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CONJUGATE HEAT TRANSFER ANALYSIS FOR GAS TURBINE FILM-COOLED BLADE

15th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES

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Agenda

- Introduction and Motivation
- Geometry and Computational Domain
- Model Mesh Details
- Numerical Set Up and Boundary Conditions
- Model Convergence
- Results and Discussion
  - Comparison against thermocouple data
- Conclusions and Further Investigation

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Introduction and Motivation

- Modern gas turbine engines operate at high temperatures and speed to obtain high power. High turbine inlet temperature can lead to excessive thermal stress and reduced component life.

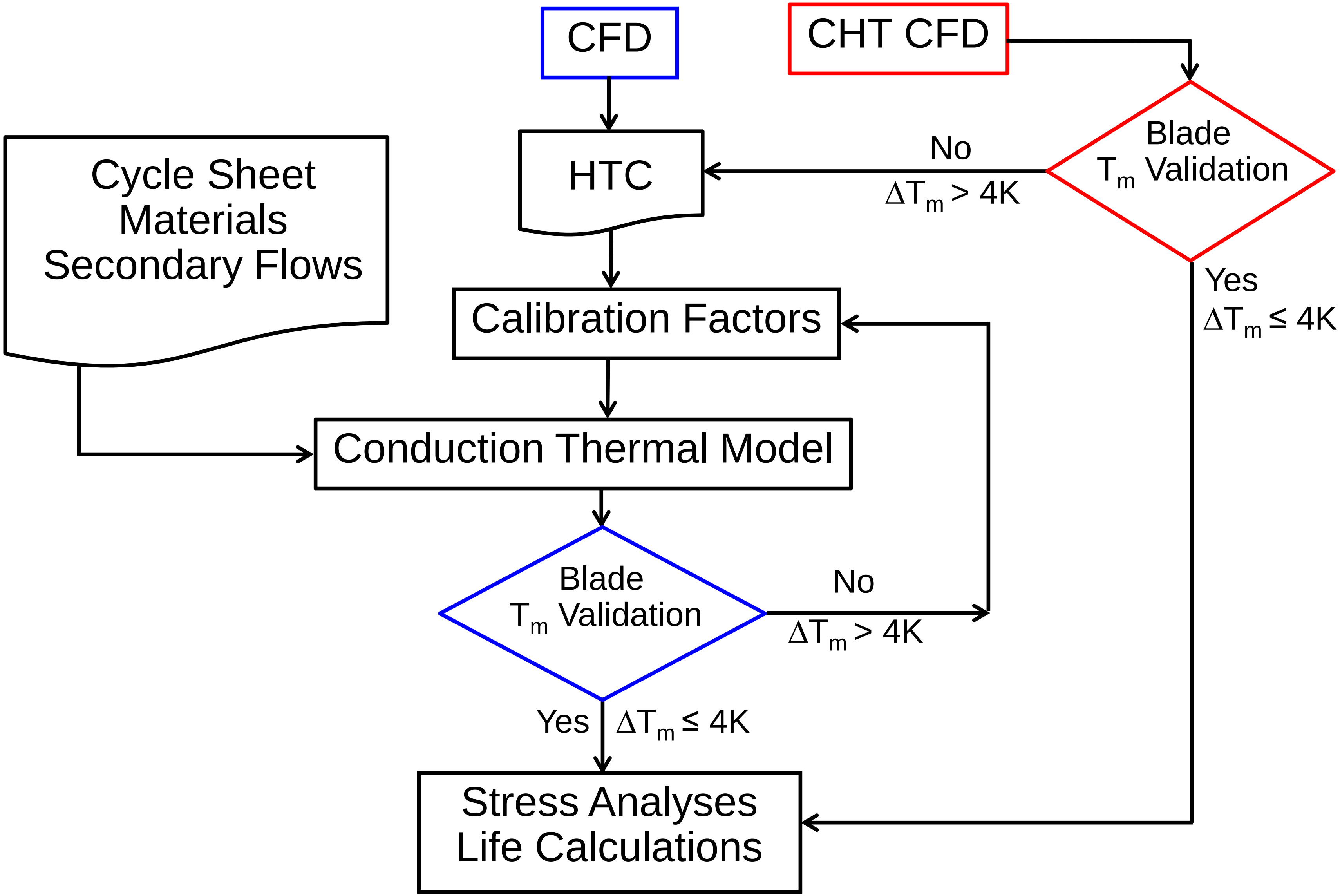
- In order to correctly calculate cyclic thermal stress and component life, blade metal temperature predictions within the accuracy range of ± 4K (7°*F*) are required.

- CHT T_m calculation is within η_{th}=5-10% which implies ΔT_m=20-73K (50-140^{o}F). This may cause 10-20x error in life prediction.

