The 8th International Conference on Jets, Wakes and Separated Flows, ICJWSF-2024
September 23-25, 2024, Firenze, Italy

Experimental characterization of film cooling performance of a double row of cylindrical holes on a nozzle guide vane

S. Galeotti[1*], T. Bacci[1] A. Picchi [1] S. Giuntini[2] and B. Facchini[1]

1: Dept. of Industrial Engineering, University of Florence, Italy
2: Baker Hughes, Florence, Italy

[*] Corresponding author: sofia.galeotti@unifi.it

Abstract

The present work presents experimental measurements of heat transfer coefficient and adiabatic effectiveness distributions on a turbine vane equipped with a simplified film cooling system: a double staggered row of cylindrical holes has been tested on both pressure and suction side of the VKI LS89 profile in a linear cascade. The main purpose of this study is to investigate the effect of a second row of holes close downstream, comparing the results with the single row configuration. A thermal technique based on IR thermography has been employed and different operating conditions have been tested. Results show that the double row generally provides better performance than single row, with higher effectiveness coupled with a limited increase in HTC, except for the hole's proximity region. On the pressure side the beneficial effect of the second row is more pronounced at high BR, while on the suction side the improve in performance is lower.
Keyword: *Film cooling, Heat Transfer experiments, Adiabatic effectiveness*

1. Introduction

The accurate prediction of surface temperature is fundamental in the design of vanes cooling systems in gas turbines. Injecting film cooling to limit the heat exchange with high temperature flow alters velocity and thermal boundary layers, with significant effects on the vane external temperature. Detailed experimental measurements provide an irreplaceable support for improving the capability of numerical simulations to capture the complex heat loads distribution on the vane surface in the presence of film cooling. The present work fits in this context, providing a detailed evaluation of film cooling performance on a literature vane, the VKI LS89.

After the accurate characterization of the behavior of a single row of cylindrical holes on both pressure and suction side [1, 2], the present work investigates the effect of adding a second row at a close distance. Spatial resolved distribution of adiabatic effectiveness and HTC have been measured on both pressure (PS) and suction side (SS) of the vane with different operating conditions, varying the freestream turbulence level (Tu), and blowing ratio (BR).

2. Experimental apparatus and measurement technique

As anticipated the experimental campaign has been performed on the VKI LS89 axial turbine profile [3]. A detailed description of the adopted single vane cascade rig as well as of the geometric parameters is available in [4], where HTC measurements were performed on the uncooled vane, and will be not reported here for the sake of brevity.

The adopted technique is based on two transient thermal tests for each operating point; the temperature step is enforced on either the mainflow or the coolant flow, making use of the Dual Linear Regression Technique (DLRT), developed by Xue [5], to retrieve heat transfer coefficient, adiabatic effectiveness and mainstream recovery temperature. The description and validation can be found in [1]. Due to measurement uncertainty reasons (see [1] for details), the measurement area has been defined starting 5 diameters downstream of the cooling holes (of the second row for the double row configuration), and limited to 40 and 55 diameters downstream of the first film cooling row for PS and SS respectively.

