

STEADY CFD SIMULATIONS OF TRAILING EDGE FILM COOLING IN A LINEAR NOZZLE VANE CASCADE

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ABSTRACT

The present study concentrates on a cooled trailing edge in a linear cascade of high-pressure turbine nozzle guide vanes. The pressure side cooling features two rows of cooling holes followed by a trailing edge cutback with film cooling slots, stiffened by evenly spaced ribs in an inline configuration. The present study evaluates the reliability of steady RANS predictions in such a complex cooling system. Coolant-to-mainstream mass flow ratio values in the range of 1% to 2.8% were simulated at exit Mach number of $M_{2is} = 0.2$. The computed performance of the trailing edge cooling scheme was compared to aerodynamic and thermal measurements, with the aim of understanding the coolant-mainstream interaction at the cutback slot exit. Despite the well-known limitations of the steady framework in simulating film cooling effectiveness, the modeling provided reasonable predictions of the discharge behavior of both cutback slot and cooling holes.

NOMENCLATURE

c	blade chord	U	velocity
D	hole diameter	$VR = U_c/U_e$	velocity ratio
H	vane height	X, Y, Z	cascade coordinate system
l	length scale	α	injection angle
m	mass flow rate	β	flow angle (tang. direction)
M	Mach number	η	film cooling effectiveness
$MFR = m_c/m_e$	overall coolant to mainstream mass flow ratio	Subscripts	
n	direction normal to the wall	1	inlet
$Re_{2,is} = U_{2,is}c/\nu$	isentropic outlet Reynolds number	2	exit
s	vane pitch	ax	in axial direction
Tu	turbulence intensity level	aw	adiabatic
		c	cooling flow
		e	free stream
		is	isentropic condition

INTRODUCTION

In the last years Bergamo University has been involved, together with other Italian Universities, in a National Research Project (PRIN 2007) entitled "Trailing edge cooling concepts of high temperature gas turbine blades". Bergamo University task was focused on the experimental and numerical analysis of a nozzle vane cooling configuration with a pressure side trailing edge cutback preceded by two cooling rows. Various papers have already been published on findings from the experimental activity. Here measurements at low speed from Barigozzi et al. (2012) are used to validate the computational fluid dynamics (CFD) modeling of the vane cascade with trailing edge cutback film cooling.

In the technical literature, studies dealing precisely with the pressure side cutback on a cascade model are not as numerous as expected. Comprehensive experimental investigations, facing both thermal and aerodynamic aspects, were carried out by a very few authors: Ames et al. (2007a and

b), Fiala et al. (2010a and b). Some others focused on the influence of cutback geometry and main flow conditions either on specific aerodynamic aspects (Uzol and Camci (2001); Montis et al. (2009)) or thermal features (Dannhauer (2009)). The trailing edge cutback was also deeply investigated on simplified models, with or without the presence of an accelerating mainstream. In these cases, measured data were occasionally compared against CFD predictions.

Holloway et al. (2002a and b) combined both experiments and computations to investigate pressure-side bleed on a trailing edge model, at realistic mainstream conditions ($M = 0.7$ at the coolant injection point). Blowing ratio was varied between 0.5 and 2.0. 3D simulations were run according with the steady and unsteady method. At all blowing ratios the measured adiabatic film cooling effectiveness η monotonically decreased at increasing distance from the cutback slot while stayed almost constant for the steady computations. Moreover the steady simulated values of η were greater than the experimental results. The key mechanism that caused the unexplained η measurements was revealed by the unsteady modeling. The coolant on the cutback surface was found to depend on vortex shedding off from the coolant and the passage side of the cutback lip.

Experimental tests and steady RANS simulations were also performed by Martini et al. (2003a and b) to evaluate cutback surface film cooling effectiveness together with slot discharge coefficients in a trailing edge model with a double in-line rib array. Different blowing ratio values ranging from 0.35 to 1.1 were tested into an atmospheric hot wind tunnel; the mainstream velocity was around 45 m/s. The discharge coefficients were measured to be in the range of 0.65. They were found to be over predicted by about 10% by CFD simulations. The numerical results on η showed significant deviations to the measurements on the cutback surface: quantitative differences in the range of 0.1 to 0.3 were observed, leading to overprediction of the coolant coverage, particularly close to the trailing edge. In a subsequent paper Martini et al. (2005) applied the unsteady detached eddy simulations (DES) to the same trailing edge model. DES were found to overcome the limitations of the steady approach: the simulated adiabatic film cooling effectiveness showed good agreement with experiments, indicating that the unsteady mixing process between coolant and hot gas is captured more realistically. However, steady computations with respect to discharge coefficients and heat transfer coefficients performed quite well. The role of unsteadiness in trailing edge cooling flows was examined also by Medic and Durbin (2005). They performed Reynolds averaged simulations for a surface jet in co-flow, resembling the geometry of a pressure side cutback. Once again steady simulations showed very effective cooling; however adiabatic effectiveness on the cutback surface decreased substantially when unsteadiness was allowed.

