International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:5, 2016

The Influence of Step and Fillet Shape on Nozzle Endwall Heat Transfer

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Abstract**—**There is a gap at combustor-turbine interface where leakage flow comes out to prevent hot gas ingestion into the gas turbine nozzle platform. The leakage flow protects the nozzle endwall surface from the hot gas coming from combustor exit. For controlling flow's stream, the gap's geometry is transformed by changing fillet radius size. During the operation, step configuration is occurred that was unintended between combustor-turbine platform interface caused by thermal expansion or mismatched assembly. In this study, CFD simulations were performed to investigate the effect of the fillet and step on heat transfer and film cooling effectiveness on the nozzle platform. The Reynolds-averaged Navier-stokes equation was solved with turbulence model, SST k-omega. With the fillet configuration, predicted film cooling effectiveness results indicated that fillet radius size influences to enhance film cooling effectiveness. Predicted film cooling effectiveness results at forward facing step configuration indicated that step height influences to enhance film cooling effectiveness. We suggested that designer change a combustor-turbine interface configuration which was varied by fillet radius size near endwall gap when there was a step at combustor-turbine interface. Gap shape was modified by increasing fillet radius size near nozzle endwall. Also, fillet radius and step height were interacted with the film cooling effectiveness and heat transfer on endwall surface.

Keywords**—**Gas turbine, film cooling effectiveness, endwall, fillet.

I. Introduction

FOR enhancing gas turbine thermal efficiency and output of power, turbine inlet temperature has increased. Combustion method has been developed to reduce NOx. Pre-mixed combustion method effected to reduce NOx; however, temperature on endwall has increased prior to past combustion method. Consequently, endwall increased heat loads on turbine components. Cooling methods consist of slot cooling and discrete hole for protecting endwall from hot gas stream. Slot is created at combustor-turbine interface gap for protecting endwall surface from hot gas. The interface gap is an area where cooling performance is improved.

This paper reports effects of step and fillet shape at combustor-turbine interface on endwall heat transfer. In addition, time-resolved vector and streamline predictions within the vane stagnation plane are presented. Film cooling effectiveness, Nusselt number, and Net Heat Flux Reduction are simulated by varying fillet radius size and step height size.

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II. Literature Review

Several past studies have investigated the performance of purge flows from upstream gaps at combustor-turbine interface. Many studies have preceded film cooling from discrete holes and purge flow. Reference [1] measured secondary flows in a vane passage and combustor-turbine leakage flow and found cooling performance according to mass flow rate (MFR). Reference [2] found effect of leakage flows on endwall cooling.

Reference [3] researched the effects of mass flux ration and momentum flux ratio by varying MFR and slot width. They [3] also included mid-passage gap and film cooling holes. Momentum flux ratio is dominant for film cooling effectiveness [3]. Reference [4] researched for slot injection angle compared with 90 degree and 45 degree. 45 degree injection angle caused to enhance much more than 90 degree injection angle. Also, 45 injection angles caused to reduce horseshoe vortex near leading edge. Reference [5] researched same geometry and found that decreasing slot with while maintaining a constant mass flow resulted in larger coolant coverage areas and increased film cooling effectiveness. Reference [6] performed to study heat transfer on vane endwall by computational simulation compared experiment results. Reference [7] researched for adiabatic effectiveness an axisymmetric contoured endwall on a nozzle guide vane. Contoured endwall caused to reduce film cooling performance compared flat endwall. Reference [8] examined heat transfer with non-axisymmetric endwall. The effect of contouring on the endwall heat transfer was tested for off-design performance according to Reynolds number. If Reynolds number is high, heat transfer coefficient is increased. Reference [9] performed cooling effectiveness about mid-passage gap and upstream slot on vane endwall. Comparisons indicated that the computational predictions agreed relatively well with measured adiabatic effectiveness. Reference [10], [11] investigated backward facing step and forward facing step. Reference [12] examined heat transfer on endwall at forward facing step and backward facing step. Forward facing step caused increasing heat flux on endwall and made decreasing NHFR compared to nominal case. Backward facing step produced slight reduction in NHFR compared to nominal case.

Many studies [3]-[9] were performed about MFR on mid-passage gap and combustor-turbine interface gap. Only a few studies [10]-[12] have investigated about step configuration. The study reported in this paper seeks to understand film cooling effectiveness and heat transfer varying fillet radius size and step height size. In addition, the resulting film cooling effectiveness and heat transfer will be supported by time-resolved flow field predictions in the stagnation plane of the nozzle guide vane.

