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Comparative Performance of New Surface Roughness Element and Pin-fin in Converging Channel for Gas Turbine Application

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ABSTRACT

Thermal performance of a novel surface roughness element, named as Double 45 Dimple (D45D), is compared with pin-fin element in a converging channel with rectangular cross section and presented. The Surface Roughness Element (SRE) is derived by combining protrusion & dimple in a particular fashion such that area available for transfer of heat increases. The objective of this study is to demonstrate the applicability of D45D element channel for trailing edge channel of a typical nozzle guide vane where typically pin-fin element is used. New cooling configuration of Nozzle Guide Vane (NGV) with D45D element is also proposed. All thermal and flow related results are derived using validated CFD approach with EARSM turbulence model for a typical value of Reynolds number. From this investigation, it is found that D45D element provides remarkable improvement in the averaged as well as heat transfer in local region for the corresponding surface which makes it a candidate for trailing edge channel cooling application.

Keywords: Converging channel; Thermal performance factor; Surface roughness element; Heat transfer enhancement; Nozzle guide vane

NOMENCLATURE

A	Test surface area, m^2
AR	Aspect Ratio (W/H)
D	Diameter of dimple, mm
Dh	Hydraulic diameter of duct, mm
d	Print diameter of dimple , mm
f	Friction factor defined by Darcy
H	Height of the duct, m
h	Coefficient of Heat Transfer under convective conditions, $W.m^{-2}.K^{-1}$
k	Thermal conductivity, $W.m^{-1}.K^{-1}$
L	Length of duct, mm
Nu	Nusselt number
ΔP	Rate of pressure drop w.r.t. test surface length, $Pa.m^{-1}$
P	dimple or protrusion pitch, mm
Re_{Dh}	Reynolds number calculated using hydraulic diameter
T	Temperature, K
TA	Thermal Augmentation
TPF	Thermal Performance Factor
V_{in}	Average velocity at duct inlet , $m.s^{-1}$
W	Width of duct, m
x	distance from bottom to top wall, mm
y	distance in span wise direction, mm
z	distance in stream wise direction, mm
α	Thermal diffusivity, $m^2.s^{-1}$
ρ_{air}	Air density, $kg.m^{-3}$
Avg	average
d	dimple
in	inlet
o	smooth duct
P	protrusion
w	wall condition

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1. INTRODUCTION

Modern age advancements in aero-engine design are focused on achieving higher thrust/weight ratio, lesser fuel consumption, and minimal pollutant emissions. Current developments in gas turbine industry for aero-propulsion indicates overall pressure ratio more than 40 and turbine inlet temperature more than 2000 K to achieve higher thrust and improved cycle efficiency. As modern alloys can withstand temperature of up to about 1350 K, refined cooling systems play a vital role in the design process to maintain structural integrity and life of the components in the hot gas path such as combustor liners and high pressure turbines.

For turbine airfoil, trailing edge section is designed sharp to achieve aerodynamic performance which results in availability of relatively small area of the airfoil for cooling. The designer's target is to maintaining effective cooling with the available area and ensuring metal temperature below design limit to address durability concern. Hence, more effort needs to be dedicated to enhance the basic understanding of the heat transfer management in trailing edge region of airfoil, which, in turn, shall provide design solutions.

One such possible design solution is to use D45D element in the trailing edge section in place of currently used pin-fin element. Although turbine blade trailing edge has converging cross section, most of the heat transfer studies are carried out in rectangular channels as it eliminates flow convergence effects and allows researchers to focus on the other flow physics. Limited literature is available for wedge-shaped channel or trapezoidal channel which is a more realistic design for trailing edge section.

