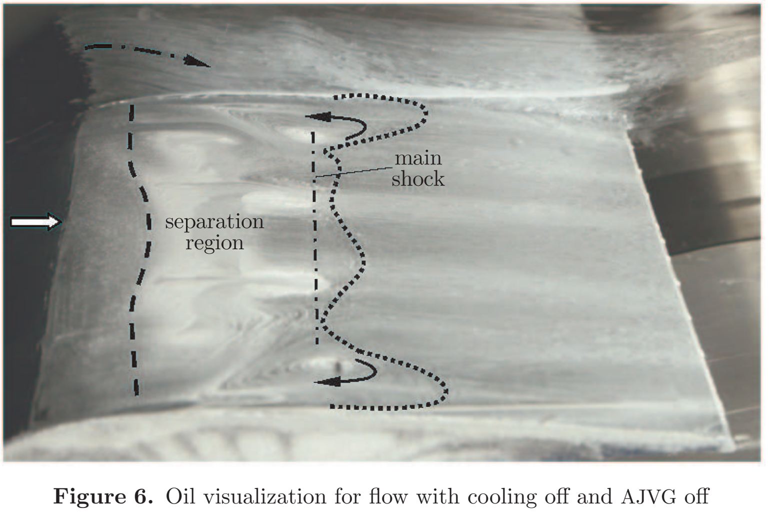

Figure 6. Oil visualization for flow with cooling off and AJVG off

In Figure 7b the traces of streamwise vortices are visible. Streamwise accumulation of oil indicates separatrices located between neighbouring vortices. The separatrices pass under the shock wave and the shock does not disintegrate the vortices. Streamwise vortices penetrate the separation area downstream of the shock, even downstream of the reattachment line. One can see a reduction of the separation, to a size similar to the case without cooling (Figure 6).

A characteristic feature of AJVGs (Figure 7b) is that the separation line becomes a cell-like, spanwise, 3-D structure with a pitch corresponding to a VG

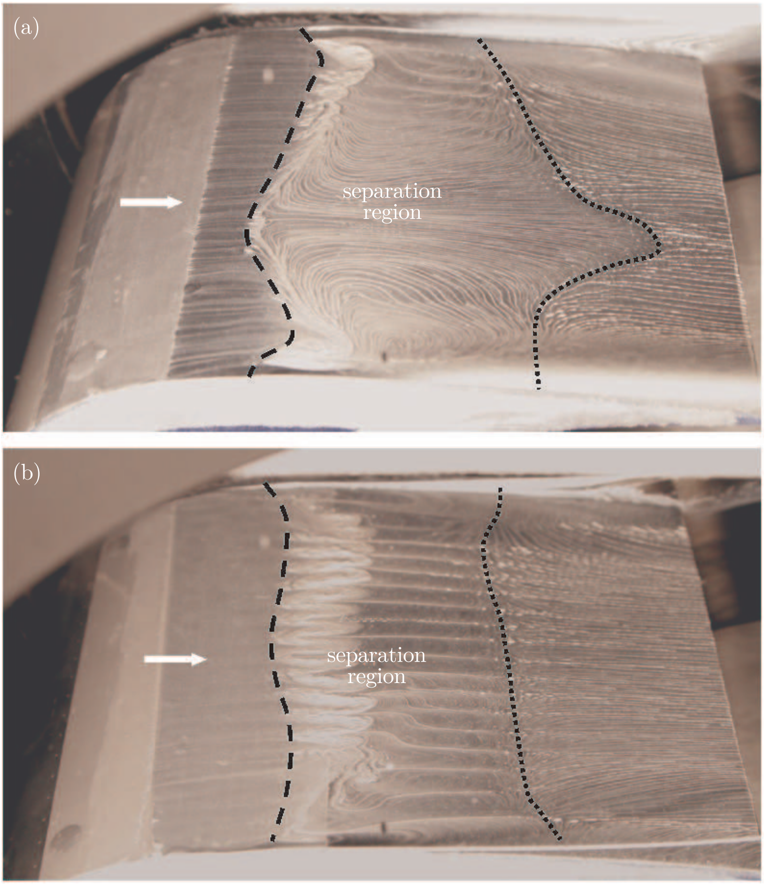

Figure 7. Oil visualization, (a) reference case, (b) flow with cooling on and AJVG on

sequence. The separation zone for the flow with an AJVG becomes 2-D in relation to the fully 3-D structure which appears in the flow without an AJVG (Figure 7a).