Recently Schneider et al. (2010 and 2011) reported on Large Eddy Simulations of Martini's trailing edge model, without land extensions and internal cooling design. They assessed that changing either the blowing ratio or the flow regime of the coolant can affect the large coherent structures which are periodically shed at the cutback lip and, consequently, the mixing process.

There are, to the authors' knowledge, no numerical studies on trailing edge film cooling with pressure side cutback and cooling holes, in cascade arrangement. This is the original contribution of the present paper. Steady computations have been carried out by means of the commercial code Fluent v13. The RNG $k\epsilon$ turbulence model was chosen to provide closure. Predictive capabilities were assessed in comparison with measurements of vane loading, coolant-to-mainstream velocity ratios, boundary layers in the cutback region and adiabatic film cooling effectiveness, for different MFR values up to 2.8%.

VANE GEOMETRY AND OPERATING CONDITIONS

The object of this investigation is a high loading profile (Zweifel coefficient of 1.18) typical of a first stage nozzle guide vane of a modern heavy duty GT. Details of the cooled vane geometry are reported in Fig. 1. The vane profile is characterized by a pitch to chord ratio of 1.04 and an aspect ratio of 0.69. The flow turning angle at design point is 73.5° . The pressure side is equipped with two staggered rows of cylindrical holes and a trailing edge cutback. The 1st row is composed of 23 cooling holes and it is located at $X/c_{ax} = 0.52$. The 2nd row is composed of 24 holes and it is located

at $X/c_{ax} = 0.64$. Within each row, the hole-to-hole pitch is $2.76D$ and the hole length is $4.9D$. The diameter of the cooling holes D is 1.05 mm. The holes are angled at 30° to the surface. Holes and cutback are spread over 70% of the blade height. The cutback starts at $X/c_{ax} = 72\%$. It consists of eight equally spaced rectangular slots. An arrangement of rib arrays was adopted (Fig. 1) in order to increase the stiffness of the thin trailing edge and to enhance the internal heat transfer.

Measurements used for validation were obtained by testing a 6-vane linear cascade in the low speed wind tunnel available at the Turbomachinery Laboratory of Bergamo University. The focus of this study is on data collected at low speed ($M_{2is} = 0.2$, $Re_{2is} = 6.5 \cdot 10^5$) and low inlet turbulence intensity ($Tu_I = 1.6\%$). Experimental data used for validation consisted in the following:

- solid vane loading measured by means of instrumented vanes;
- boundary layer velocity profiles close to the pressure side trailing edge, at $X/c_{ax} = 0.92$, measured using a 2D LDV system. Measurement uncertainty in mean velocity component from LDV data was about $\pm 0.3\%$;
- adiabatic film cooling effectiveness distributions downstream of the holes and on the cutback surface, measured by means of ThermoChromic Liquid Crystals. Uncertainty in measured η ranged from $\pm 4.2\%$ with $\eta = 0.8$, up to about $\pm 15\%$ when $\eta = 0.1$.

COMPUTATIONAL METHODOLOGY

The 3D computational domain included the coolant plenum and the trailing edge cutback with full details of its geometry, the coolant channels arranged into two staggered rows and the vane passage. With the aim of reducing the computation effort, only a portion of the airfoil was simulated. Since the injection of the coolant was aligned with the z axis and normal to the mainstream flow, periodicity could not be applied in the spanwise direction. So one cutback slot (span equals to $8D$) was modeled. Symmetry planes at the mid-planes of the 1st row - jet were set to simulate a section of the vane passage including two cutback slots (Fig. 2). No slip walls were set at both end walls. This procedure was based on the assumption that the coolant cavity in the real airfoil is uniformly filled so that the central slots are fed quite homogeneously from opposite sides. The effects of blockage and secondary flow due to the side walls were confined to a small region. The total pressure contours in the span wise direction, at locations approaching and just downstream the trailing edge, changed no more than 0.7% over the whole span. Moreover the vane loading remained unchanged for at least half of the span. Given these results, it was determined that no less than one slot needed to be included in the computational domain to still capture the physics of the coolant exiting the plenum to the external pressure side of the vane.

