A SYSTEMATIC EXPERIMENTAL STUDY ON THE AERODYNAMICS OF LEADING EDGE FILM COOLING ON A LARGE SCALE HIGH PRESSURE TURBINE CASCADE

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ABSTRACT
Systematic isothermal investigations on the aerodynamic effects of leading edge film cooling were carried out on a large scale high pressure turbine cascade named AGTB. In the vicinity of the stagnation point the AGTB turbine cascade has one injection site on the suction side and one on the pressure side. Three injection geometries were tested: Slots (two dimensional geometry), streamwise inclined holes (symmetrical three dimensional geometry) and compound angle holes (fully three dimensional geometry). The injection angle in streamwise direction, the blowing ratio, the inlet turbulence intensity, the inlet Mach number, and the inlet Reynolds number were kept constant at values typically found in modern gas turbines.

The measured data comprise the coolant plenum state, the cascade inlet conditions, the flow field in the cascade exit plane including secondary flows, the static pressure distribution in the mid span section of the blade and in the near hole region, the coolant flow field close to the injection site on the leading edge. Schlieren images of the coolant penetration height and oil-dye flow visualizations of the blade surface. The experimental data are summarized and documented as a test case that can be used for validation purposes of prediction methods.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>[mm²]</td>
<td>area</td>
</tr>
<tr>
<td>c₂ina</td>
<td>[-]</td>
<td>pressure coefficient (= (p₂ - p₀)/(ρ₁ * p₁))</td>
</tr>
<tr>
<td>D</td>
<td>[mm]</td>
<td>hole diameter</td>
</tr>
<tr>
<td>Ds</td>
<td>[mm]</td>
<td>slot width</td>
</tr>
<tr>
<td>G</td>
<td>[m/s]</td>
<td>magnitude of the velocity vector</td>
</tr>
<tr>
<td>H</td>
<td>[m]</td>
<td>blade height</td>
</tr>
<tr>
<td>k</td>
<td>[-]</td>
<td>turbulent kinetic energy (= (u² + v² + w²)/2)</td>
</tr>
<tr>
<td>L</td>
<td>[mm]</td>
<td>chord length</td>
</tr>
<tr>
<td>l</td>
<td>[mm]</td>
<td>hole/slot length</td>
</tr>
<tr>
<td>M</td>
<td>[-]</td>
<td>blowing ratio (= (pG)₂/(pG)₁)</td>
</tr>
<tr>
<td>Ma</td>
<td>[-]</td>
<td>Mach number</td>
</tr>
<tr>
<td>m</td>
<td>[kg/s]</td>
<td>mass flow rate</td>
</tr>
<tr>
<td>N</td>
<td>[-]</td>
<td>number of holes per row</td>
</tr>
<tr>
<td>P</td>
<td>[mm]</td>
<td>pitch of the holes</td>
</tr>
<tr>
<td>p</td>
<td>[hPa]</td>
<td>static pressure</td>
</tr>
<tr>
<td>q</td>
<td>[hPa]</td>
<td>dynamic pressure</td>
</tr>
<tr>
<td>Re</td>
<td>[-]</td>
<td>Reynolds number (Re = (G L)/ν)</td>
</tr>
<tr>
<td>s</td>
<td>[mm]</td>
<td>coordinate along the blade surface</td>
</tr>
<tr>
<td>T</td>
<td>[K]</td>
<td>temperature</td>
</tr>
<tr>
<td>t</td>
<td>[mm]</td>
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</tr>
<tr>
<td>Tu</td>
<td>[%]</td>
<td>turbulence intensity (k = 3/2 Tu²)</td>
</tr>
<tr>
<td>U</td>
<td>[m/s]</td>
<td>velocity parallel to the surface (x)</td>
</tr>
<tr>
<td>Uₓ</td>
<td>[m/s]</td>
<td>velocity parallel to the X-coordinate</td>
</tr>
<tr>
<td>u</td>
<td>[mm]</td>
<td>circumferential coordinate of the cascade exit plane</td>
</tr>
<tr>
<td>uu, vv, ww</td>
<td>[%]</td>
<td>Reynolds stresses (uu = (u²) / Gₙ₁)</td>
</tr>
<tr>
<td>V</td>
<td>[m/s]</td>
<td>velocity normal to the surface (y)</td>
</tr>
<tr>
<td>W</td>
<td>[m/s]</td>
<td>velocity in lateral direction (z)</td>
</tr>
<tr>
<td>x</td>
<td>[mm]</td>
<td>coordinate parallel to the blade surface</td>
</tr>
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INTRODUCTION

Film cooling is still one of the main challenges in the design of highly effective gas turbines because high turbine inlet temperatures, that can only be realized by extensive cooling, increase the cycle efficiency while the use of compressor bleed air for cooling purposes leads to a decrease of the component efficiency and thus reduces the cycle efficiency. The design of film cooling configurations is influenced by many interacting parameters which can be optimized at reasonable cost on a numerical test platform only. In order to attain ample confidence in the numerical design process it is necessary to validate the numerical code forming the heart of the test platform by means of experimental data. The validation should progress gradually from simplified to realistic conditions so that the origin of possible deviations can be revealed. Parallel to the code validation the understanding of the governing flow phenomena with respect to film cooling can be improved because the numerical treatment renders a higher resolution of the flow field so that the generation of the flow structures can be observed closely. At present detailed data of film cooling experiments are mostly available for simplified geometries. But the progress of the numerical code validation has reached a stage which requires experimental data at more realistic conditions.