III. Computational Methods

Simulations of the combustor-turbine interface geometry were performed using the computational fluid dynamics software CFX [13]. A summary of the geometry was shown in Table I. The RANS equation was interpreted by SST k-omega turbulence model. The SST K-omega turbulence model [14] had shown reasonable prediction with experimental results in gas turbine [15], [16]. Transition turbulence model was Gamma Theta model modifies turbulent transport equations to simulate laminar, transition, and turbulence states in a fluid. The Numerical setup was described in Fig. 1. To predict the endwall heat transfer upstream of the platform, the computational grid was extended $1.77C_x$ upstream of the vane leading edge and the outflow boundary condition was extended $1.67C_x$ downstream of the trailing edge as shown in Fig. 1 (a).

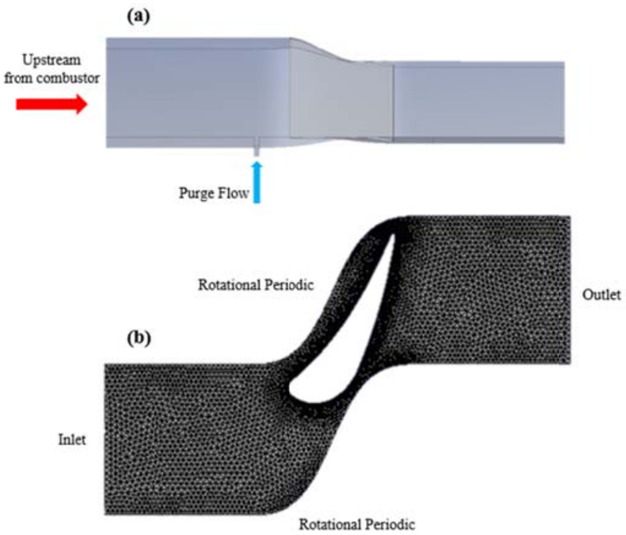

Fig. 1 Depictions of (a) computational domain, (b) the endwall grid

TABLE I
SUMMARY OF ENDWALL / ENDWALL SLOT FEATURES

	Parameter	Computational Value
Vane	Re_{outlet}	6.2×10^6
	C_{ax} - Axial chord length (mm)	22.5
	C - chord length (mm)	40
	Pitch / Axial Chord (P/C_{ax})	1.33
	Span / Axial Chord (S/C_{ax})	0.98
Upstream Slot	W – Upstream slot width (mm)	0.025×C
	Slot length to width	1.9
	Slot injection angle	90°

TABLE II
COMPUTATIONAL BOUNDARY CONDITION

	Parameter	Computational Value
Inlet	P_{total}	30.68 bar
	Temperature	Inlet Profile
Coolant Inlet	T_c	837 K
	$\dot{m}_c$	MFR = 1%
Outlet	$\dot{m}_{outlet}$	0.3571 kg/s

A. CFD Mesh

The computational mesh is shown in Fig. 1 (b). The commercial grid was used by CFX Auto-mesh. The total number of elements in this geometry was around 5,000,000. The momentum, energy and turbulence equations were performed until the residual values of the computations converged. The convergence of residuals for x-momentum, y-momentum, and z-momentum were resolved to levels lower than 10^{-4}. Area-averaged endwall temperature valued less than 0.1% over 500 iterations for satisfaction for convergence. After convergence, the mesh was adapted y^+values less than 1.

B. Boundary Condition

The rotational periodic boundary condition was applied to this domain and the outflow boundary condition is extended 1.67 C_x downstream of the trailing edge. The boundary condition in this geometry was shown in Table II. In this study, the inlet temperature boundary condition had a temperature profile. The inlet temperature profile was referred to KARI (Korea Aerospace Research Institute).