Periodicity conditions in the tangential direction were applied to simulate multiple vane passages in a linear arrangement. The inlet of the passage was located $1.6 c_{ax}$ upstream of the vane leading edge, where freestream velocity and turbulence measurements were available from experiments. The outlet was located well downstream. The boundary conditions prescribed constant velocity inlet for the mainstream (20.7 m/s) and static pressure at the outlet (97200 Pa), in order to assure M_{2is} of 0.2. The freestream turbulence intensity and dissipation length scale were 1.62% and 10.4 mm, respectively (Barigozzi and Ravelli (2010)). For the injection of the coolant into the plenum, a mass flow inlet condition was specified. The coolant mass flow rate was varied to match the *MFR* of 1%, 2% and 2.8%. The coolant turbulence intensity was not measured but computed according to the following:

$$Tu_c = 0.16 Re^{-1/8} \quad (1)$$

This is derived from an empirical correlation for the core of a fully-developed duct flow. Coherently with this hypothesis, the length scale for the coolant was computed by

$$l_c = 0.07D_{in} \quad (2)$$

where D_{in} is the diameter of the coolant inlet (Fluent user guide). Air properties were set to be temperature dependent. Adiabatic conditions were applied to solid surfaces. The steady state

simulations were performed using Fluent v13. The solutions were obtained by solving the incompressible RANS equations. The RNG $k\epsilon$ model with enhanced wall treatment was chosen to provide closure in view of future modeling of high velocity flows. Actually, the RNG $k\epsilon$ model was proven to work well for transonic flows (Holloway et al., 2002). All equations were discretized with second-order accuracy.

A multi-block unstructured and adaptive grid was made in POINTWISE by Pointwise, Inc. Progressive refinements (from a mesh size of $6.7 \cdot 10^6$) in the wake region, inside the coolant channel and around the vane were achieved through mesh adaption based upon y^+ values and total pressure gradient. After adaption a grid made up of $9.8 \cdot 10^6$ cells was considered to be sufficient for computations: y^+ was less than 5 near the walls, except in an upper portion of the vane suction side where the maximum y^+ was around 10. Verification that further refinements did not change the solution was based on surface temperature values at some locations on the pressure side of the vane.

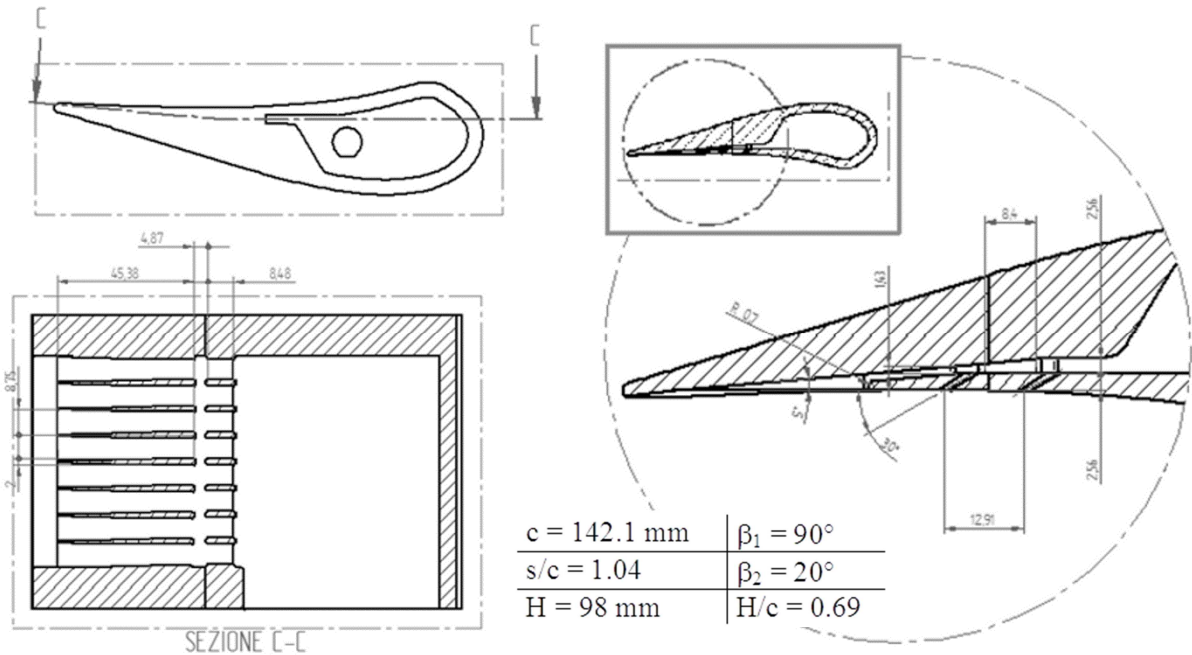


Fig. 1: Trailing edge cooling geometry (dimensions in mm).