Through their study of a wedged duct with dimples & protrusions, Lei[1], *et al.* examined the convergence angle's effect on thermal characteristics. They determined that as the convergence angle increases, the heat transfer also increases due to flow acceleration but reduces flow recirculation and also increases the friction factor resulting in local thermal performance reduction. However the reduction in performance of wedged duct with protrusion was lesser than that of dimples as the flow structure around protrusion has not altered significantly. Through experimental study of transfer of heat and loss of pressure at end walls with pin fins in a wedge duct, Hwang & Lui[2], have concluded that end wall heat transfer increases in the stream wise direction due to flow acceleration. Tarchi[3], *et al.* have suggested pentagonal arrangement of elliptic pin fins for trailing edge cooling as this arrangement provides the same thermal performance as the standard staggered array with lower pressure loss. Their results are numerically verified by Bianchini[4], *et al.*. Crossing jets in rib-roughened trailing edge channel is studied by Filippo[5], *et al.*. They concluded that flow structure's interaction with the end walls determine heat transfer coefficients (both locally and globally) which results in increases of thermal performance both on rib-roughened wall and on the opposite smooth wall. In a systematic study, Kulasekharan & Prasad[6, 7] have concluded that straight converging channel with staggered pins in straight flow produces highest heat transfer closely followed by cambered converging channel which is the most practical geometry for gas turbine trailing edge. They also proposed that diamond shaped pins[8] are superior to the circular pins in terms of thermal performance.

To increase heat transfer over flat surface, either protruding structural element in the cooling flow like Protrusion, ribs, Pin-fins etc. can be utilised or cavities like dimples are introduced in the surface. Both methods rely on increasing heat transfer by flow separation/ reattachments by breaking the thermal boundary layer & resulting in turbulence increase. Periodically placed dimple-protrusion pattern is experimentally studied by Hwang[9], *et al.*.

Ligrani[10] have compared different heat transfer elements and their thermal performance for rectangular uniform cross section duct and expressed that heat transfer elements derived by combining dissimilar heat transfer elements can produce higher heat transfer. Some research effort in this direction has successfully achieved higher heat transfer which validates this thought. Various explorations on combining different heat transfer elements/ techniques like pin-fins by Rao[11], *et al.*, ribs by Choi[12], jet impingement by Kanokjaruvijit and Botas[13] and protrusion by Hwang[4], *et al.* and Xie[5,16], *et al.* with the dimples have reinstated the fact that by combining different heat transfer elements/ techniques, higher thermal performance is achievable.

A new surface roughness element, with 1st half as protrusion and 2nd half as dimple, as shown in Fig. 1, is conceptualised by the authors[17]. The surface roughness element, named as

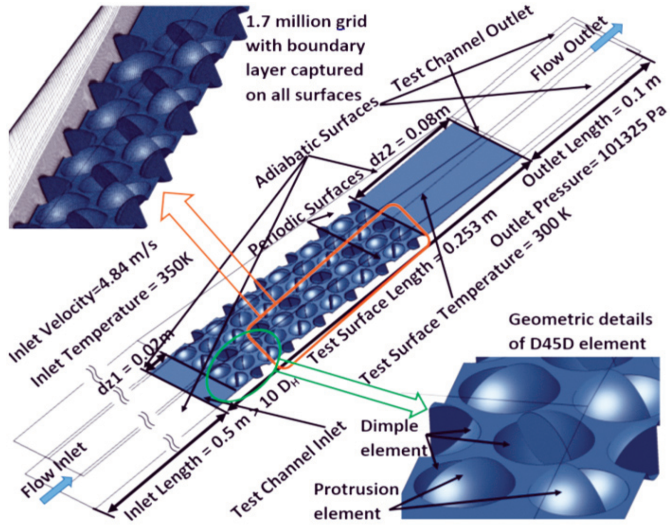


Figure 1. Geometry, computational domain and boundary condition details.

Double 45 Dimple – D45D, with this particular orientation and arrangement of array has shown better thermal performance for a constant rectangular cross section duct. In that study, grid independence, applicability and selection of turbulence model is also detailed. Study of various geometric parameters of the element[18] on heat transfer enhancement indicates that thermal performance degrades with the change in parameters. Thermal performance of this element decrease[19] with the increase in Reynolds number till 30,000 and becomes constant for higher Reynolds number values.

Application of D45D element array as a thermal performance enhancement element for a converging trapezoidal channel with 5^0 convergence angle is computationally investigated in the present study. Smooth wall converging trapezoidal duct is analysed which served as the baseline geometry. Thermal performance, at constant inlet Reynolds number of 10000, is evaluated for D45D channel, pin-fin channel and smooth wall channel configurations. This work will pave way for application of array of this element (D45D) for trailing edge channel of a typical nozzle guide vane and help in its better thermal management.