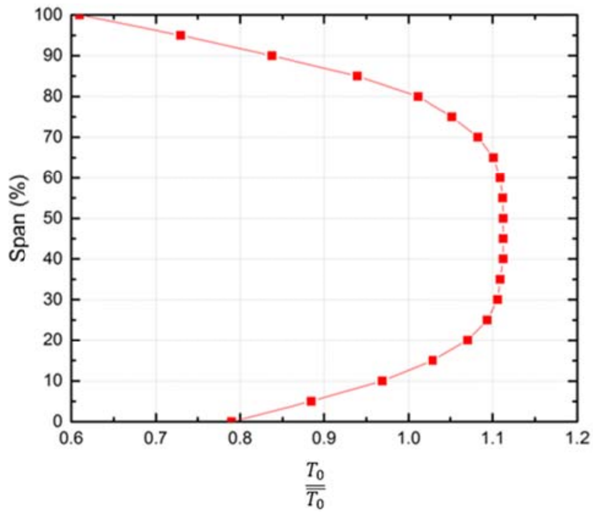

Fig. 2 Temperature inlet profile from combustor exit

TABLE III
COMPUTATIONAL TEST CASES

Fillet Radius (r/C_x) (%)	Step Height (ε/C_x) (%)
0	0
2.2	2.2
4.4	4.4
6.6	6.6

The inlet temperature profile was calculated by combustor exit temperature distribution assuming pattern factor and RTDF. Fig. 2 shows temperature inlet profile. In this study, simulation was performed by using this inlet temperature profile.

IV. Results and Discussion

The variables are shown in Table III. Steady 3D RANS predictions for endwall surface are performed where there is a slot at combustor-turbine interface. Film cooling effectiveness and heat transfer with slot geometry are simulated in this study. The predicted results are analyzed.

A. Film Cooling Effectiveness at Fillet Geometry

Efficiency for the numerical research was computed using definition in (1):

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \quad (1)$$

T_∞ is a mainstream temperature, T_c is a coolant temperature, and T_{aw} is an adiabatic wall temperature on endwall surface.

In this study, film cooling effectiveness with fillet geometry and without fillet geometry is predicted on adiabatic condition. Predicted film cooling effectiveness contours are shown in Fig. 3. Film cooling effectiveness with fillet geometry appears to be more endwall cooling effects than without fillet geometry. Without fillet, coolant and hot stream are mixed because coolant flows upstream from slot. Coolant cannot protect on endwall surface that causes film cooling effectiveness is low on endwall without fillet. However, with fillet, fillet geometry controls the coolant direction to protect endwall flow so that film cooling effectiveness with fillet is higher than without fillet. Line plots of film cooling effectiveness augmentation in Fig. 4 were created by extracting data from Fig. 3. Film cooling effectiveness of each fillet radius sizes is made little difference. Fig. 3 shows that film cooling effectiveness is reduced around leading edge and passage between pressure side and suction side. One of the reasons for film cooling effectiveness is low is horseshoe vortex that is occurred by leading edge. Because of horseshoe vortex, fluid flows around leading which causes coolant cannot protect endwall surface from hot stream.

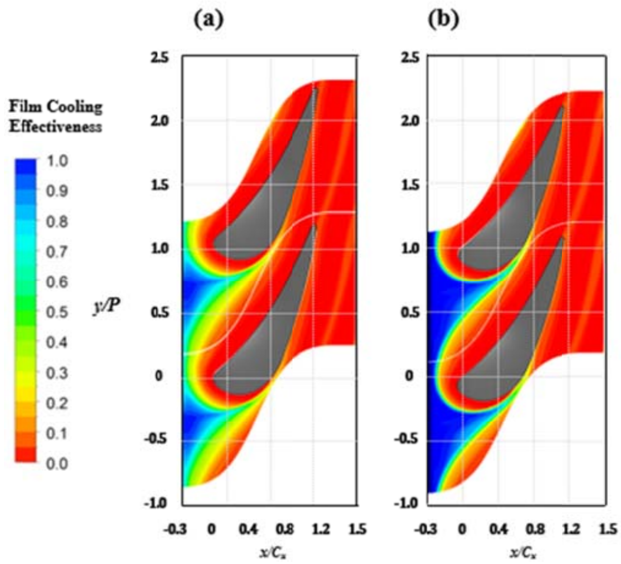

Fig. 3 Contours of film cooling effectiveness (a) Without fillet (b) With fillet (r/C_x=6.6%)

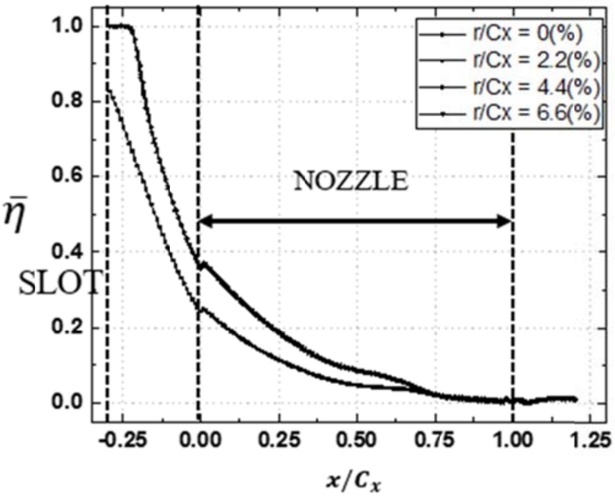

Fig. 4 Lateral averaged film cooling effectiveness according to fillet radius size

Another reason is passage vortex that leads fluids to move toward suction side as pressure difference between pressure side and suction side.