One of the crucial points in the design of a film cooled turbine is the aero-thermal optimization of the blade leading edge region. Therefore experimental data on leading edge film cooling are foremost required in order to calibrate the design tools. As a contribution to the validation process this paper summarizes experiments concerning the aerodynamics of leading edge film cooling that were carried out on a large scale high pressure turbine cascade named AGTB at the High Speed Cascade Wind Tunnel of the Universität der Bundeswehr München. All experimental results presented in this paper are available as standardized data files which are described in detail in an accompanying manual (Ardey and Fottner, 1998). The report and the data can be obtained via the internet. For more information please contact the authors. To maintain the way of stepping from simplified to realistic conditions, three geometrical types of blowing configurations were tested: slots (AGTB-S, two dimensional geometry), holes without radial injection angle (AGTB-B1, symmetrical three dimensional geometry) and holes with radial injection angle (AGTB-B2, fully three dimensional geometry). The cascade was proportioned relative to the size of the wind tunnel and the available probes in order to keep up a periodic blading character while still permitting reasonable spatial resolution of the single film cooling jet. The aerodynamic boundary conditions - the Reynolds number, the Mach number, and the turbulence intensity - fit to those of real turbomachine blades. The facility uses an isothermal flow creating temperature and density ratios of unity. The effects concerning the large scale aerodynamics of bladings and the small scale aerodynamics of single jets could be observed on one test set-up maintaining the aerodynamic boundary conditions of real turbomachines. The experiments comprise the investigations of Beeck (1992a) and Ardey et al. (1997a, 1997b) that have repeatedly been used as a test case for numerical studies (Beeck et al., 1992b, Benz et al., 1993, Vogel, 1994, Irmsch, 1995, Bohn et al., 1997).

EXPERIMENTAL SET-UP

Turbofoil Cascade

The experimental investigations were carried out on a large scale high pressure turbine cascade named AGTB (Fig. 1). The cascade consists of three blades with a maximized chord length in order to reach a high spatial resolution while still maintaining periodicity. Solely the center blade was used for the measurements. The aerodynamic and geometric data of the cascade are listed in Tab. 1.

![Figure 1: Test section of the wind tunnel with turbine cascade AGTB](image-url)
Figure 2: Leading edge of the turbine blade AGTB with film cooling

**GEOMETRY**

- **Chord Length:** $L = 250$ mm
- **Blade Height:** $H = 300$ mm
- **Pitch/Chord Ratio:** $V/L = 0.714$
- **Stagger Angle:** $\beta_s = 73^\circ$

**AERODYNAMICS**

<table>
<thead>
<tr>
<th>Inlet:</th>
<th>Exit:</th>
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<tbody>
<tr>
<td>$Ma_1 = 0.37$</td>
<td>$Ma_{25} = 0.95$</td>
</tr>
<tr>
<td>$Re_1 = 370000$</td>
<td>$Re_{25} = 695000$</td>
</tr>
<tr>
<td>$\beta_1 = 133^\circ$</td>
<td>$\beta_2 = 28.3^\circ$</td>
</tr>
</tbody>
</table>

*Table 1: Design data of the turbine cascade AGTB*

Three geometrical types of blowing configurations were tested: slots (AGTB-S [formerly also called ATBS]), holes without radial injection angle (AGTB-B1) and holes with radial injection angle (AGTB-B2). The holes are aligned along the whole blade height and

have a parallel shape. They are fed by the plenum and inject the secondary air into the mainstream flow of the cascade. The slots have two interceptions for the leading edge retainers (Fig. 3). Internally the injection geometry surfaces are smooth. The edges are trimmed but not rounded. The data of the blowing configurations are summarized in Tab. 2.