2. COMPUTATIONAL DETAILS

Menter et al.[20] has proposed S-BSL-EARSM (Simplified BaSeLine Explicit Algebraic Reynolds Stress Model) turbulence model, which is utilised in this work[17]. Steady state results of time-averaged N-S equations are used to extract the thermal performance of the newly proposed D45D element arrays and pin-fin arrays. The computational domain is discretised (grid generation) using commercial software package Hexpress[21]. Four grid sizes (0.5, 1.1, 1.7 and 2.4 million) are considered for grid independence study. This study indicated that the 1.7 million grid captures details of average Nusselt number and friction factor ratio. Central difference scheme with 2nd order accuracy is utilised for discretisation of space variables in the governing equations (N-S equations) in FINE-Open[22]. The governing equations are considered converged after difference between two successive iterations is less than 10^{-6}.

Details of the test surface adapted for the computational study are shown in Fig. 1. Inlet length of 0.5 m which is more than 10 hydraulic diameter (D_H = 4.3 cm) is considered to guarantee fully developed flow at converging cross section entrance. To achieve oscillation free converged solution, duct length of 0.1 m is added at the outlet of test section. The periodic boundary condition is applied in the transverse direction to model one pair of D45D element of a wide channel, by taking advantage of symmetry, without losing the physics of the flow.

For converging zone, upper surface is considered at 5 degree angle from the lower flat surface and the length of the lower flat test surface is 253 mm. This flat test surface is considered as constant temperature surface with temperature of 300 K. All other surfaces are considered adiabatic. Geometry, computational domain details and associated boundary conditions along with mesh details are shown in Fig. 1.

Incompressible dry air, serves as working fluid, enters the flow domain at 4.84 m/s velocity (Re = 10000) with total temperature of 350 K. Constant thermo-physical properties is considered for air in this study which implies constant Prandtl number. As temperature variation in the flow domain is small, constant thermo-physical properties are acceptable.

3. GOVERNING EQUATIONS

The flow mechanism & corresponding transfer of energy for the fluid is described by Navier Stokes Equations, which are solved till convergence for each cell of discretised computational domain (mesh/ Grid) and solution is integrated throughout the computational domain to arrive at smooth variation of flow variables in computational domain. In Cartesian reference frame, Navier-Stokes equations is defined as:

$$\frac{\partial}{\partial t}\int U d\Omega + \int_s \vec{F}.d\vec{S} - \int_s \vec{G}.d\vec{S} = \int_\Omega S_{Td}\Omega \tag{1}$$

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{bmatrix} \tag{2}$$

where S is the control surface, Ω is the control volume, S_{Td} is the source term, U is the set of conservative variables and $\vec{F}$ & $\vec{G}$ are representing advection (inviscid) and diffusion (viscous) fluxes respectively. For U = (density), the diffusive flux along with the source term turns out to be zero (as mass cannot diffuse and it cannot be created or destroyed), the mass conservation (continuity) equation can be derived. Similarly, U = (ρu , ρv,ρw) denotes the momentum equation in x, y and z directions respectively. For U = ρE (Internal Energy), the Energy equation can be derived.

$$\vec{F} = \left(\begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho uw \\ \rho uH \end{bmatrix}, \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ \rho vw \\ \rho vH \end{bmatrix}, \begin{bmatrix} \rho w \\ \rho uw \\ \rho vw \\ \rho w^2 + p \\ \rho wH \end{bmatrix} \right) \tag{3}$$

where H denotes the total enthalpy per unit mass:

$$H = E + p/\rho \tag{4}$$

$$\vec{G} = \left(\begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xz} \\ u\tau_{xx} + v\tau_{xy} + w\tau_{xz} - q_x \end{bmatrix}, \begin{bmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} \\ \tau_{yz} \\ u\tau_{yx} + v\tau_{yy} + w\tau_{yz} - q_y \end{bmatrix}, \begin{bmatrix} 0 \\ \tau_{zx} \\ \tau_{zy} \\ \tau_{zz} \\ u\tau_{zx} + v\tau_{zy} + w\tau_{zz} - q_z \end{bmatrix} \right) \tag{5}$$

For Newtonian fluids, the stress tensor has a linear relationship with the shear rate as described in the subsequent equation.

$$\tau = \mu\left(\vec{\nabla}\otimes\vec{v} + \left(\vec{\nabla}\otimes\vec{v}\right)^T - \frac{2}{3}\left(\vec{\nabla}.\vec{v}\right)I\right) + \zeta\vec{\nabla}.\vec{v} \tag{6}$$

where μ denotes the dynamic molecular viscosity, $\vec{v}$ denotes velocity vector and I denotes Identity (unit) tensor.