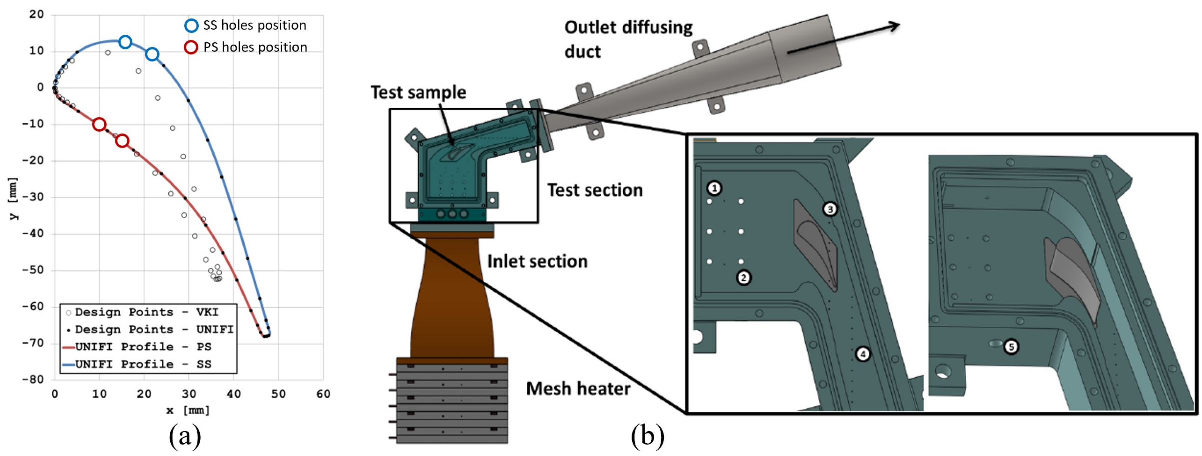

Fig. 1: Investigated NGV profile (a) and sketch of the test rig (b)

TA	Configuration	D	α	p/D	L/D	x	s
-	-	[mm]	[°]	[-]	[mm]	[mm]	[mm]
PS-1R	PS-Single row	1	30	4	10	10	-14.7
SS-1R	SS-Single row	1	60	4	7	15	22.03
PS-2R	PS-Double row	1	30	4	10	10; 13.8	-14.7; -19.7
SS-2R	SS-Double row	1	60	4	7	15 ; 18.8	22.03; 26.03

Tab. 1: Test articles geometric characteristics

3. Test articles

Four different test articles were manufactured for the experimental campaign, with a simplified film cooling system composed by a single (1R) and double row (2R) of cylindrical holes for both PS and SS. A small plenum was realized inside the vane, feeding either one or two rows of cooling holes.
The holes inclination angle is 30° and 60° for the pressure and suction side respectively. Holes diameter D=1 mm and spanwise pitch-to-diameter ratio p/D=4 is kept constant for all the test articles.
The double row has a staggered configuration for both pressure and suction side. The upstream row is composed by 11 holes, located between $h/H = 0.1$ and 0.9, and the downstream row is staggered in the spanwise direction by half a pitch and has 10 holes. The streamwise distance between the two rows is 5D on the PS and 4D on the SS. This small difference is due to the plenum shape, that would result in downstream holes not intersecting with the plenum without such a reduction. Geometrical parameters of the simplified film cooling systems are summarized in Table 1.

4. Operating conditions

Operating conditions have been selected in order to match one of the operating point tested at VKI [3], in terms of outlet isoentropic Mach and Reynolds numbers at the values of $Re_{2,is} = 1 \cdot 10^6$ and $M_{2,is} = 0.7$. It was chosen to study a case with natural turbulence (Tu=1%) and a case with high inlet freestream turbulence (Tu=15%) generated with a passive grid.
During the experimental campaign four different blowing ratios (BR) were tested on pressure and suction side, but only the results referred BR=0.5-1 will be presented here.

5. Results and discussion

The employed measurement technique allows to retrieve detailed 2D distribution of adiabatic effectiveness and heat transfer coefficient on the vane surface; still, 2D distributions are presented only for the BR=0.5 condition, taken as a significant case to show the map morphology and draw some conclusions regarding the occurring phenomena and the physics of the investigated aspects. Spanwise averaged profiles provide more quantitative comparisons, and will show also the effect of different BRs.
Throughout all the discussion, the starting point (s/D=0) of the curvilinear abscissa is positioned at the exit

of the first row of holes. Following the standard convention the sign of the curvilinear abscissa is positive for the suction side and negative for the vane pressure side. Spanwise averaged profiles are evaluated over 5 hole pitches across the midspan (h/H=0.3-0.7).