**Table 2: Design data of the blowing configurations S, B1 and B2**

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s/L_{SS}$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$s/L_{PS}$</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td>$\gamma_{c,SS}$</td>
<td>$110^\circ$</td>
<td>$110^\circ$</td>
<td>$110^\circ$</td>
</tr>
<tr>
<td>$\gamma_{c,PS}$</td>
<td>$120^\circ$</td>
<td>$120^\circ$</td>
<td>$120^\circ$</td>
</tr>
<tr>
<td>$\gamma_{r,SS}$</td>
<td>-----</td>
<td>$90^\circ$</td>
<td>$45^\circ$</td>
</tr>
<tr>
<td>$\gamma_{r,PS}$</td>
<td>-----</td>
<td>$90^\circ$</td>
<td>$45^\circ$</td>
</tr>
<tr>
<td>$D_{eff}/L$</td>
<td>0.01018</td>
<td>0.012</td>
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<tr>
<td>$P/D$</td>
<td>-----</td>
<td>5</td>
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<tr>
<td>$N$</td>
<td>-----</td>
<td>20</td>
<td>19</td>
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<tr>
<td>$D_{eff}$</td>
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<td>0.24</td>
<td>0.19</td>
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<tr>
<td>$A_{c,SS/PS}/A_1$</td>
<td>0.03371</td>
<td>0.00722</td>
<td>0.00686</td>
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</table>

**High Speed Cascade Wind Tunnel**

The experiments were carried out in the High Speed Cascade Wind Tunnel of the Universität der Bundeswehr München (Fig. 4). This facility operates continuously in a large pressurized tank. Setting the compressor delivery pressure and the pressure level inside the tank allows for the independent variation of Mach number and Reynolds number while the total temperature is kept constant at $30^\circ$C. The turbulence intensity in the test section can be varied using different turbulence generators in front of the nozzle.

*Figure 4: High Speed Cascade Wind Tunnel*

The film cooling air is supplied by a separate screw compressor which compresses air from the tank and is working on the same pressure level as the test facility. A cooler sets the temperature of the film cooling air in order to maintain isothermal conditions, i.e. the...
coolant total temperature is also set to 30°C. Therefore the density ratio of coolant and mainstream is about unity. Adjustable guide vanes were mounted at the upper and lower wind tunnel walls in order to achieve a constant inlet pressure distribution (Fig. 1). An orifice was set up in the duct of the film cooling air for the determination of the mass flow rate. Quartz-Glass windows were installed in the front part of the side walls in order to obtain optical access to the leading edge of the center blade.

The following data were used in order to monitor the flow conditions of the cascade main stream flow (Sturm and Fottner, 1985): the total temperature in the settling chamber, the static pressure in the tank (downstream conditions), the static pressure and the total pressure of the main stream flow upstream of the cascade (Fig. 1). The inlet turbulence intensity was surveyed on-line by a retractable single sensor hot film probe. For the setting of the film cooling air mass flow rate, temperature, static pressure, and pressure drop at the orifice were measured. In addition to the coolant mass flow the internal boundary conditions of the coolant are specified by observing the temperatures and total pressures inside the plena of the blades.

TEST PROGRAM

Since the cascade flow is transonic the flow conditions depend strongly on the mass flow rate of the cooling injection. Uniform conditions at the leading edge can only be guaranteed for all investigated blowing ratios by adjusting the upstream conditions to the design values $M_x = 0.37$ and $Re_x = 370000$. The distribution of the coolant mass flow rate on the two injection sites was determined by means of calibration measurements that provided individual discharge coefficients (Fig. 5).

![Figure 5: Discharge coefficients of the film cooling configurations](image)

The test program and the investigated blowing configurations are displayed in Tab. 3. Figure 6 shows a compact overview of some typical results. The loading of the cascade was measured by means of static pressure tappings in the mid span section of the blade (PD). They were located at half pitch of the film cooling holes. For the B1 and B2 film cooling configurations an additional number of static pressure tappings were spread close to the holes in order to gain information about the influence of the cooling jets on the local static pressure distribution. The cascade losses were detected with two types of probes. A wedge probe was traversed 32 % chord length downstream of the cascade in the two dimensional flow of the mid span section measuring the local values of the static and the total pressures as well as the circumferential flow angles (WW). In order to determine the secondary flow field of the cascade, additional information is needed about the lateral flow angle. For the B1 and B2 configurations it was measured with a five hole probe being traversed pitchwise and spanwise 32 % chord length downstream of the cascade [W5].

<table>
<thead>
<tr>
<th>M</th>
<th>PD</th>
<th>WW</th>
<th>W5</th>
<th>OF</th>
<th>SCH</th>
<th>LTV</th>
<th>HWA</th>
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<tbody>
<tr>
<td>0.0</td>
<td>S</td>
<td>B1</td>
<td>B1</td>
<td>S</td>
<td>(S)</td>
<td>S</td>
<td>B1</td>
</tr>
<tr>
<td>0.3</td>
<td>B1</td>
<td>B1</td>
<td>B1</td>
<td>B2</td>
<td>B1</td>
<td>B2</td>
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</tr>
<tr>
<td>0.5</td>
<td>S</td>
<td>B1</td>
<td>B1</td>
<td>S</td>
<td>(S)</td>
<td>S</td>
<td>B1</td>
</tr>
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<td>B1</td>
<td>B1</td>
<td>B1</td>
<td>B2</td>
<td>B2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>S</td>
<td>B1</td>
<td>B1</td>
<td>S</td>
<td>(S)</td>
<td>S</td>
<td>B1</td>
</tr>
<tr>
<td>1.7</td>
<td>B1</td>
<td>B1</td>
<td>B1</td>
<td>B2</td>
<td>B2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| PD | Static Pressure Distribution Measurements on the Blade Surface |
| WW | Wake Traverse Measurements at Mid Span with a Wedge Probe |
| W5 | Wake Traverse Measurements of the Secondary Flow Field with a Five Hole Probe |
| SCH | Schlieren Images of the Coolant Flow Path (S: only photographic image, no digital data set) |
| OF | Oil-and-Dye Visualizations of the Blade Surface Flow |
| LTV | Flow Field Measurements on the Leading Edge with the Laser-2-Focus Velocimetry |
| HWA | Flow Field Measurements on the Leading Edge with the Hot Wire Anemometry |