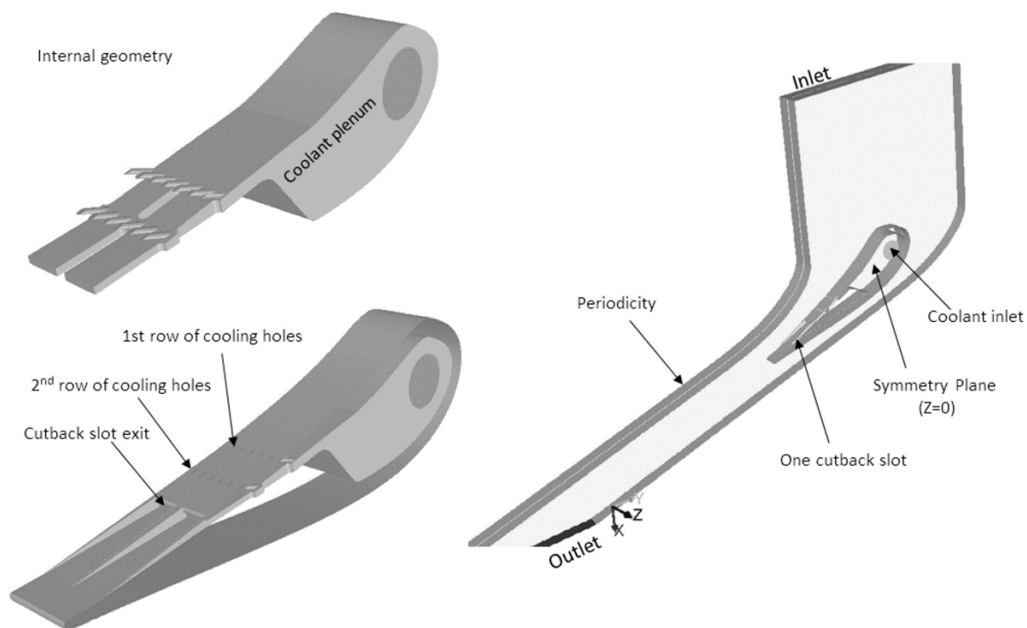


Fig. 2: Computational domain and boundary conditions.

Convergence of a simulation was determined through: residuals level off at values lower than 10^{-5} with the exception of the energy equation which was set to a level of 10^{-8} ; the local temperature over the cutback surface changed no more than 0.0006% for at least 200 iterations.

RESULTS AND DISCUSSION

Low speed measured and computed data on the cooled vane were compared in a steady framework for different MFR values. Features of the mainstream and coolant flow were examined together with the surface effectiveness contours. This in order to validate the steady predictions of the trailing edge cooling scheme performance.

Vane loading

Experimental and numerical M_{is} profile distributions, normalized by the M_{is} value at the trailing edge, are shown in Fig. 3 for the solid and the cooled vane, by varying injection conditions. Since a very good agreement between the measured and the numerical vane load was found for the solid vane (Barigozzi and Ravelli (2011)), the simulations were supposed to provide reliable loading information even for the cooled vane. In this case, no load measurements are available. The cooled vane velocity distributions are almost the same, whatever the MFR . However, some differences can be noticed between the solid and the cooled vane loading. The coolant injection is responsible for a slight reduction of the velocity maximum on the suction side of the profile, between $0.2 c_{ax}$ and $0.6 c_{ax}$. This was confirmed by measurements reported in Puddu et al. (2011). On the pressure side, the effects of the coolant injection on the loading are clearly evident: the spike at $X/c_{ax} = 0.52$ reveals the outgoing coolant from the 1st row of holes while the minor discontinuities at $X/c_{ax} = 0.64$ and $X/c_{ax} = 0.72$ identify the position of the 2nd row of holes and the cutback slot, respectively. Moreover, the cooled vane load shows lower M_{is} values than the solid one in the region extending from the cutback slot up to the trailing edge ($X/c_{ax} > 0.72$). A reason for this can be the different vane profile geometry imposed by the presence of the cutback, as suggested by Puddu et al. (2011). It is interesting to note that similar conclusions were drawn by Montis et al. (2009b) from their investigation of trailing edge bleeding in linear nozzle vane cascade at high speed. They found that the trailing edge blowing is responsible for the increase in the static pressure at the trailing edge, and the reduction in the maximum M_{is} , compared to the case without coolant ejection.

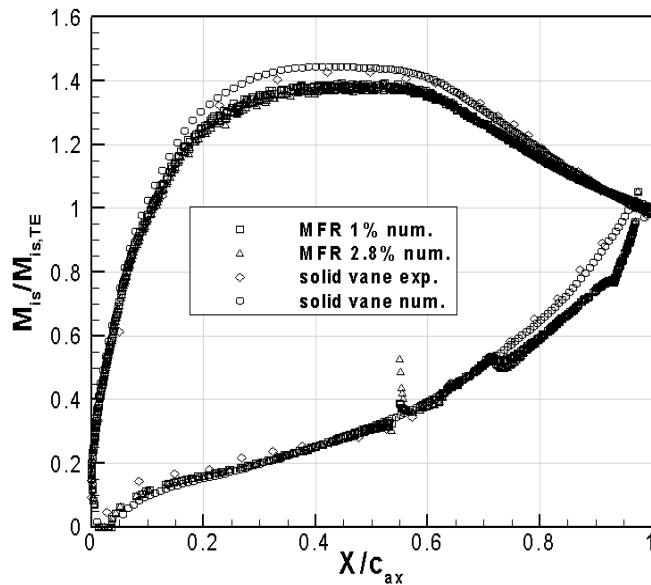


Fig. 3. Normalized profile M_{is} distributions for the solid and cooled vane ($MFR = 1\%$ and 2.8% , $Z=0$).