3.3. Static pressure along the wall

The distribution of normalised static pressure on the suction side of the measurement blade is shown in Figure 8. For the flow cases with a large λ-foot (Figure 5a, b), the pressure jump on the front oblique shock of the λ-foot starts approximately at $X/Cax = 0.37$. A slight difference of the shock position is visible between these two flow cases. This is caused by a different size of the λ-foot. For the flow case of cooling and the VG off the location of the pressure jump on the shock is even more downstream because of the much smaller λ-foot.

The pressure jump on the normal shock wave leads to subsonic velocities, hence to high static pressure in relation to shock upstream conditions. In the case of the wall presence downstream the shock separation may occur. The separation zone is pushing away the area of shock downstream conditions and some intermediate conditions are established at the wall, showing a weaker

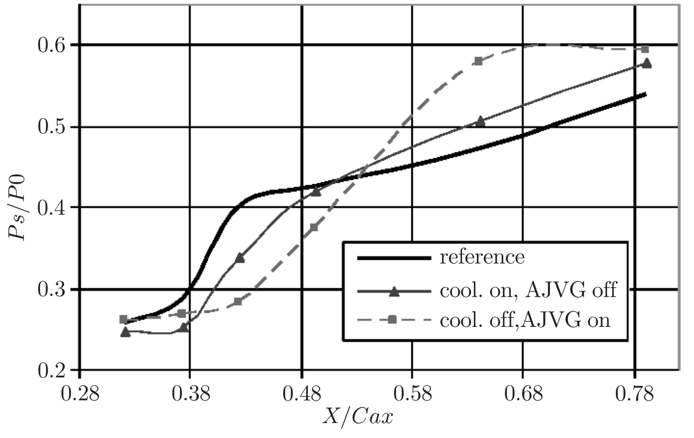

Figure 8. Static pressure along the wall

pressure drop due to the shock wave, hence, lower pressure and higher velocity than in a fully attached flow. Therefore, higher pressure and lower velocity downstream of a shock wave means that the separation or "tendency towards separation" is weaker.

The pressure downstream of the shock for the flow with an AJVG is higher in relation to the flow without jets. The higher pressure indicates a weaker tendency towards separation and means reduction of the separation size. A larger separation bubble is the reason why the pressure recovery is weaker and as a consequence the pressure downstream of the shock decreases. This phenomenon is visible in the curve for the reference case (the continued line without markers). High pressure in the flow with cooling and the AJVG off is a result of both the reattachment location being is more upstream in relation to other flow cases and the separation not being so much severe with regard to the others.

4. Numerical model description

Numerical simulations were performed by means of the finite volume code SPARC (Structured Parallel Research Code) developed at the University of Karlsruhe [7]. Central difference approximation is used for convection terms in SPARC, where the scheme is stabilized by an artificial dissipation model introduced by [8] and [9]. The geometry of the test section, including cooling holes and a vortex generator jet, requires fine meshes especially in the vicinity of the holes. It was decided to make a simulation for one pitch of the cooling holes and the AJVG (the number of cooling holes and the AJVG is the same). It means that a slice of the whole geometry was taken into account assuming periodic conditions in the spanwise direction. Such an approach can be justified in the case of the turbine test section model due to very weak secondary flows in comparison with the reference linear cascade [5] (lower main flow deflection than in the cascade). The block structured mesh (~ 3.9 mln cells) was generated in IGG/Numeca. It was refined close to the wall in order to keep $y^+ \sim 1$ (Figure 9 and 10). The