Table 3: Test program of the AGTB turbine cascade with leading edge film cooling
Figure 6: Experimental results on the AGTB cascade with leading edge film cooling
Detailed flow field investigations on the leading edge were carried out by means of the Laser-2-Focus Velocimetry and the Hot Wire Anemometry. The Laser-2-Focus Velocimetry as installed in the wind tunnel gives the two dimensional data of the flow vector in axial and circumferential direction and the turbulence intensity. It is non-intrusive and allows measurements very close to walls as well as in regions with large velocity gradients or in reverse flow areas. The measurements with the Hot Wire Anemometry were carried out using a subminiature triple hot wire probe with an active probe volume of 1 mm³ to determine the three dimensional flow vector and the components of the Reynolds stress tensor.

The two dimensional flow field of the mid span section at the leading edge of the AGTB-S cascade was measured by means of the Laser-2-Focus Velocimetry only (Fig. 6g). The investigations include the stagnation zone, the jet exit plane, and boundary layer profiles downstream of the injection. The symmetrical three dimensional flow field downstream of the AGTB-B1 holes was measured by means of the Laser-2-Focus Velocimetry and the Hot Wire Anemometry. The measuring planes were located in the mid span area of the blade at 5 positions downstream of the suction and pressure side holes. They were oriented perpendicular to the surface (Fig. 2) and spanned a complete hole pitch in lateral direction. The Laser-2-Focus Velocimetry was selected for the investigations at Δs/L = 0.01 and Δs/L = 0.025 because a very sensitive flow pattern with high gradients and reverse flow areas was observed near the blowing holes. In addition, the injected flow was measured 0.25 mm above the exit plane of the holes. At Δs/L = 0.05, 0.075, and 0.10 the flow field appeared stable enough to use a triple hot wire probe. The fully three dimensional flow field downstream of the AGTB-B2 holes was measured by means of the Hot Wire Anemometry only. The measuring planes were the same as for the AGTB-B1 cascade (Δs/L = 0.05, 0.075, and 0.10, Fig. 2).

**EXPERIMENTAL RESULTS**

Within the scope of this paper all experimental results will be presented in principle but they can only be discussed briefly. A more detailed description of the investigations on the AGTB-S cascade is reported by Beeck, 1992a and Beeck et al., 1992b. Detailed results of the AGTB-B1 cascade are reported by Ardey and Fottner, 1997a and Ardey et al., 1997b.

**Cascade Inlet Conditions**

For the experiments on the AGTB cascade the turbulence intensity in the wind tunnel was set to 5%. The inlet side wall boundary layer was measured 30 mm in front of the cascade inlet plane (Fig. 6i). The boundary layer thickness is about 5% of the blade height and the velocity profile fits to the 1/7-power law of a turbulent boundary layer.

**Static Pressure Distribution on the Blade Surface**

The static pressure distribution in the mid span section of the cascade can be normalized as the pressure coefficient cₚ. The data of all configurations including the AGTB cascade without any film cooling are summarized in Fig. 6f for a blowing ratio of M = 0.0. At x/d₀ = 0.05 there is a suction peak on the pressure side because the cascade is not operated at its optimum inlet angle. The transition of the boundary layer at x/d₀ = 0.7 is indicated by a slight bend in the pressure coefficient distribution. The bend is smoothed out when the blowing ratio is increased because the leading edge film cooling increases the turbulence in the boundary layer and creates a less pronounced transition. Fig. 7 displays the isentropic Mach number on the blade surface of the AGTB-B1 cascade that was calculated from the static pressure distribution. The local velocity maximum on the pressure side leading edge is increased because of the coolant injection. The static pressure at the suction side injection is higher than on the pressure side causing a circulation through the plenum chamber at zero blowing ratio and resulting in a non-uniform distribution of the coolant mass flow rates. Keeping the upstream flow conditions constant and increasing the blowing ratio at the leading edge implies rising velocities throughout the cascade because of higher mass flow rates.

