Conjugate Heat Transfer Enhancement of an Internal Blade Pin-finned Tip-wall

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Reference Paper: IMECE2009-10296

1. Background
Background

To satisfy the desire to achieve higher power, the gas turbine inlet temperature is raised increasingly.

However, the heat transferred to a blade increases with the increase of the blade inlet temperature. Thus the blade must be cooled.
Background

Due to the hot leakage flow through the clearance gap, the turbine blade tip encounters high thermal load and hence high temperature.

Thus the blade tip must be cooled to ensure a long lifetime!
A common way to cool a turbine blade tip is to adopt internal cooling by designing serpentine (two-pass, three-pass or multi-pass) channels with a 180-deg turn/bend inside a blade.

Many investigations have found that pin-fins can improve the cooling in low aspect ratio channels for gas turbines, typically at the trailing edges.
Dr Bunker, GE, presented a method to increase the convective heat flux on the internally cooled tip-cap of a turbine blade, where arrays of discrete shaped pin-fins were placed.

- Tall Al pins,
- Short Al pins
- Plastic pins
- Dense Al pins

- Heat transfer augmentation is up to a factor of 2.5
- Negligible increase in tip turn pressure drop

Reference
Motivation

- To present detailed flow field and heat transfer enhancement over tip walls, and to facilitate better understanding of three dimensional flow and heat transfer for pin-finned tips.

- To investigate heat transfer enhancement over pin-finned tips with a conjugate heat transfer approach.

- To compare the overall performances of pin-finned tip two-pass channels.
2. Physical Models
Physical Models

Channel:
- Aspect Ratio (AR) = 1:2
- Two-pass with a turn
- No turbulators

Pins:
- Circular, staggered
- H/D=2
- Made of aluminium.

(a) Smooth-tip, Case I
(b) Pin-finned-tip, Case II
3. Computational Method
Computational Method

3.1 Overview:

- FLUENT 6.3.26 (64-bit)
- GAMBIT 2.4.6 (32-bit)
- Realizable \( k-\varepsilon \) turbulence model (selection based on pre-study)
- SIMPLEC (coupling velocity and pressure)
- 3D, Incompressible, Steady-state
- Stationary (Non-rotating)
- Constant thermal properties
Computational Method

3.2 Boundary Conditions:

- Inlet velocity temperature: uniform
- Outlet: outflow
- Tip bottom wall: const. heat flux
- The remaining walls: adiabatic
- Standard wall function
- Convergence, $10^{-4}$ for $u,v,w,k,\varepsilon$, $10^{-7}$ for $T$
- Steady-state, incompressible, Stationary
- Fluid-Solid interfaces: auto-coupled
Computational Method

3.3 Grid independence:

- GAMBIT 2.4.6 (32-bit)
- Multi-block
- About 93% cells for near the tip
- One case needs about 45 hrs (64-bit Windows-XP, Core 2 @3.0G CPU, 8 G of RAM)
- Total number of cells is about 2.5M

More than 90% cells
4. Results and Discussion
4.1 Parameter Definition:

Fanning friction factor

\[ f = \frac{\Delta p}{2 \rho u_i^2} \cdot \frac{D_h}{L} \]

Local Nusselt number

\[ Nu(i) = \frac{q_w}{T(i) - T_f} \cdot \frac{D_h}{k} \]

Overall Nusselt number

\[ Nu_{ave} = \sum A_i Nu_i / A \]
Results and Discussion

Supplement: conjugate HTC

\[ h(i) = Nu(i) \cdot \frac{k_{\text{fluid}}}{D_h} \]

\[ \frac{1}{h_i} = \frac{1}{h_o} + \frac{\delta}{k_{\text{Al}}} \]

For example:

\[ h_o = 400 \text{ W/(m}^2\text{.K)} \]
\[ \delta = 0.5 \text{ in} = 0.0127 \text{ m} \]
\[ k_{\text{Al}} = 210 \text{ W/(m}^2\text{.K)} \]

\[ h_i = 391 \text{ W/(m}^2\text{.K)} \]

\[ \frac{(h_i - h_o)}{h_i} = -2.3\% \]

The outer HTC nearly represent inner HTC
4.2 Velocity field

Higher velocity is produced around the turn of Case II.
Results and Discussion

4.2 Temperature contour

A much lower temperature region occurs at the bottom wall of Case II due to the cold fluid impingement and pin-fin crossflow. Besides, through the heat conduction in pins and tips, a more uniform temperature is observed by Case II.
Results and Discussion

4.2 Pressure drop and heat transfer

The HTE of Case II lies 1.9~3.0 over the baseline of Case I. Case II offers 1%~7% higher pressure drop than Case I.
Results and Discussion

4.2 Normalized friction factor and heat transfer

The HTE of Case II lies 2.15~3.62 while that of Case I lies 1.13~1.21. The increase factors of the pressure drop lie 4.3~5.5 and 4.64~5.87.
5. Overall Comparison
With the different layout of the variously shaped pin-fins, the augmentations are different.

5.1 Comparison with Experimental Data

\[ \text{Re} \times 10^5 \]

\[ \text{Nu}_{\text{ave}} \]

- This work, Case II
- Al pins, H=8.13mm, Bunker [25]

Deviation from
- pin shape
- pin layout

exp

CFD
5.2 Evaluation of Heat Transfer Enhancement

Overall Comparison

The pin-finned tip two-pass channels provides good performance for gas turbine blade tip cooling.
6. Conclusions
Conclusions

(1) The pin-fins are very effective heat transfer enhancement devices for gas turbine blade tips due to combination of turn, impingement and pin-fin crossflow. The pin-fins force the vortices towards the tip wall and thereby improve the turbulent mixing of the approaching cold fluid and hot fluid near the tip.

(2) Compared to the smooth tip channel, the heat transfer enhancement of the pin-finned tip channel is a factor of up to 3.0 higher associated with around 7% higher pressure loss.

(3) With the conjugate heat transfer method, the distribution of tip heat transfer and pin surface heat flux can be used for turbine blade tip thermal design.

(4) By applying the criteria, it is found that the pin-finned tip channel provides good overall performance. It is suggested that usage of pin-fins is an effective way to enhance tip heat transfer and cooling.