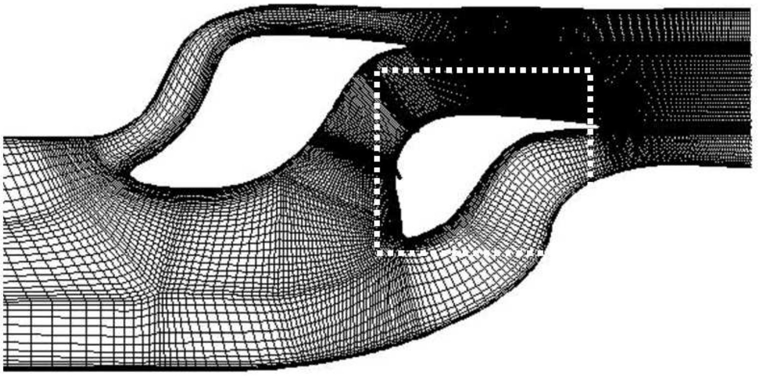

Figure 9. Side view on the mesh

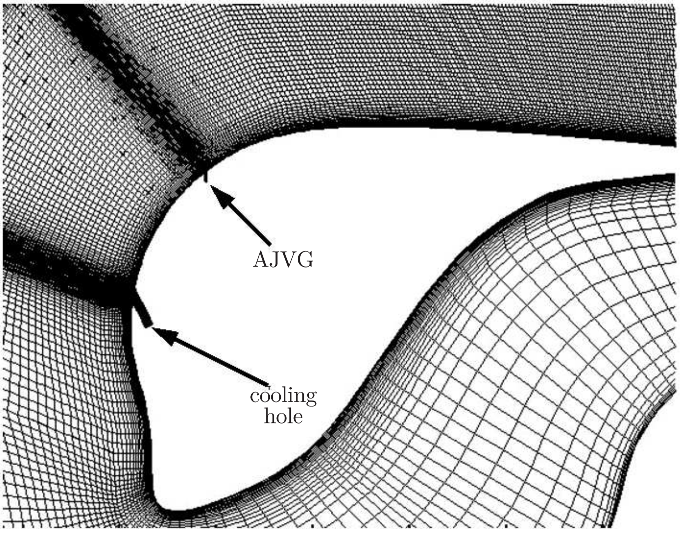

Figure 10. Cooling hole and AJVG location

presented results were obtained with the steady approach and Spalart-Allmaras turbulence model.

The inlet/outlet boundary conditions are shown in Table 1. The boundary conditions at the outlet were adjusted in order to keep the shock wave location as on the reference turbine profile [5] for the same Mach number.

Table 1. Boundary conditions

Section	Parameter	Value
Inlet (main, cooling hole, AJVG)	Total pressure	100 kPa
	Total temperature	293 K
	Viscosity ratio	10
Outlet	Static pressure	66.6 kPa (Ma ∼ 0.8)

5. Numerical results and experimental data comparison

In order to predict the proper flow structure on the cooling wall the first step at the beginning of the numerical simulation was to compare some flow features obtained from the CFD with experimental data. The results of numerical simulations are presented for the following cases:

- FC off – AJVG off – no film cooling and no air-jet vortex generator – base case
- FC on – AJVG off – film cooling and no air-jet vortex generator – reference case
- FC on – AJVG on – film cooling and an air-jet vortex generator – flow control case

Isentropic Mach number comparison for the base case (FC off – AJVG off) is shown in Figure 11. There are only few measurement points, but they indicate that the isentropic Mach number maximum and the distribution upstream of the shock wave were predicted properly. Discrepancies can be noticed within the λ-foot range. The discrepancies arise from the λ-foot size overpredicted by numerical simulations (see Figures 4 and 12).

Schlieren photos (Figure 4 and 5a) present strong influence of the cooling flow on the λ-foot in the experiment. However, in CFD, the effect of the cooling flow on the λ-foot is much weaker (see Figure 12 and 13). One can notice that if the cooling flow is applied, the λ-foot increases slightly. The cooling flow and the AJVG influence the boundary layer evolution downstream of the shock wave and finally enforces the boundary layer differences between numerical simulations and experimental data.