![Figure 7: Isentropic Mach number at the leading edge of the mid span section, AGTB-B1](image)

![Figure 8: Relative isentropic Mach number ΔMa = Ma - M₀, no holes on the leading edge surface, M = 1.1, AGTB-B2](image)

The deformation of the surface flow field around the cooling holes was also measured by means of static pressure tappings on the B1 and B2 configurations. In Fig. 8 the differences between the isentropic Mach numbers on the surface of the film cooled blade and the blade without film cooling holes are displayed. Due to the compound angle film cooling configuration the deceleration zones in front of the injection sites are oriented laterally. The pressure side jet penetrates into a sensitive flow pattern of the main stream flow and causes the extent of the deceleration area upstream of the holes to be bigger than on the suction side. The main stream flow passing in between the jets is accelerated reaching its maximum on the side of the jet facing in the lateral injection direction.
Wake Traverse Measurements at Mid Span

Although the main stream flow of the AGTB-B1 cascade is clearly influenced by the leading edge film cooling, the wedge probe results indicate no significant deviation of the averaged circumferential exit flow angle at mid span for blowing ratios up to $M = 2.0$. The wake of the cascade (Fig. 6e) grows with increased blowing ratios. Taking the coolant energy into account the total pressure loss coefficient at mid span is calculated from the wake data. It is displayed in Fig. 9 versus the estimated loss values gained by applying the mixing layer model (Ardey and Fottner, 1997a, Ardey et al., 1997c). The losses rise with increased blowing ratios. The slot configuration generates higher losses because at the same blowing ratio its mass flow rate is about five times higher than the mass flow rate of the hole configurations. The loss prediction by the mixing layer model is exceedingly good in spite of injection angles larger than 90°, strong curvature and high pressure gradients (Ardey et al., 1997c).

Schlieren Images of the Coolant Flow Path

Schlieren images visualize density gradients normal to the applied knife edge. In isothermal flow they can be interpreted as velocity gradients. Fig. 6a displays gradients in the direction of the cascade inlet flow. The prominent white streaks denote the acceleration due to the velocity profile of the coolant in the hole exit. The jet penetration height on the suction side is always lower than on the pressure side due to a reduced mass flow rate. The imbalance of the mass flux occurs because the pressure difference between plenum and the hole exit is always smaller on the suction side due to the local suction peak on the pressure side. The stagnation zone at the leading edge of the cascade and the deceleration towards the wake of the jets are indicated in a dark gray color.

Oil-and-Dye Visualizations of the Blade Surface Flow

The flow pattern on the blade surface can be judged qualitatively by means of unwrapped oil-and-dye pictures that visualize the surface shear forces. In the side wall regions the formation of the passage vortex can be seen on the suction side from about 30% distance downstream of the stagnation line onwards (Fig. 6c). The dark zone without dye indicates the transitional area which is permeated by streaks of turbulent flow generated by the coolant injection. At the stagnation line the shear forces are very low so that most of the dye remains on the surface giving it a light color.

If the coolant has no lateral injection angle (B1) the secondary flow field is not influenced by the leading edge film cooling. The lateral velocity component introduced by the compound angle film cooling at the leading edge of the B2 configuration is still present in the wake (Fig. 6d). It creates asymmetric vortices and shifts boundary layer material in spanwise direction as can be seen from the radial distribution of the circumferentially averaged total pressure loss coefficients (Fig. 10).

Wake Traverse Measurements of the Secondary Flow Field

The secondary flow field was observed for the hole configurations B1 and B2 only. It consists mainly of the passage vortex and the trailing edge vortex (Fig. 6d).
small. The deceleration behind the local suction peak of the pressure side induces flow separation. This leads to the formation of separation bubbles between the coolant jets which are also present with the compound angle film cooling configuration. At high blowing ratios the vortices of the recirculation zones and the separation bubbles merge.

In the slot film cooling configuration the recirculation zone due to the lift-off of the coolant jet transforms into an area of separated flow as can seen from the zoom on the leading edge region of the oil-and-dye flow visualization (Fig. 11). The deceleration downstream of the local suction peak on the pressure side enlarges the area of separated flow drastically. At the slot interceptions for the leading edge retainers main stream flow enters the zone of separated flow. This three dimensional phenomenon effects the extent of the separation region at mid span. As a first approach the calculation of the mid span flow field of the slot film configuration can be assumed to be a two dimensional problem. But to reach a good agreement with the measured length of the separation zone the slot geometry should be modeled three dimensionally incorporating the interceptions for the leading edge retainers.

Flow Field Measurements on the Leading Edge with the Laser-2-Focus Velocimetry

The flow field measurements on the leading edge of the AGTB-S cascade were carried out by means of the Laser-2-Focus Velocimetry only because its two dimensional capacity is sufficient to investigate the flow pattern which can be expected at the mid span of the slot film cooling configuration (Fig. 6g). The large separation zone on the pressure side that was already observed in the oil-and-dye flow visualization is easily discernible in its large vertical and streamwise extent. The area of separated flow downstream of the suction side slot was also detected but can not be resolved in Fig. 6g due to its small size. Measurements in the jet exit plane reveal that the coolant exits perpendicularly from the hole according to the injection angle. But it is deflected instantaneously towards a more tangential direction creating a small recirculation of main stream flow into the upstream edge of the slot. With increasing blowing ratios the stagnation zone on the leading edge of the AGTB-S cascade is enlarged and intensified.