B. Film Cooling Effectiveness at Step & Fillet Geometry

Based on fillet geometry (r/C_x =6.6%), film cooling effectiveness is predicted on step configuration. In Fig. 5, contours of film cooling effectiveness according to step height are shown. There is no big change; however, film cooling effectiveness is decreasing after passing the leading edge. Fig. 6 shows that line plots of film cooling effectiveness for four cases. The influence of film cooling effectiveness has increased until step height (ε/C_x=4.4%) after then film cooling effectiveness has decreased. Step configuration causes pressure distribution change so that main stream flows differently comparing no step configuration. Main stream flows upstream because of step configuration. In case of step height (ε/C_x=4.4%), main stream flows upstream and coolant flows along the fillet configuration. For relative pressure distribution, coolant is mixing with hot main stream less than no step configuration which causes enhancing film cooling effectiveness. However, in case of step height (ε/C_x=6.6%), film cooling effectiveness is reduced compared to the step height (ε/C_x=4.4%). Increasing step height causes to accelerate main stream velocity that coolant cannot be covered with endwall surface.

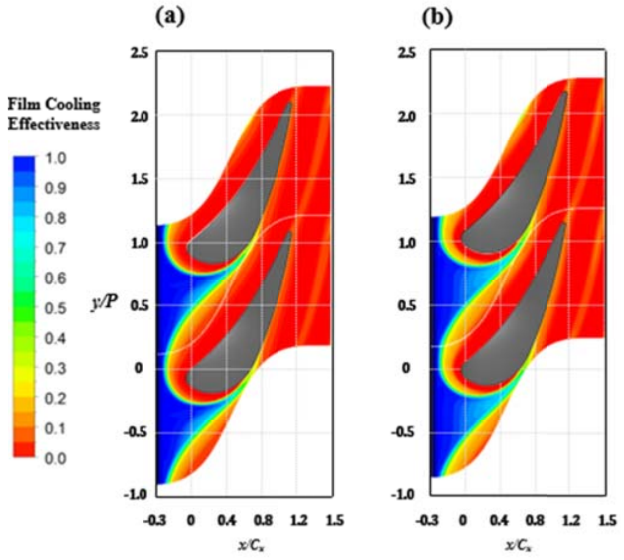

Fig. 5 Contours of film cooling effectiveness at fillet (r/C_x=6.6%) (a) Without Step, (b) With Step (ε/C_x=6.6%)

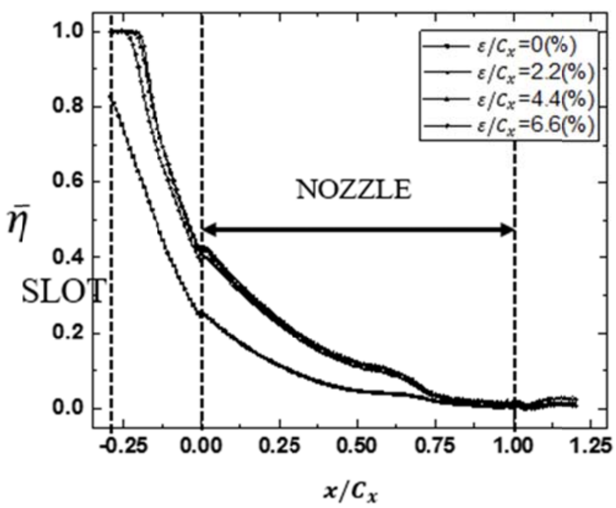

Fig. 6 Lateral averaged film cooling effectiveness according to step height size

V. Conclusion

Computational simulations of fillet and step configuration were performed with a steady RANS compared to film cooling effectiveness and heat transfer. The simulations were performed by SST K-omega turbulence model as the fillet and step configuration.

The trend of film cooling effectiveness enhanced for increasing fillet radius size. Fillet radius controlled coolant flow to be spread on endwall surface. Fillet was key role of film cooling effectiveness on endwall. However, there was a hot gas injection with fillet geometry into slot which caused to fracture due to high temperature.