Cooling system characterization

The coolant flow rates exiting the holes and the cutback were divided by the coolant flow rate entering the plenum ($m_{c,tot}$), thus obtaining results of Fig. 4. The simulations are in good agreement to the experimental results. The measured trend towards increasing coolant flow exiting the holes with increasing MFR up to about 2% is correctly computed, as well as the plateau at $MFR > 2\%$. However, the coolant discharged through the holes was slightly under-predicted whatever the MFR . It should also be noted that the discrepancies between the experimental and the simulated coolant distribution between cutback and holes decrease while increasing the MFR . This can be partially explained considering that low MFR measurements can be affected by high level of uncertainty.

The interaction of the outgoing coolant from holes and cutback with the mainstream was documented in terms of velocity ratio VR . Results of Fig. 5 are plotted versus the MFR . Holes and cutback coolant exit velocity were calculated and compared to the corresponding free stream velocity values, both experimentally and numerically. In the former case they were computed assuming an even sharing between all holes belonging to both rows. The mainstream velocity at holes/cutback location was derived from the profile pressure distribution, assuming that coolant injection does not significantly alter the solid vane load profile. In the latter case holes and cutback exit velocity were directly available from the simulations as mass weighted average values over the holes and slot surface. The computed VR values show the same trend as the experimental data. The variation of VR as a function of the injection conditions is predicted quite accurately for the cutback, however with an overestimation by about 10% at $MFR > 1\%$. Simulations performed reasonably well also for the 2nd row of holes, at least at $MFR > 1\%$. Conversely, the simulated VR values for the 1st row of holes are largely overestimated. The differences between measured and predicted data are tremendous at the lowest MFR (0.05 vs. 0.39) while become acceptable at the highest MFR (1.78 vs. 2.02). The reason for this difference can be related to the assumption of an even mass flow sharing among holes in the calculation of VR values from experiments: CFD simulations instead show that a larger amount of coolant is discharged by the 1st row, as compared to the 2nd one. This result has been confirmed by LDV measurements performed by the authors at near hole exit locations.

In addition, the computed and measured values of the total pressure in the coolant plenum were found to be very similar for all MFR values. This, combined with reasonable predictions of the static pressure at the exit of cooling holes and cutback slots, gave the confidence that the coolant flow ejection is well reproduced in the simulations.

The physical mechanisms of the mixing between the accelerating mainstream and the coolant flow exiting the cutback slot were assessed by means of boundary layer measurements at $X/c_{ax} = 0.92$ (see Fig. 1), on a traverse located in the center of the slot. Results were reported in terms of mean velocity U divided by the local free stream velocity U_e . The simulated boundary layer at the MFR of 1% and 2% are very similar to the experimental measurements (Fig. 6). This means that the computations can correctly predict the boundary layer re-energization due to the coolant ejection. However, at the highest MFR of 2.8%, the over-speed, i.e. $U/U_e > 1$, which is measured at a distance from the wall ranging from 0.5 to 1.5 mm, is overestimated both in extension and intensity.

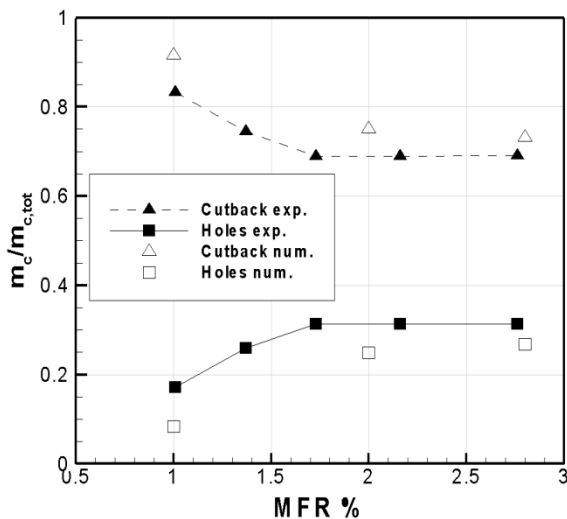


Fig. 4. Predicted and measured coolant flow distribution between cutback and holes.

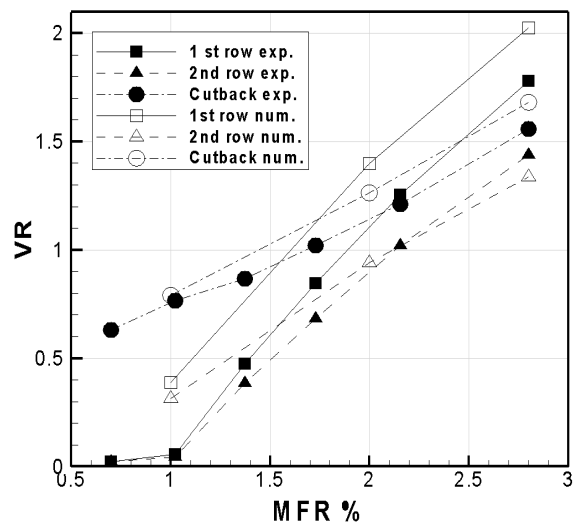


Fig. 5. Predicted and measured velocity ratio VR for holes and cutback slot.