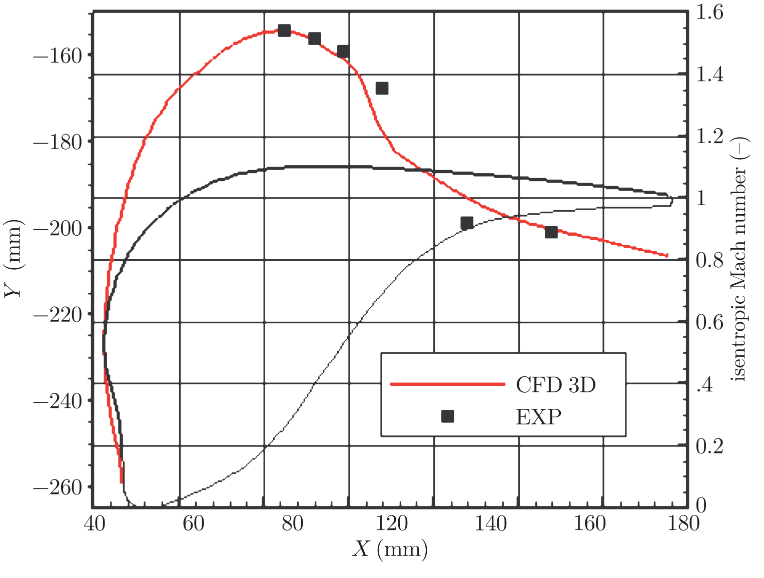

Figure 11. Isentropic Mach number

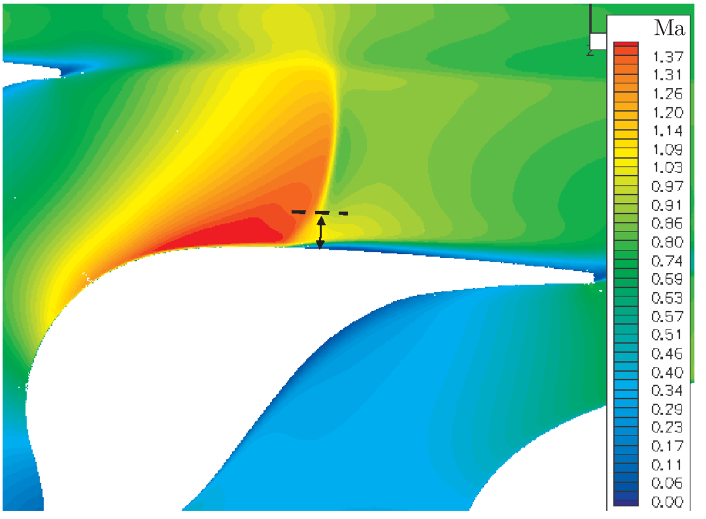

Figure 12. CFD – Mach contours – FC off – AJVG off

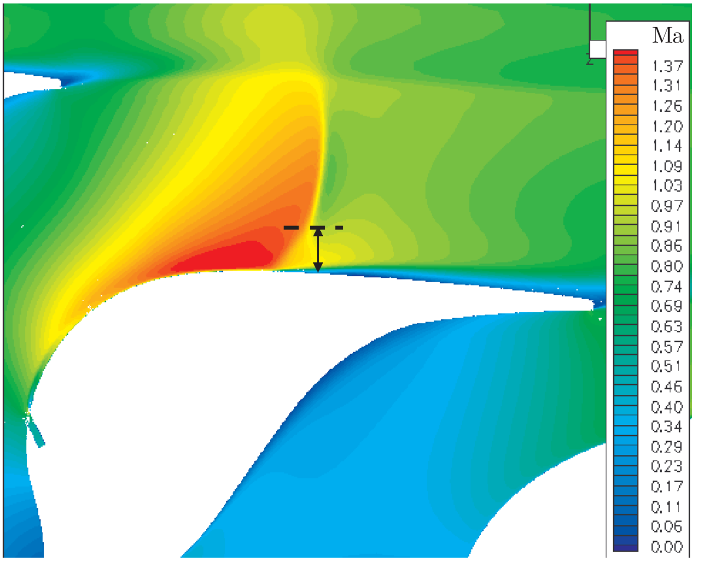

Figure 13. CFD – Mach contours – FC on – AJVG off

Nevertheless, comparing the pressure distributions in the boundary layer, based on the numerical results and experimental data [10], one has to remember that it is done at a certain location in the spanwise direction. Possible spanwise non-uniformity downstream of the film cooling holes or the AJVG is shown in Figure 14. Such non-uniformity can be an additional reason for the difficulties in a quantitative prediction by numerical simulations of AJVG effectiveness and comparison with experimental data. The quantitative assessment should be performed by integration over one pitch, at least.

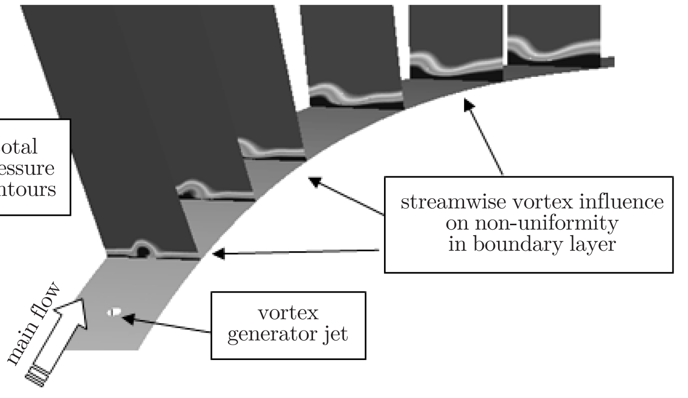

Figure 14. Total pressure at cross-sections downstream of AJVG (FC on – AJVG on)