Fourier's law defines the heat flux vector:

$$\vec{q} = -k\left(\vec{\nabla}T\right) \tag{7}$$

where T & k denotes the static temperature and the molecular thermal conductivity.

S_T consists of the source terms of equations:

$$S_T = \begin{bmatrix} 0 \\ \rho f_{ex} \\ \rho f_{ey} \\ \rho f_{ez} \\ w_f \end{bmatrix} \tag{8}$$

where the vector $\vec{f}_e$ represents external force's effect and W_f indicates the work performed by those external forces, which is accounted as

$$W_f = \rho\vec{f}_e.\vec{v} \tag{9}$$

Other details regarding turbulence model, the effective turbulence eddy viscosity coefficients and other terms can be referred from the FINE-Open[22] manual.

4. PERFORMANCE PARAMETER DEFINITION

The dimensionless heat transfer coefficient (Nusselt number) is described as,

$$\text{Nu} = \frac{hD_h}{k} \tag{10}$$

Nusselt Number (Nu) is used to compare the thermal performances of different configurations with different fluids using dimensional parameters like fluid's local heat transfer coefficient (h) depends upon the boundary conditions, duct's hydraulic diameter (D_h) and thermal conductivity (k) of working fluid. For present case, since inlet cross section (D_h) and working fluid (k) is same for both pin-fin and D45D configurations, the change in Nusselt number depends on h only.

In the observation area, scalar average of local Nusselt number is derived and integrated along the length with elemental area to calculate the overall average Nusselt number. The observation area is defined from 8th row's mid plane to the 11th row's mid plane encapsulating 9th and 10th row of protrusion & dimple.

$$Nu_{avg} = \frac{\iint_A Nu dA}{A} \tag{11}$$

where Nu and A represent local Nusselt number and actual surface area respectively.

Darcy friction factor, f, is described as:

$$f = \frac{\Delta P * D_h}{2 * \rho_{air} * V_{in}^2} \tag{12}$$

where ΔP represents rate of pressure drop w.r.t. test surface length.

As $D_{h,}$ ρ_{air} & V_{in} are not changing, the friction factor's change becomes a function of ΔP. For arriving at ΔP, average values of static pressure at test channel's inlet and outlet planes is pulled out from the numerical results.

The heat transfer values for the smooth channel Nu_o (obtained through computations) are used to obtain non-dimensional heat transfer enhancement, which is described as follows:

$$\text{TA} = \frac{Nu}{Nu_0} \tag{13}$$

The criteria to judge the overall thermal performance of a configuration is given by Fan[23], *et al.* which combines the result of enhanced heat transfer and the loss of pressure, which is described as follows:

$$\text{TPF} = \frac{\dfrac{Nu}{Nu_0}}{\left(\dfrac{f}{f_0}\right)^{1/3}} \tag{14}$$

where, Nu_o and f_o are represents the smooth channel Nusselt number and the smooth channel friction factor with respect to same boundary conditions.

5. SMOOTH TRAPEZOIDAL CHANNEL

For smooth trapezoidal channel, which is considered as baseline case, high Nusselt number at the entry is due to the initiation of thermal boundary layer and higher values at the duct exit is due to higher Reynolds number. The average Nusselt number for observation/ test zone, as shown in Fig. 2 (b), is found to be 49.97.

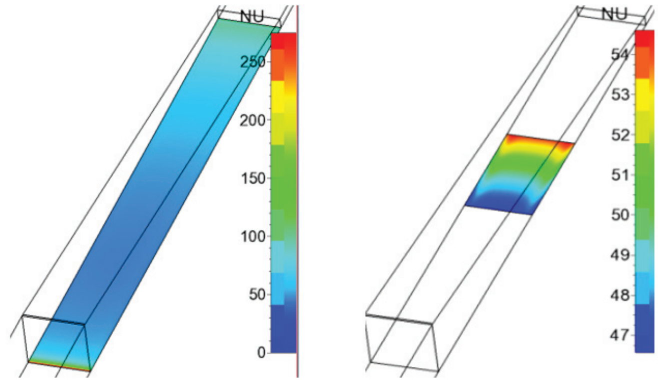


Figure 2. Performance of smooth trapezoidal duct.