5.1. Adiabatic effectiveness

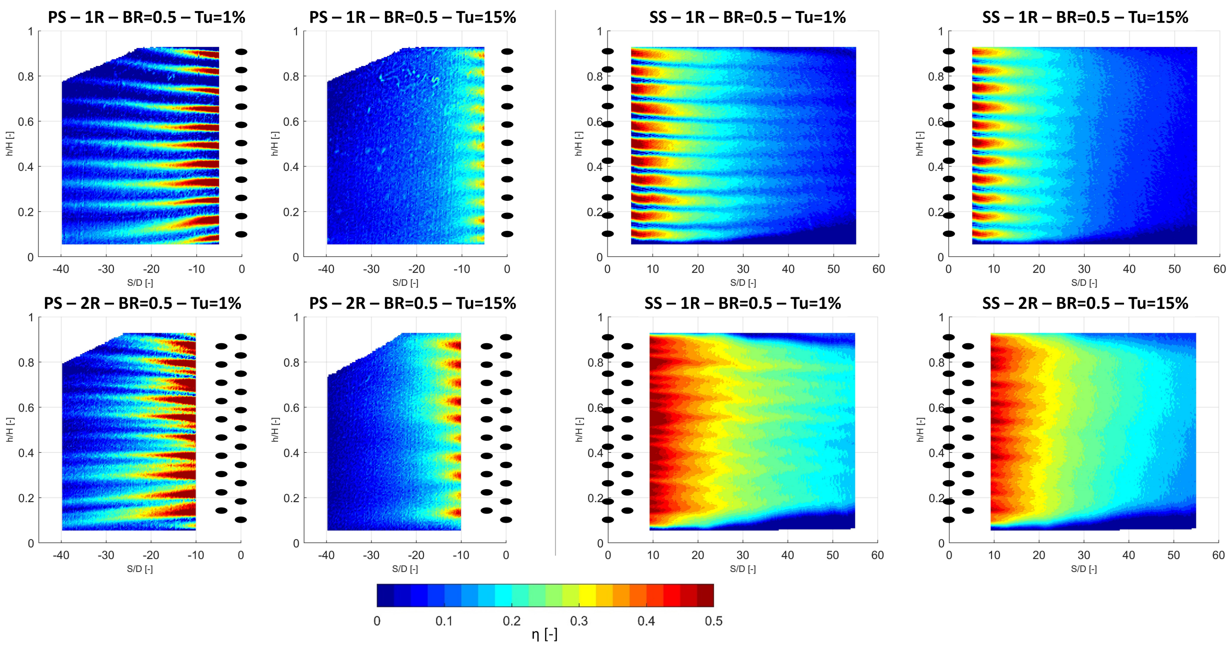

Fig. 2: Measured adiabatic effectiveness distributions on PS and SS for single and double row configuration

Adiabatic effectiveness maps are reported in Figure 2. From a general point of view, it can be seen that the pressure-to-suction pressure gradients keep coolant jets attached to the SS surface, therefore widening the coolant traces on this side; an opposite effect occurs on the PS, which shows thinner traces and reduced coverage. Turbine secondary flows, in the form of hub and tip passage vortexes, make the coolant traces converge towards the midspan for the suction side, and diverge towards the endwalls for the pressure side, according to the expected behaviour. On the PS with low inlet turbulence coolant jet traces are sharply defined, while increasing Tu enhances main-coolant mixing as well as coolant spanwise spreading, disrupting the coherent jets. As a result, adiabatic effectiveness rapidly decays moving away from the holes exit, but jet traces become larger, promoting a better coverage in the areas between the holes. On the other end the effect of freestream turbulence is much less intense on the vane SS because of the flow acceleration (i.e. reduced Tu at injection location).
Concerning the comparison between 1R and 2R, at the same BR the coolant mass flow rate is almost double for the double row configuration, obviously leading to higher effectiveness and improved covering. Limited additional differences can be recognized in terms of maps morphology.