The flow structure along the test wall can be shown by means of the oil flow visualization. In Figure 7b, a general view on the suction side of the profile for the flow with cooling and vortex generators is shown. One can see traces of streamwise vortices as the oil accumulation along lines in the streamwise direction. A comparison of the numerically predicted flow structure with the visualized one is shown in Figure 15. A close-up of the oil flow visualization picture and the streamlines near the wall from the numerical results is shown. The two zones

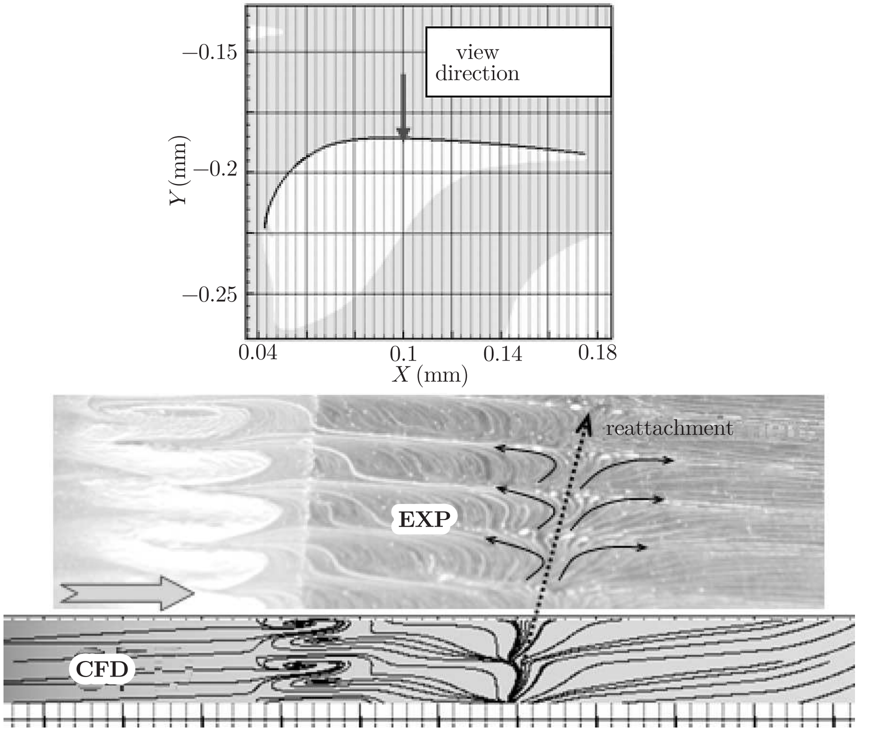

Figure 15. Oil flow visualization (EXP) vs. surface streamlines (CFD) – (FC on – AJVG on)

can be easily distinguished. The first one, it is just downstream of the shock wave where the spanwise structure is observed and the second one, close to the reattachment line. In spite of the quantitative differences (smaller separation length in CFD), the qualitative similarity is obtained.

6. Conclusions

To summarise the above presented investigations one can say that application of AJVGs has a very positive effect on the flow in the blade passage, significantly reduces the separation size.

The numerically investigated geometry is simplified and only one pitch of the AJVG is taken into consideration. The presented approach can be justified by the relatively weak secondary flows existing in the investigated test section. The following conclusions can be drawn from the above described experimental and numerical investigations:

- AJVGs are very effective and therefore they can be used as passive devices.
- Application of cooling increases the boundary layer thickness and causes formation of a large λ-foot.
- The results displayed in static pressure measurements show that AJVGs reduce the tendency towards separation, which means reduction of the separation size.
- Oil visualization has shown that the streamwise vortices pass under the shock wave and the shock does not disintegrate the vortices; streamwise vortices penetrate the whole area downstream of the shock wave; application of AJVGs reduces the separation size significantly (up to 50%).
- The shock wave location in numerical simulations is predicted properly for the case without the cooling flow and the AJVG. The λ-foot predicted numerically is slightly higher than the measured one.
- The application of the cooling flow influences an increase in the λ-foot size. The reason for that is the thicker boundary layer upstream of the shock wave as a result of the cooling flow existence. The effect of the cooling on the λ-foot size obtained numerically is lower than observed experimentally.
- The flow structure downstream of the shock wave obtained numerically is similar to the measured one, but the results are quantitatively different. The reduction of the separation zone by means of the AJVG is not resolved properly. The Spalart-Allmaras turbulence model does not predict such a complex vortical structure correctly.

Acknowledgements

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