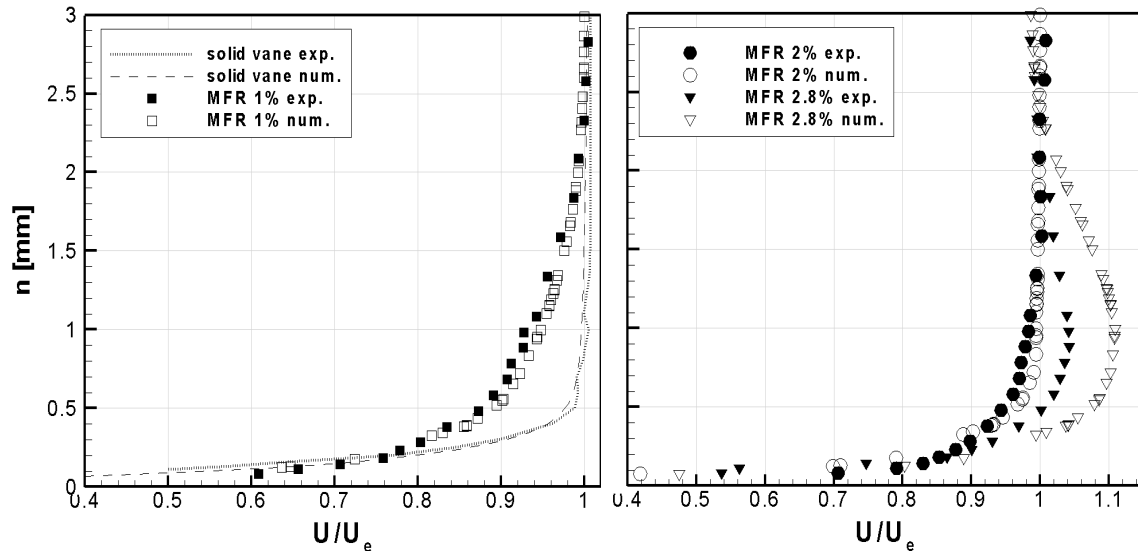


Fig. 6. Pressure side predicted and measured boundary layer traverses at $X/c_{ax} = 0.92$, in the center of the cutback slot, for the solid and the cooled vane, at $MFR = 1\%$, 2% and 2.8% .

This is consistent with the computed VR value for the cutback slot which is also higher than measurements for the $MFR = 2.8\%$ case. Data for the solid vane are here reported for reference: they show a very good correspondence between computational results and experiments.

Adiabatic film cooling effectiveness

The performance of the cooling scheme was evaluated by examining surface adiabatic effectiveness on the vane pressure side, in the region extending from the 1st row of cooling holes up to the trailing edge. The spatial distributions of η predicted with CFD simulations and measured experimentally are compared in Fig. 7 for different injection conditions. At a first glance, the general pattern of the η contours are similar for predictions and experiments, at all MFR values. In fact some trends can be qualitatively observed both in the computed and the measured contour plots: the cooling efficiency downstream of the cutback is promoted by increase in MFR ; conversely, the effectiveness downstream of the 1st row of holes is reduced with increasing MFR ; moreover, the thermal coverage just downstream of the 2nd row of holes is higher at MFR of 2% , as compared to the $MFR = 2.8\%$ case. However, there are distinct differences in some locations. At the exit of the cutback, the computations yield η values near 1, for all MFR , whereas experiments do not show area with a perfect coolant coverage. The overestimation of η levels becomes more and more significant with increasing distance from the slot exit. For the experiments, η gets the peak approximately close to the slot exit, then moving downstream, it starts to decrease up to the trailing edge while it stays almost constant at a very high level for the computations. The largest difference between computational and experimental η values can be detected approaching the trailing edge, at the lowest MFR . The modeling is not able to capture the degeneration of film cooling effectiveness along the streamwise direction for the selected MFR values. This is surely attributed to the unsteadiness that exists in the experiment, which is not being computationally modeled. Holloway et al. (2002a) stated that the hot mainstream and the coolant vortices cannot shed in a steady simulation, therefore the test surface does not experience the periodic hot and cold temperatures that exist in the experiment. When unsteadiness is included in the modeling, the correct trend in effectiveness over the cutback surface is produced (Holloway et al. (2002b), Martini et al. (2005), Medic and Durbin (2005)).