(a) Distribution of Nusselt Number over test surface
(b) Distribution of Nusselt Number over test zone.

6. D45D ELEMENT CHANNEL & PIN-FIN ELEMENT CHANNEL

For D45D element channel, 12 rows of D45D elements are incorporated and a length of 81 mm at the end of last element is left as smooth channel. Pin-fin channel is designed with first pin placed exactly at same location as that of first D45D element. Total 6 rows of pin-fins are used in a staggered fashion with streamwise pitch of 2d and spanwise pitch of 2.3 d where d is pin diameter which is same as D45D element diameter.

From contours of turbulent viscosity distributions, as shown in Fig. 3, higher values of turbulence are indicated by higher turbulent viscosity which is indicative of higher heat transfer. The pairs of D45D elements create converging and

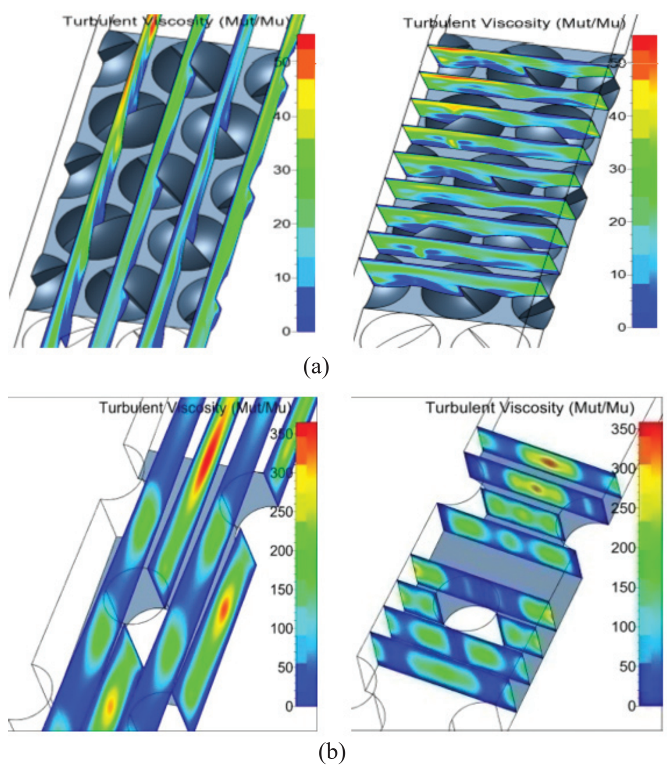
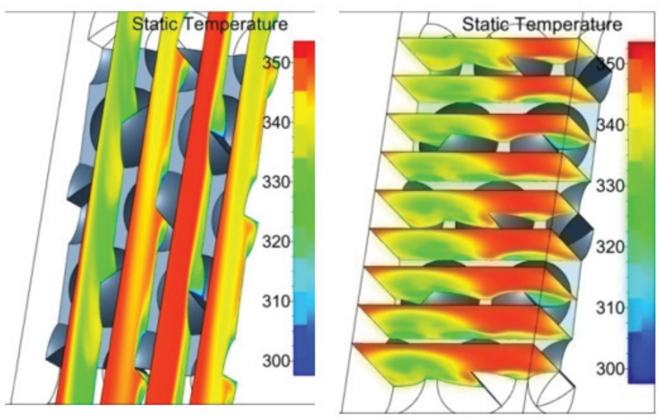


Figure 3. Turbulent viscosity distribution in (a) stream wise and (b) span wise direction on selected planes.

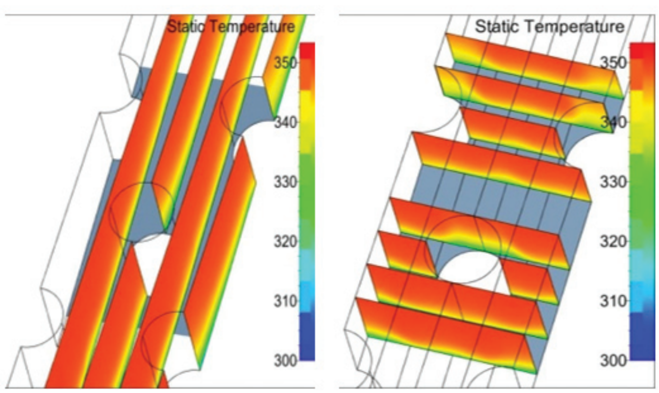
diverging channels. Difference in flow field is clearly visible on cut planes with respect to the channel's centerline plane in the flow direction. Left part in D45D channel, in Figs. 3 (a & b) is generating uniform and higher magnitudes due to higher secondary flows. For pin-fin, as shown in Figs. 3 (c & d), turbulent viscosity is increasing mainly due to converging channel.