The measurements in the exit plane of the film cooling holes can give a clue about the formation of the flow field inside the hole. The effects will be discussed for the pressure side only because the suction side results are very similar. The two maxima of the velocity

Figure 12: Velocity in the X-direction (inlet flow direction) on the leading edge of the turbine cascade AGTB-S, M = 1.1

The distribution of the velocity component Ux parallel to the inlet flow direction of the cascade (Fig. 12) indicates the locations of separated flow and the exit area of the coolant above the slots by the dark gray color which denotes negative velocities. The jets force the stagnation line to develop into a stagnation field between the two injection sites which is characterized in Fig. 12 by the middle gray color.

The Laser-2-Focus Velocimetry measurements on the AGTB-B1 cascade at Ax/L = 0.01 downstream of the pressure side holes reveal the big lateral and normal extent of the reverse flow area (black color, Fig. 13) that was observed in the oil-and-dye flow visualizations. The main stream flow evades the coolant and is accelerated. It reaches its maximum velocities next to the reverse flow area (white color, Fig. 13). The velocity gradient from -80 m/s up to 180 m/s at z/D = ± 0.5 creates strong turbulence because of high shear forces (Fig. 14). The core of the jet is to be found at y/D = 1.5. Around the jet at y/D = 1.0 and y/D = 2.0 the turbulence is increased because of the interaction of the coolant with the reverse flow zone and the main stream. In principle the flow field measurements at Ax/L = 0.01 downstream of the suction side holes which are not depicted here feature the same flow phenomena. But the reverse flow zone and therefore all effects related to it are much smaller.

Figure 13: Tangential velocity U on the pressure side of the turbine cascade AGTB-B1, Ax/L = 0.01, M = 1.1

Figure 14: Turbulence intensity on the pressure side of the turbine cascade AGTB-B1, Ax/L = 0.01, M = 1.1

The measurements in the exit plane of the film cooling holes can give a clue about the formation of the flow field inside the hole. The effects will be discussed for the pressure side only because the suction side results are very similar. The two maxima of the velocity
component normal to the blade surface in the downstream part of
the film cooling hole indicate probably the formation of the kidney
vortices (Fig. 15) but due to the missing lateral velocity component it
can not be verified. At s/D = -0.5 negative vertical velocities of about
-5 m/s point to a small recirculation of mainstream flow into the
upstream edge of the hole. The core of the coolant jet maintains a low
turbulence intensity when exiting from the hole (Fig. 16). It is
surrounded by a belt of high turbulence which is created along the jet
boundary by the shear forces. The highest turbulence level is reached
in the stagnation zone on the upstream border of the jet at s/D = -0.4.

Figure 15: Normal velocity V in the exit plane of the pressure side
hole of the turbine cascade AGTB-B1, M = 1.1

Figure 16: Turbulence intensity in the exit plane of the pressure side
hole of the turbine cascade AGTB-B1, M = 1.1

Flow Field Measurements on the Leading Edge with the
Hot Wire Anemometry

The vortex structures and the anisotropy of the turbulence related
to the film cooling jets can be detected by means of the three
dimensional Hot Wire Anemometry. In Fig. 6h and Fig. 13 to 22
s/D = 0.0 denotes the position of the hole center line. Each vector
represents one measured data set. Judging the results the probe size
being 1 mm³ compared to a hole diameter of 3 mm should be kept in
mind. On the suction side of the AGTB-B1 cascade the kidney vortices
forming around the core of the jet can be observed clearly (Fig. 6h).
The size and the intensity of the kidney vortices are found to be
proportional to the blowing ratio. The flow vectors distant from the
blade surface seem to indicate a flow towards the wall since the
measuring planes are normal to the blade surface whereas the
curvature of the streamlines at the leading edge causes the mainstream
flow to be non-orthogonal to the measuring plane. Data from the
downstream measuring planes not presented in this paper show the
dissipation of the kidney vortices in the course of the jet.

Figure 17: Flow vectors in the measuring plane (V,W-components) at
the suction side, As/L = 0.10, M = 1.1, AGTB-B2

Because of the asymmetric shear forces on the surface of the jet
the compound injection angle of the AGTB-B2 cascade features a
rotational flow that favors one of the two kidney vortices and hinders
the development of the other one. On the suction side the stronger
vortex dominates the flow field (Fig. 17) whereas the weak vortex is
dissipated completely at an early stage. The lateral velocity component
of the coolant is present in the near wall region. It shifts the jet from
the hole center line towards positive z/D values. This lateral velocity
component on the blade surface is weakened but prevails throughout
the whole cascade so that it can still be found in the wake traverse
measurements (Fig. 6d).