A general over prediction of the cooling effectiveness is also visible on the vane surface downstream the cooling holes, whatever the MFR . In particular the computed η values are much higher than the measured ones on the surface downstream of the 1st row, at $MFR = 1\%$. In this case,

the experiment showed traces of coolant while the simulation showed $\eta > 0.5$ at the exit of the holes. Such high predicted values of η can be explained by looking at the cooling jet on the symmetry plane (Fig 8a). Nevertheless the mainstream blockage effect, the coolant exits the hole from the front edge and stays attached to the vane surface. This discharge behavior is expected to change with increasing MFR . At $MFR = 2.8\%$ the simulations predicted the separation of the coolant jet exiting the 1st row (Fig. 8b): this is consistent with experiments which indicate jet lift-off for $MFR > 2\%$. Anyways, CFD seems to overpredict the jet vertical spreading, as no coolant traces are detected in the experiments for these injection conditions. For the 2nd row, measurements of η and VR suggested that the coolant is detached from the surface at $MFR > 2.2\%$. Coherently a higher thermal coverage was computed downstream the 2nd row at $MFR = 2\%$, as compared to the $MFR = 2.8\%$ case, but again the simulated η levels were overestimated, especially at the highest blowing condition.

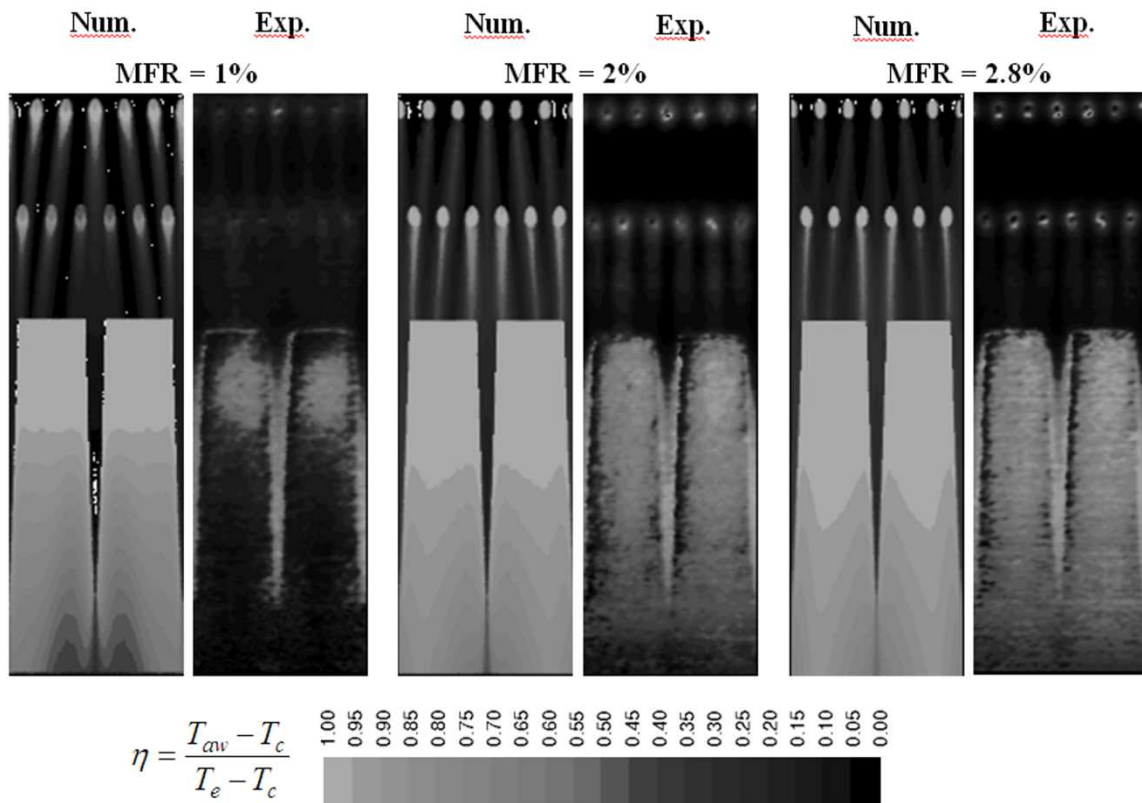


Fig. 7. Contours of simulated and measured η at $MFR = 1\%$, 2% and 2.8% .