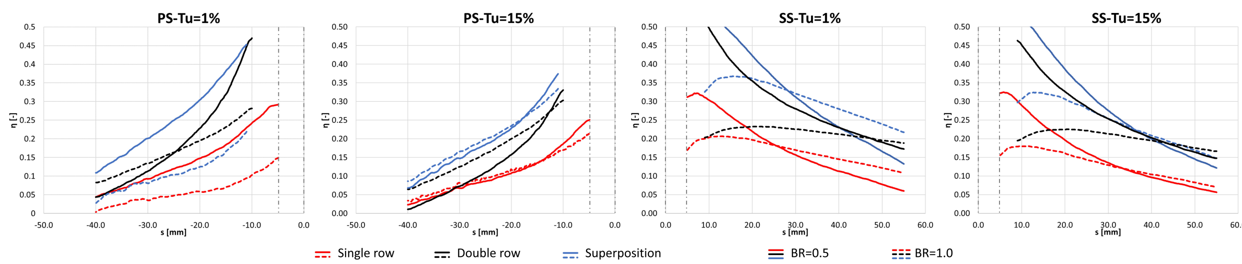

Fig. 3: Adiabatic effectiveness spanwise averaged profiles on PS and SS for single and double row configuration compared with Seller's superposition

Spanwise averaged profiles are shown in Figure 3. The double row configuration has higher effectiveness both if the comparison is made at the same BR (higher injected coolant mass flow) and if the same mass flow is considered, due to reduced jets velocity (compare 2R at BR=0.5 with 1R with BR=1). On the PS, moving from BR=0.5 to BR=1 seems to be less detrimental for the 2R configuration, than it is for 1R; limited differences can be seen, on the other hand for the SS, thus hinting to a different behaviour. Seller's superposition principle [6] can be used to provide an "expected" 2R behaviour, starting from measured 1R results, to be compared to 2R measurements. Seller's methods was developed for slot cooling and is known to present limitation when describing 3D film cooling, especially with closely spaced rows [6]; still, it can be used to draw some conclusions regarding the different behaviour between PS and SS. On the vane PS with BR=0.5 Sellers prediction overestimates measured values for both turbulence levels. At higher BR for the low turbulence case measured values exceed Seller's superposition principle, while for the higher turbulence case values are quite close. Overall the beneficial effect in terms of film coverage with the second row is amplified at high BR. This can be explained by the fact that on the vane PS with the single row at high BR adiabatic effectiveness is very low and coolant jets penetrate into the mainstream. With the addition of the second row, the upstream jets seem to help preventing jet lift off of the downstream row. At low BR coolant jets are already attached to the vane surface, and the addiction of a second row does not improve the performance in this regard. On the other hand, on the vane SS jets are attached also at high BR, and Sellers superposition generally overestimates measured values, indicating a less beneficial effect of addition of second row than on the PS.