On the pressure side of the AGTB-B1 the interaction of the
coolant jet with the big reverse flow zones and the separation bubbles
generates a flow field with two pairs of vortices and a trough flow
(Fig. 18). The kidney vortices located on top at y/D = 2.3 can hardly
be detected from the vector field because their influence on the flow
vectors is blurred by the streamline curvature effects of the main
stream flow mentioned above. But they are still present as can be seen
from the plot of the vorticity normal to the measuring plane (Fig. 19).
Underneath the kidney vortices the main stream flow is drifting
towards the centerline of the hole at the blade surface generating a
second counter-rotating vortex pair. This trough flow fills up the
deficit of the kinetic energy created by the reverse flow behind the
holes. It evades the coolant jet, that is stably entrained in the kidney
vortices. On its way it has to pass above the separation bubbles before
it drops down to the surface. These turning mechanisms induce the
second vortex pair - the trough vortices. As on the suction side the size
and the intensity of the vortices are found to be proportional to the
blowing ratio. At low blowing ratios the trough vortices are dominant
but with increasing blowing ratios their ratio of growth is smaller than
the one of the kidney vortices.

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The lateral velocity component of the coolant shifts the jet from the hole center line towards negative z/D values. It must be mentioned that this shift has the same direction with respect to the blade as the suction side drift, but due to the definition of the boundary layer coordinate system the sense of the z-axis is changed (Fig. 2). The lateral velocity component on the blade surface is weakened but prevails throughout the whole cascade so that it can still be found in the wake traverse measurements (Fig. 6d).

Because of the lateral velocity component due to the compound angle injection of the AGTB-B2 cascade, the velocity deficit downstream of the pressure side injection is filled up mostly from one direction so that one branch of the trough flow vortices dominates the other one (Fig. 20). As on the suction side of the AGTB-B2 cascade only one branch of the kidney vortex pair is favored. The two dominating vortices have the same rotational direction and merge to a single vortex in the course of the coolant flow path. The lateral velocity deficit of the coolant jet is filled up mostly from one direction so that one branch of the trough flow vortices dominates the other one (Fig. 20).

In addition to the averaged velocities the three dimensional Hot Wire Anemometry measures the Reynolds stress tensor. When using Hot Wire techniques the observation of turbulence should be preferred to using absolute velocity values because the fluctuating data are far less subject to drifting. In the contact area of the coolant and the main stream flow turbulence is generated by shear forces. Another source of turbulence is the interaction region of the vortices in the center of the jet. Because of these two phenomena the extent and shape of the coolant jet can be observed easily by means of turbulence values (Fig. 21). The simplest structure can be found for the suction side jet of the AGTB-B1: The jet inside of the kidney vortices stands out clearly. The highest level of turbulence is reached on the blade surface downstream of the hole center line where the lateral velocities of the two kidney vortices collide and turn towards a vertical direction. The lateral to vertical turning of the flow vectors corresponds also to the location of the maximum turbulence on the suction side of the AGTB-B2 compound angle injection. At z/D = -1.0 the smooth lateral flow between the jets on the blade surface renders a local turbulence minimum. The turbulence structures of the AGTB-B1 pressure side jet can be deduced from Fig. 14: The reverse flow zone downstream of the hole center line characterized by a relatively small turbulence level is surrounded by a highly turbulent belt. The turbulence maxima at z/D = ± 1.0 originate from the shear of the reverse flow and the accelerated main stream flow. The compound angle injection of the AGTB-B2 causes the pressure side turbulence belt to develop asymmetrically. Above y/D = 1.0 the turbulence distribution of the pressure side is related to the kidney vortices and can be judged in the same way as the suction side results for both configurations.

The turbulence generated by the vortices on a film cooling jet is not only dependent on the flow pattern but is also highly anisotropic as can be seen from the uu, vv and ww components of the Reynolds stresses.
stress tensor on the AGTB-B1 cascade (Fig. 22). The turbulent kinetic energy being the sum of the Reynolds stress components is equivalent to the turbulence intensity already discussed. The uu-component displays the well known kidney shape that corresponds to the kidney vortices. The maximum value of the vv-component is twice as high as the maximum uu value. It occurs where the vertical downwash of the kidney vortices has turned into a lateral direction. The ww-component reaches its highest level on the blade surface downstream of the hole center line where the lateral velocities of the two kidney vortices collide and turn towards a vertical direction. The maximum of the ww-component is about four times higher than the maximum uu value. Such a high degree of anisotropy can not be covered by common two equation turbulence models and may cause an underprediction of the jets lateral spread and the heat transfer coefficients.