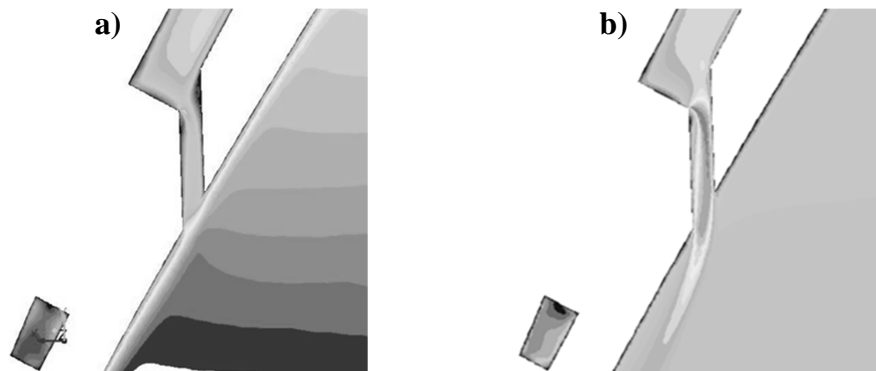


Fig. 8. Qualitative plots of the coolant jet exiting the 1st row on the symmetry plane ($Z=0$), at $MFR = 1\%$ (a) and $MFR = 2.8\%$ (b).

Finally, taking inspiration from Holloway et al. (2002a) the vortices behind the cutback lip are shown in Fig. 9. At $MFR = 1\%$ the coolant and the mainstream side vortex are almost equal in intensity. With increasing MFR up to 2.8%, the coolant velocity at the slot exit is increased. So a larger amount of the main flow is entrained into the wake behind the lip allowing the mainstream side vortex to grow at the expense of the coolant side vortex. Because of the steady approach, these vortices do not shed and their contribution to increasing the film mixing is totally missed.

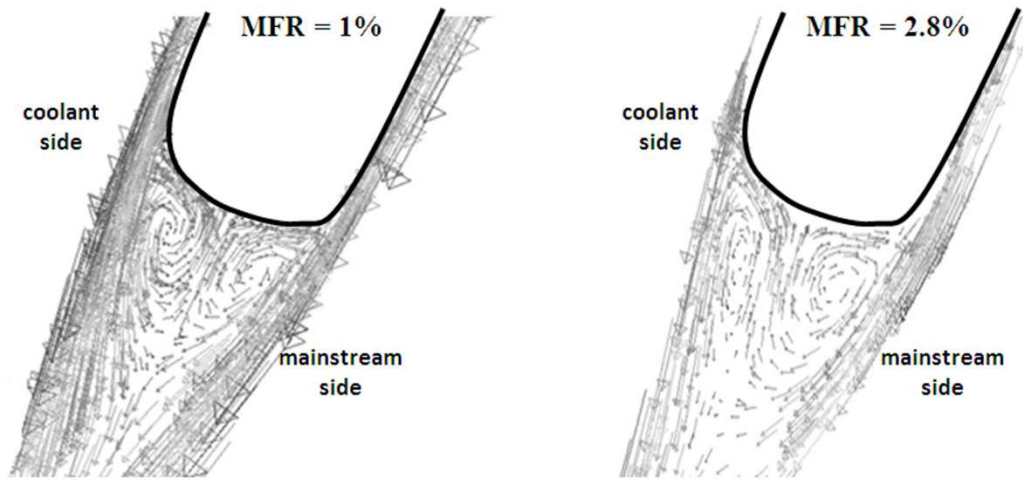


Fig. 9. Qualitative plots of the velocity vectors on the symmetry plane ($Z=0$) at the cutback lip, for $MFR = 1\%$ and $MFR = 2.8\%$.

CONCLUSIONS

This study examined numerically the problem of trailing edge film cooling on a high pressure turbine vane in a linear cascade. The cooling scheme featured a pressure side cutback, together with two rows of cooling holes. Low speed conditions were investigated ($M_{2is} = 0.2$) by varying coolant flow rate up to $MFR = 2.8\%$. Thermal and aerodynamic measurements were used for validation. The computed coolant flow distribution between cutback and holes was in fair agreement with experiments even though the amount of coolant exiting the holes was slightly under-estimated, whatever the MFR . The computed VR as a function of the injection conditions for cutback slot and cooling holes showed the same trend as the experimental data. Moreover, CFD simulations allowed to evaluate the mass flow sharing between the two rows of holes not available from experiments, thus giving a better estimation of VR values, especially at the lowest MFR . The coolant interaction with the mainstream was investigated on a traverse located in the center of the cutback slot, just upstream of the trailing edge. The mechanisms of boundary layer re-energization because of cutback bleeding was captured by the modeling and somehow amplified at the highest MFR .

Consistently with published literature, the steady approach failed in simulating the adiabatic film cooling effectiveness on the cutback region and along the path of the coolant jets exiting the holes. For all MFR , predicted values of adiabatic effectiveness were distinctly higher than measured values at the slot exit. Moreover a less strong decrease of cooling effectiveness was computed in the stream-wise direction, thus leading to a significant overestimation of the thermal coverage at the trailing edge. In addition the simulations did not predict as much coolant jet separation as actually occurs at the exit of the cooling holes.

In conclusion two main issues should be addressed to improve predictions. First, unsteady simulations are needed to capture the mixing process in the near slot region which is mainly affected by turbulent wake flow instabilities, from the cutback lip or the turbulators. Secondly, turbulence modeling should account for anisotropy.

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