7. THERMAL ANALYSIS

As noticed in the flow field of turbulent viscosity distributions about the cut plane, with respect to the channel's centerline plane in the flow direction, the static temperature distribution also shows distinct values on left and right part from centerline plane. Due to lower mixing in the right part, except near the surface, the static temperature maintains higher value as shown in Figs. 4 (a & b). This can be ascribed to the strong secondary flows near test surface for the left side and lack of it for the right side. Effect of thermal boundary layer and mixing in the pin-fin wake zone is visible in Figs. 4 (c & d).



(a)



(b)

Figure 4. Static Temperature distribution in (a) stream wise and (b) span wise direction on selected planes.

Normalised Nusselt number distribution over observation zone, as shown in Fig. 5, indicates higher average Nusselt number value for D45D channel as compared to the channel with Pin-fins. However, channel with Pin-fins exhibits more uniform heat transfer as compared to D45D channel. For D45D channel, this is due to higher peak value as compared to average value as very high heat transfer is limited to very small zone which is present at the top end of joining surface. Typical heat transfer characteristics of channel with Pin-fins like high value of heat transfer over the leading edge and low value of heat transfer behind the Pin-fin trailing edge, are clearly visible.

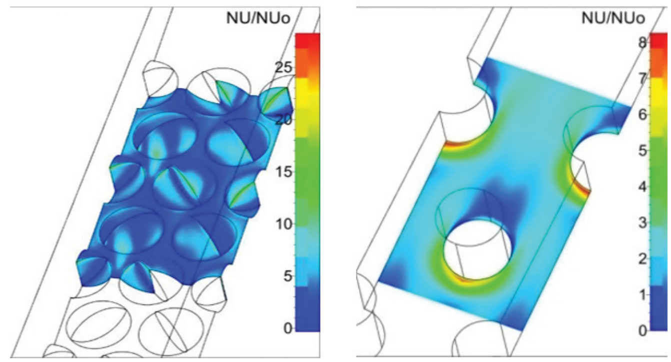


Figure 5. Normalised Nusselt number distribution over observation zone.

Relative comparison of thermal performance is presented in Table 1 which indicates that thermal augmentation for D45D element channel is 29.3% more than the pin-fin channel with the remarkable 68.1% lesser pressure loss which resulted in increase in thermal performance factor by 40.5%. Fig. 6 displays Nusselt number variation over the centerline of test surface. It indicates higher heat transfer from D45D channel as compared to smooth and Pin-fin channel except at the location of first D45D element.

Table 1. Thermo-hydraulic performance of different channels

Channel	Smooth	D45D	Pin-fin
Nu	49.97	167.65	118.58
f	0.03	0.08	0.14
Nu/ Nu_o	1.00	3.36	2.37
f/ f_o	1.00	2.53	4.25
TPF	1.00	2.46	1.47