5.2. Heat Transfer Coefficient

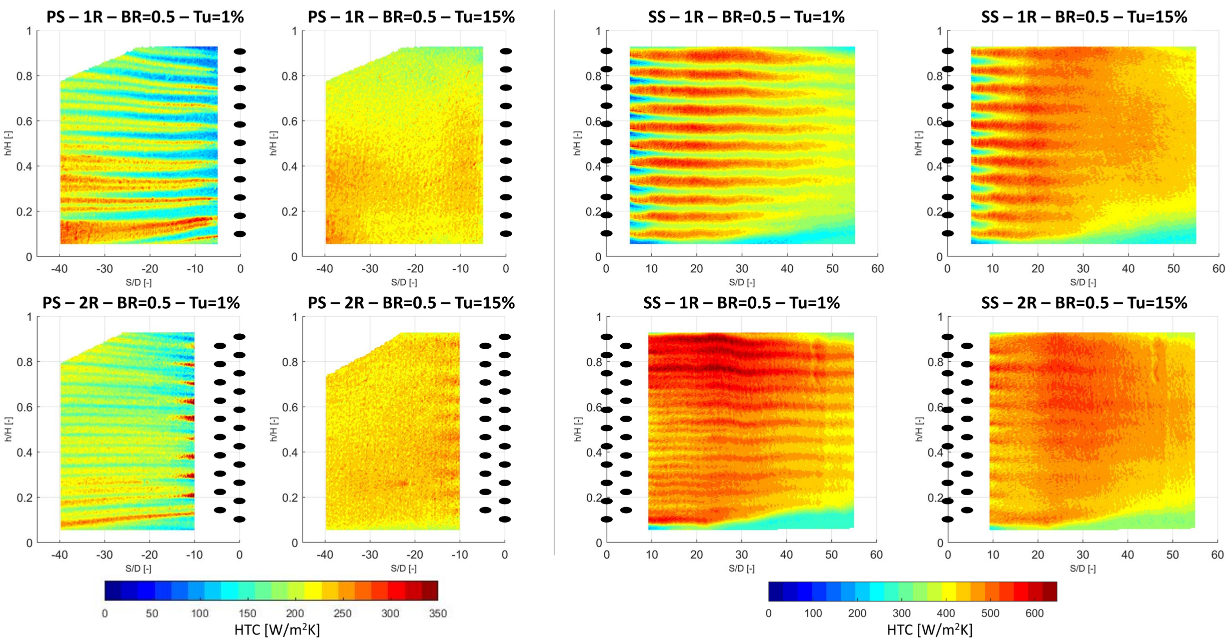

Fig. 4: Measured HTC distributions on PS and SS for single and double row configuration

Figure 4 presents the measured HTC distributions. At Tu=1% areas of higher HTC corresponding to coolant wakes are sharply defined on both PS and SS, and visible up the end of the measurement area in the streamwise direction. On the vane PS a double trace is visible, which corresponds to the Counter Rotating Vortex Pair (CRVP), causing HTC augmentation. This phenomenon can be observed for the low turbulence case at all BRs (not reported), for both single and double row configuration. On the SS the double trace is not visible, as the PS-to-SS pressure gradients pushing the coolant traces towards the suction surface are suppressing, or at least strongly weakening, the CRVPs; wider effectiveness traces were coherently measured on this surface. Increasing inlet turbulence maps are significantly more uniform, and jet traces are smoothed out and HTC increases, with limited effect on the SS as seen for effectiveness.

For a quantitative comparison Figure 5 presents the HTC span averaged profiles together with the uncooled smooth vane profile. Predictions from Kays and Crawford correlation [7] are also reported for the low turbulence cases, computed for laminar and turbulent boundary layer over a flat plate. For the low turbulence case

on both PS and SS the non-cooled profile shows a slightly decreasing trend, due to the progressive development of the laminar boundary layer, which shows a good matching to the laminar correlation predictions. For the high turbulence condition HTC on the PS is almost constant, while boundary layer turbulent transition can be detected on the SS around s/D=25 with a strong HTC increase.
On the PS at low turbulence with film cooling injection HTC increases significantly with respect to the uncooled case, and even if the slope and values do not reach the ones expected from a turbulent case (see turbulent correlation), and the occurrence of boundary layer transition is hard to assess, it is clear that the coolant structures prevent a laminar layer to fully develop. Exception is made for 1R-BR=1, since values remain quite low, as the coolant lifts-off and marginally interact with the boundary layer downstream. With the double row configuration HTC increases with respect to the single row, even more if the conditions with similar coolant flow rate are compared (1R-BR=1.0 and 2R-BR=0.5), as jet are well attached on the vane surface at low BR. The effect of BR remains coherent also with the double row configuration, with higher HTC values at low BR, but the difference is reduced, as jet penetration is limited by the upstream row (i.e. significant increase also at BR=1).
On the vane SS near the holes exit HTC values for the double row are higher than the corresponding case with single row, especially at higher BR, since the injected coolant flow increases and the effect is amplified for higher BR. In the downstream turbulence region instead values are closer and similar to the turbulent correlation, indicating that the higher boundary layer perturbance is limited to the region near the holes exit. Similar considerations can be made for the higher turbulence case, with even more limited differences between 1R and 2R. The effect of turbulence (comparing adjacent plots) for the double row is lower than with the single row, as the injection of higher coolant mass flow rate, makes local boundary layer conditions to be determined more by coolant injection and the resulting main-coolant interaction and mixing, and less by the freestream turbulence.