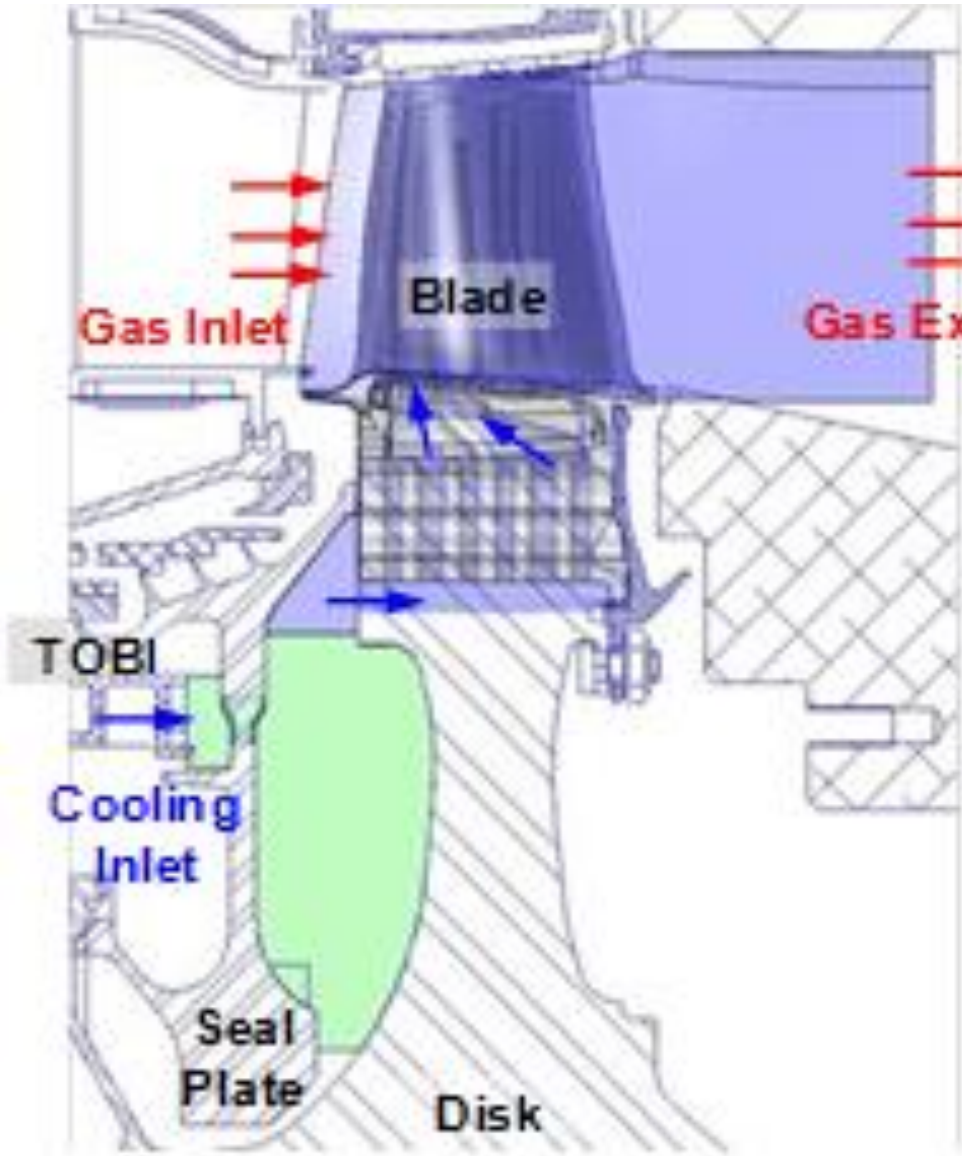
- Accuracy of CHT in film cooled blades will be explored in this presentation.

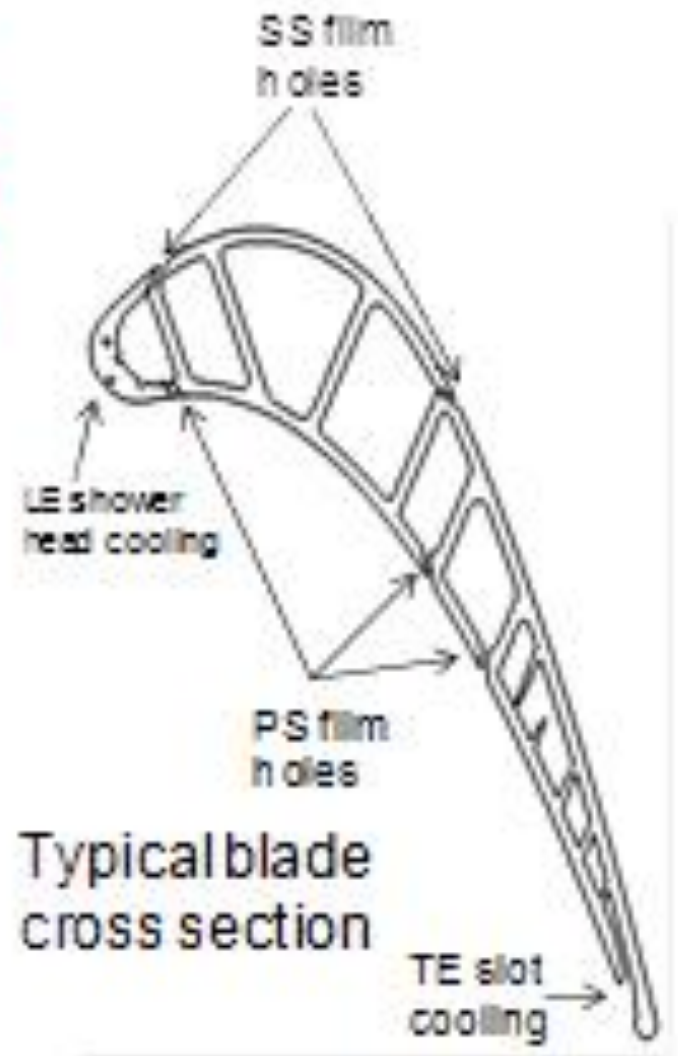
Calculating Blade Temperature Is Challenging