Step configuration could be occurred by thermal expansion and tolerance. In this study, step configuration was simulated at fillet (r/C_x=6.6%). The trend of film cooling effectiveness was similar to changing fillet geometry. However, after step height (ε/C_x=4.4%), film cooling effectiveness had reduced. The tendency for upstream of coolant caused that coolant could not cover on endwall which effected to heat transfer on endwall. At step height (ε/C_x=6.6%), there was no hot gas injection into slot.

Overall, the steady RANS simulations showed film cooling effectiveness and heat transfer on step and fillet configuration. Film cooling effectiveness had increased at step geometry compared to no step geometry. To design at combustor-turbine interface, it was important to consider cooling performance and hot gas injection which effect to durability and fully gas turbine efficiency.

Acknowledgment

This study was supported by the aerospace research program (KA00157) of Korea Aerospace Research Institute (KARI) and the human resources development program (No. 20144030200560) of the Korean Institute of Energy Technology Evaluation and Planning (KETEP). Those programs are funded by the Korean government Ministry of Trade, Industry and Energy.

References

[1] Karen A. Thole and Daniel G. Knost, 2005, “Heat transfer and film-cooling for the endwall of a first stage turbine vane”, Int. J. Heat and Mass Transfer 48, 5225-5269
[2] W.W.Ranson et al., 2005, “Adiabatic Effectiveness Measurements and Predictions of Leakage Flows Along a Blade Endwall”, J.Turbomach., 127, pp.609-618
[3] Cardwell et al., 2007, “The Effects of Varying the Combustor-Turbine Gap,” J.Turbomach., 129, pp. 756-764.
[4] A.A.Thrift et al., 2012, “Effects of Orientation and Position of the Combustor-Turbine Interface on the Cooling of a Vane Endwall”, J.Turbomach., 134, 061019-1~061019-10
[5] S.P. Lynch and K.A.Thole, 2008, “The Effect of Combustor-Turbine Interface Gap Leakage on the Endwall Heat Transfer for a Nozzle Guide Vane”, J.Turbomach., 130, 041019-1~04101910
[6] Stephen P. Lynch and Karen A. Thole, 2011, “The Effect of the Combustor-Turbine Slot and Midpassage Gap on Vane Endwall Heat Transfer”, J.Turbomach., 133, 041002-1~041002-9
[7] A.A,Thrift et al., 2011, “Effect of an Axisymmetric Contoured Endwall on a Nozzle Guide Vane : Adiabatic Effectiveness Measurement”, ” J.Turbomach., 133, 041007-1~041007-10
[8] Stephen P. Lynch et al., 2011. “Heat Transfer for a Turbine Blade With Nonaxisymmetric Endwall Contouring”, J.Turbomach., 133, 011019-1~011019-9
[9] Satoshi Hada and Karen A. Thole, 2011, “Computational Study of a Midpassage Gap and Upstream Slot on Vane Endwall Film-Cooling”, J.Turbomach., 133, 011024-1~011024~9
[10] H. I. Abu-Mulaweh, 2003, “A review of research on laminar mixed convection flow over backward- and forward-facing steps”, Int.J. of Thermal Sciences, 44, pp. 155-162
[11] H. I. Abu-Mulaweh, 2004, “Turbulent mixed convection flow over a forward-facing step- the effect of step heights”, Int.J. of Thermal Sciences, 42, pp. 897-909
[12] J.D. Puggush and T.W. Simon, 2006, “Measurements of net change in heat flux as a result of leakage and steps on the contoured endwall of a gas turbine first stage nozzle”, Applied Thermal Engineering, 27, pp. 722-730
[13] ANSYS CFX 15.0 version, ANSYS Inc., Canonsburg, PA.
[14] Menter, F. R., 1994, “Two-Equation Eddy Viscosity Turbulence Models for Engineering Applications,” *AIAA J.*, 32(8), pp. 1598-1605.
[15] Snedden, G., Dunn, D., Ingram, G., and Gregory-Smith, D., 2009, “The Application of Non-Axisymmetric Endwall Contouring in a single-Stage Rotating Turbine,” *ASME Paper* No. GT2009-59169.

[16] Stephen P. Lynch, 2011, "Computational Predictions of Heat Transfer and Film-Cooling for a Turbine Blade With Non-axisymmetric Endwall Contouring", J.Turbomach, Vol. 133(4), 041003-1 ~ 041003-10

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