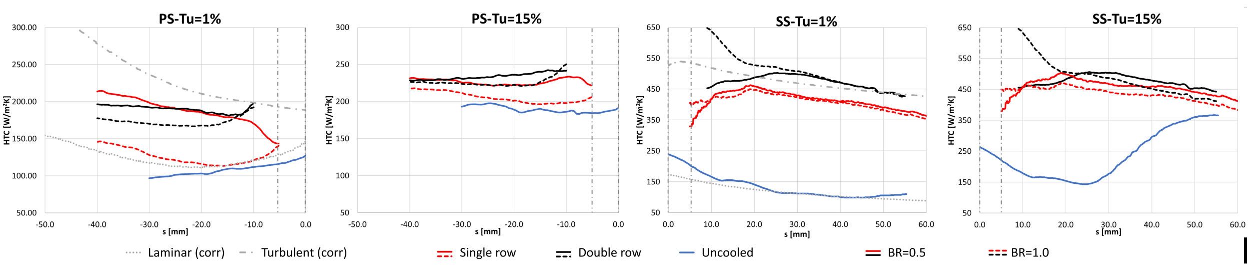

Fig. 5: HTC spanwise averaged profiles on PS and SS for single, double row and uncooled configuration. Kays and Crawford correlation [7] reported for PS.

To quantify the impact of film cooling on the vane HTC, results of the 2R configuration have been scaled by the local value measured on the uncooled smooth vane for the same inlet turbulence condition (HTC_0), obtaining profiles of Figure 6a-b. Scaled HTC is generally lower for higher freestream turbulence, as the marginal increase in heat transfer induced by the turbulence level is more intense for the uncooled case. For the low turbulence case on the PS HTC increases by a factor up to 2 inside the investigated area. Higher values are reached on the SS, where the uncooled case remains laminar, while film cooling injection triggers the boundary layer transition (see in Fig. 5 comparison with correlations).
The adopted scaling profiles have a significant effect on the evaluation of the film-induced HTC enhancement, especially on the vane SS where transition effects are crucial, HTC has been scaled also with measurements performed without coolant injection but with the holes exposed (HTC_0^*), with the results shown in Figure 6c-d. On the vane SS the different scaling leads to significantly lower values, as the exposed holes act as turbulence promoter and induce the boundary layer turbulent transition. At low BR coolant injection does not further increase HTC, while with higher BR near the holes exit the disturbance is amplified. In the downstream region profiles reaches an asymptotic value around unity, as he turbulent boundary layer develops and stabilizes similarly with and without coolant injection. On the vane PS the different scaling has a lower effect, and values are comparable with the HTC scaled with the smooth blade, even if with a different trend, as the HTC_0^* profile (not reported) is slightly increasing due to the effect of the unfed holes on the boundary layer. In general $\frac{HTC}{HTC_0^*}$ slightly decreases with higher inlet turbulence: since coolant injection

strongly contributes in the boundary layer alteration, the marginal increase is higher for the case without injection.