Figure 22: Reynolds stress components uu, vv, and ww and turbulent kinetic energy k = (uu + vv + ww)/2 at the suction side \( \Delta s/L = 0.05 \), M = 1.1, AGTB-B1

**CONCLUSIONS**

The experimental results on the aerodynamics of a turbine cascade with leading edge film cooling summarized in this paper are meant to be a contribution to the validation process of numerical codes. They are available as standardized data files which are described in detail in an accompanying report. Stepping from simplified to realistic conditions, three geometrical types of blowing configurations were tested: slots (AGTB-S, two dimensional geometry), holes without radial injection angle (AGTB-B1, symmetrically three dimensional geometry) and holes with radial injection angle (AGTB-B2, fully three dimensional geometry). The aerodynamic boundary conditions, Reynolds number, Mach number, and turbulence intensity fit to those of real turbomachine bladings. By having a local suction peak on the pressure side leading edge of the coolant jet including the Reynolds stress tensor flow structures governing the aerodynamics of a turbine cascade with leading edge film cooling.

The results cover the following aspects:
- inlet turbulence intensity
- inlet side wall boundary layer
- discharge coefficients of the film cooling slots and holes
- loading and isentropic Mach number of the cascade at mid span
- static pressure distribution and isentropic Mach number close to the coolant injection sites
- exit flow angle and wake at mid span
- secondary flow field downstream of the cascade
- total pressure loss coefficients
- boundary layer development
- flow field in the vicinity of the coolant injection sites
- flow field in the coolant exit plane
- flow field of the coolant jet including the Reynolds stress tensor

The most prominent flow phenomena observed were:
- The natural transition on the suction side takes place at 70% of the chord length. The transitional area is permeated by streaks of turbulent flow generated by the coolant injection. At the highest blowing ratios the transition could not be detected any more.
- The mid span exit flow angle is not significantly effected by the leading edge film cooling.
- The rise of the mid span total pressure loss coefficient which takes into account the coolant energy can be predicted accurately by the mixing layer model.
- The overall total pressure loss coefficient of the secondary flow is constant and independent of the blowing ratio. The lateral velocity component of the compound angle injection shifts boundary layer material in spanwise direction and alters the radial distribution of the total pressure loss coefficients.
- The secondary flow field consists mainly of the passage vortex and the trailing edge vortex. For the AGTB-B1 it is independent of the blowing ratio. The lateral velocity component introduced by the compound angle film cooling at the leading edge of the AGTB-B2 is still present in the wake and creates asymmetric vortices.
- The formation of the passage vortex can be detected in the side wall region of the suction side from about 30% distance downstream of the stagnation line onwards.
- The AGTB cascade has a local suction peak on the pressure side leading edge near the injection location because it is not operated at its optimum inlet angle.
- The static pressure at the suction side injection is higher than on the pressure side causing a circulation through the plenum chamber at zero blowing ratio and resulting in a non-uniform distribution of the coolant mass flow rates.
- The jet penetration height on the suction side is always lower than on the pressure side due to the non-uniform distribution of the coolant mass flow rates.
- Because of the local flow conditions the deceleration area on the blade surface upstream of the pressure side holes is bigger than on the suction side. The main stream flow passing in between the jets is accelerated reaching its maximum next to the jet.
- The two dimensional slot geometry AGTB-S creates a three dimensional flow field because main stream flow enters the large zone of separated flow below the jets at the slot interceptions in lateral direction. This three dimensional phenomenon produces
strong vortices and effects the extent of the separation region at mid span.

- The suction side film cooling jets of the AGTB-B1 configuration develop into the typical vortex pair generally referred to as kidney vortices keeping the coolant in its core.
- Because of the asymmetric shear forces on the surface of the jet the compound injection angle of the AGTB-B2 cascade features a rotational flow that favors one of the two kidney vortices and hinders the development of the other one. On the suction side the stronger vortex dominates the flow field whereas the weak vortex is dissipated completely at an early stage.
- The suction peak on the pressure side of the leading edge creates separation bubbles between the film cooling jets and a large recirculation area behind the injection holes.
- The flow field of the AGTB-B1 pressure side injection consists of two pairs of vortices: The two kidney vortices entraining the film cooling jet are located above a second pair of vortices (trench flow vortices) generated by a trench flow that fills up the deficit of the recirculation.
- With the compound angle injection of the AGTB-B2 the velocity deficit downstream of the pressure side injection is filled up mostly from one direction so that one branch of the trench flow vortices dominates the other one. As on the suction side of the AGTB-B2 cascade only one branch of the kidney vortex pair is favored. The two dominating vortices have the same rotational direction and merge to a single vortex in the course of the coolant flow path.
- The main part of the turbulence production on the film cooling jets occurs in the center of the coolant where the lateral velocities of the two kidney vortices collide and turn towards a vertical direction.
- The reverse flow zone downstream of the hole center line characterized by a relatively small turbulence level is surrounded by a highly turbulent belt which originates from the shear of the reverse flow with the coolant or the accelerated main stream flow.
- The turbulence generated by the vortices of film cooling jets is highly anisotropic. The degree of the anisotropy and the topology of each Reynolds stress component depends on the flow pattern.

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