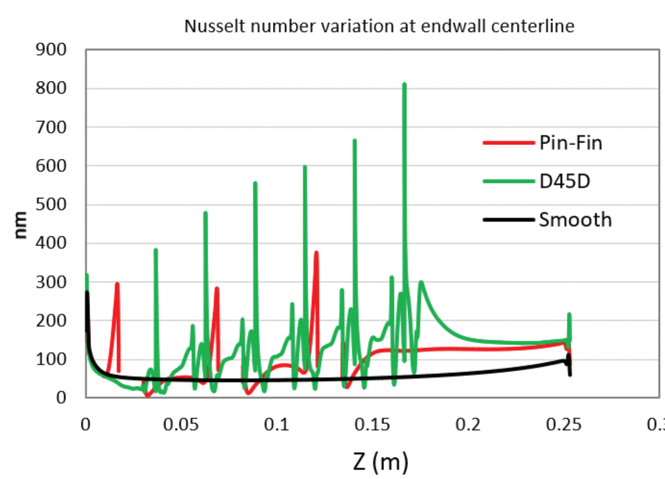
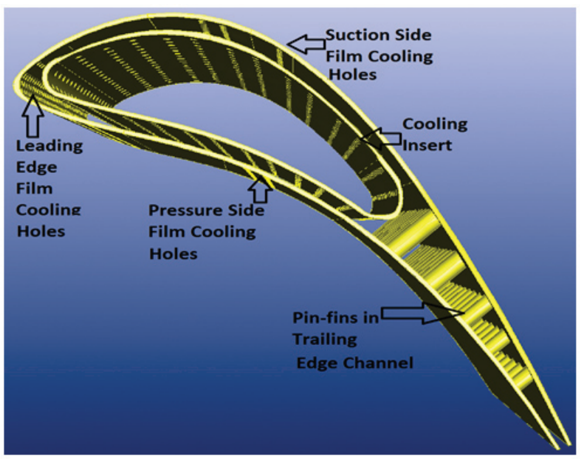


Figure 6. Comparison of Local Nusselt number over test surface along centerline.

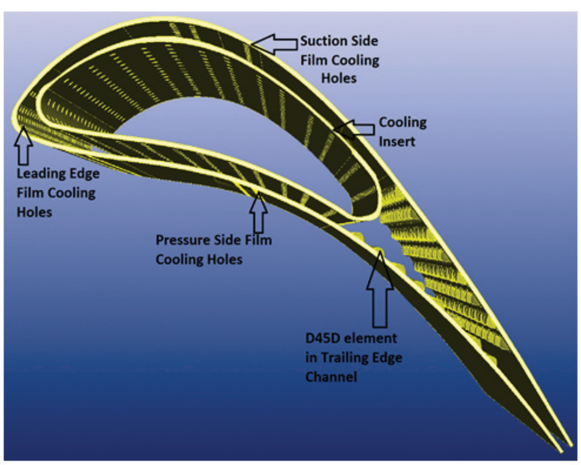
8. PROPOSED COOLING CONFIGURATION FOR NOZZLE GUIDE VANE TRAILING EDGE

For a cooling configuration, it is necessary to have higher rate of heat transfer at a lower pressure loss. From this study, it is found that D45D channel produces higher heat transfer at a lower pressure loss as compared to pin-fin channel. Therefore, to resolve the issue of high heat load at trailing edge with an added advantage of lower pressure loss, new cooling configuration is proposed in which pin-fins of the trailing edge zone are replaced by D45D element array.

Figure 7 shows the scheme of cooling arrangement of the Nozzle Guide Vane (NGV) along with the cooling air supply through cooling insert. Cooling insert has rows of cooling holes, from which the flow impinges on the inner surface of the NGV. Part of this flow ooze out from the film cooling holes and cover the external surface of the NGV. Rest of the flow passes through the trailing edge section populated by rows of pin-fins and ejects through the trailing edge slots. Application of proposed D45D element is to replace the pin-fins in the trailing edge region as shown in Fig. 7(b).



(a)



(b)

Figure 7. Comparison of Existing and Proposed Cooling Configuration for NGV Trailing Edge. (a) Existing NGV Cooling Arrangements with Pin-fins in Trailing Edge and (b) Proposed NGV Cooling Arrangements with D45D in Trailing Edge.

9. SUMMARY AND CONCLUSIONS

3D CFD investigation to predict turbulent heat transfer and associated flow in trapezoidal (converging rectangular cross-section) channel with 3 dissimilar configurations (flat surface (smooth channel), surface with D45D element and surface with Pin-fin element) is computationally investigated using EARSM turbulence model at constant inlet Reynolds number. Smooth converging channel is used as a baseline case for arriving at non-dimensional performance. Thermal performance of the two elements is studied in detail viz. pin-fin and D45D element and D45D element is found to be providing better augmented heat transfer rates for same pumping power as shown in Table 1.

Average value of normalised Nusselt number for D45D channel is higher by 41% in the observation zone which translates to 23% higher thermal performance factor as compared to the Pin-fin channel. Based on the superior performance of D45D element, new cooling configuration is proposed for better cooling of trailing edge of typical nozzle guide vane.

Conflict of Interest: None

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