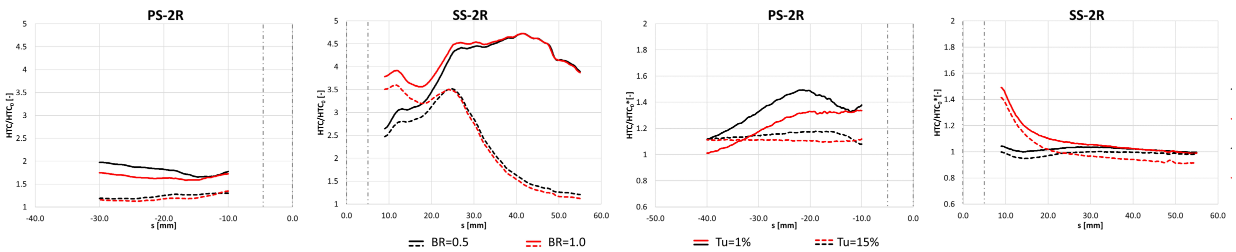

Fig. 6: Scaled HTC spanwise averaged profiles on PS and SS for double row configuration

6. Conclusions

Experimental results showed that the addition of a second row of film cooling holes leads to a major increase in coolant coverage, as expected, associated with a limited HTC increase. Noteworthy, this effect can be significantly different on the different surfaces (PS/SS) and flow conditions (BR). In particular, this beneficial effect is significant on the vane PS at high BR, where the presence of the upstream row seems to help the coolant jet to stay attached to the vane surface even for high BRs, while at low BR and on the vane SS coolant jets are already attached and the advantage offered by the double row is lower.
In addition to the above mentioned aspects, the collected results are also intended to constitute a wide database for the validation of numerical approaches, aimed at the study of film-cooling performance, in a world-known and challenging environment, like the LS89 profile.

7. Acknowledgments

Baker Hughes is thankfully acknowledged for the possibility to publish the results and for partially founding the research. The publication was made with the contribution of the researcher Tommaso Bacci with a research contract co-funded by the European Union - PON Research and Innovation 2014-2020 in accordance with Article 24, paragraph 3a), of Law No. 240 of December 30, 2010, as amended, and Ministerial Decree No. 1062 of August 10, 2021.

References

[1] T. Bacci et al. “Heat Transfer Coefficient and Adiabatic Effectiveness on a Film-Cooled Pressure Side: Results and Assessment of the IR-Based Measurement Technique Reliability”. In: *ASME Conference Proceedings* GT2022-81161 (2022).

[2] S. Galeotti et al. “Heat Transfer Coefficient and Adiabatic Effectiveness Measurements on a Nozzle Guide Vane With a Single Row of Cylindrical Holes”. In: *Journal of Turbomachinery* 146.5 (Jan. 2024), p. 051010. ISSN: 0889-504X. DOI: 10.1115/1.4064315.

[3] T. Arts and M.L. Lambert de Rouvroit. “Aero-Thermal Performance of a Two-Dimensional Highly Loaded Transonic Turbine Nozzle Guide Vane: A Test Case for Inviscid and Viscous Flow Computations”. In: *ASME J. Turbomach.* 114 (1992), p. 147.

[4] T. Bacci et al. “Effect of Surface Roughness and Inlet Turbulence Intensity on a Turbine Nozzle Guide Vane External Heat Transfer: Experimental Investigation on a Literature Test Case”. In: *ASME J. Turbomach.* 143 (2021), pp. 041006-1–12.

[5] S. Xue et al. “A Novel Transient Technique to Determine Recovery Temperature, Heat Transfer Coefficient, and Film Cooling Effectiveness Simultaneously in a Transonic Turbine Cascade”. In: *ASME J. Turbomach.* 7 (2015), pp. 011016-1–10.

[6] J. P. Sellers. “Gaseous Film Cooling with Multiple Injection Stations”. In: *AIAA Journal* 1.9 (Sept. 1963), pp. 2154–2156. DOI: 10.2514/3.2014.

[7] W.M. Kays and M.E. Crawford. *Convective Heat and Mass Transfer*. Ed. by New York McGraw Hill. 1993.