Common Thermal Analysis Process

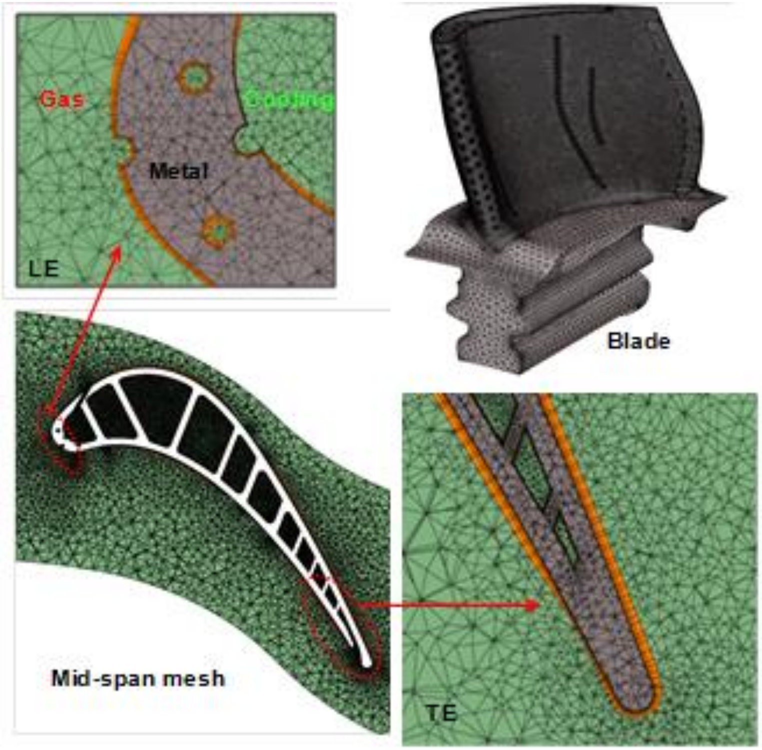


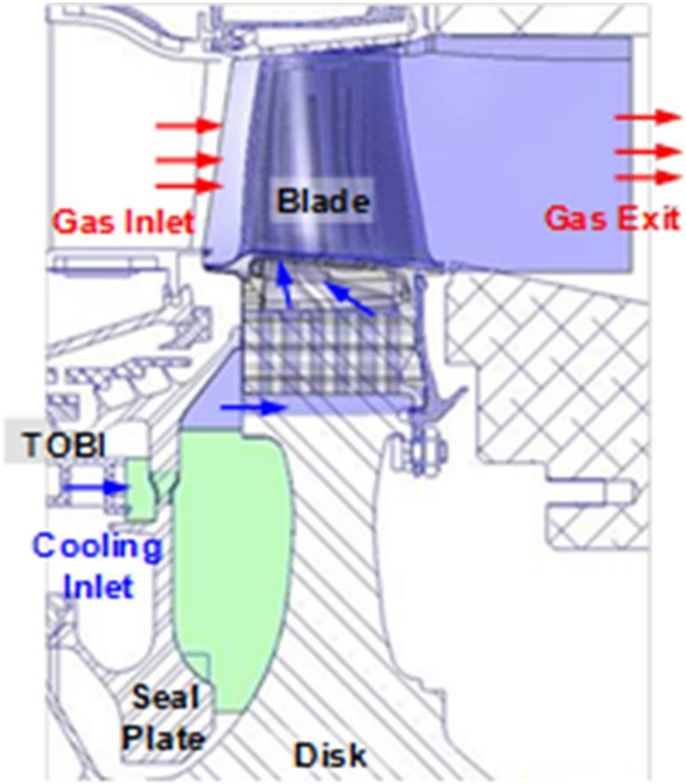
Geometry and Computational Domain





Model Mesh Details





- Grid sensitivity was completed with different Y+ values.
  - Y+ values near wall is less than 3.
- A combination of tetrahedral (Unstructured) and prism elements are used.
- The CFX CHT model consisted of 9.8 million elements:
  - 1.2 million cells in the solid domain (Blade) and 8.6 million cells in the fluid domain.
- Conformal contact interface between solid and fluid region. Prism are wrapped around the blade surface to resolve the boundary layer (higher accuracy).

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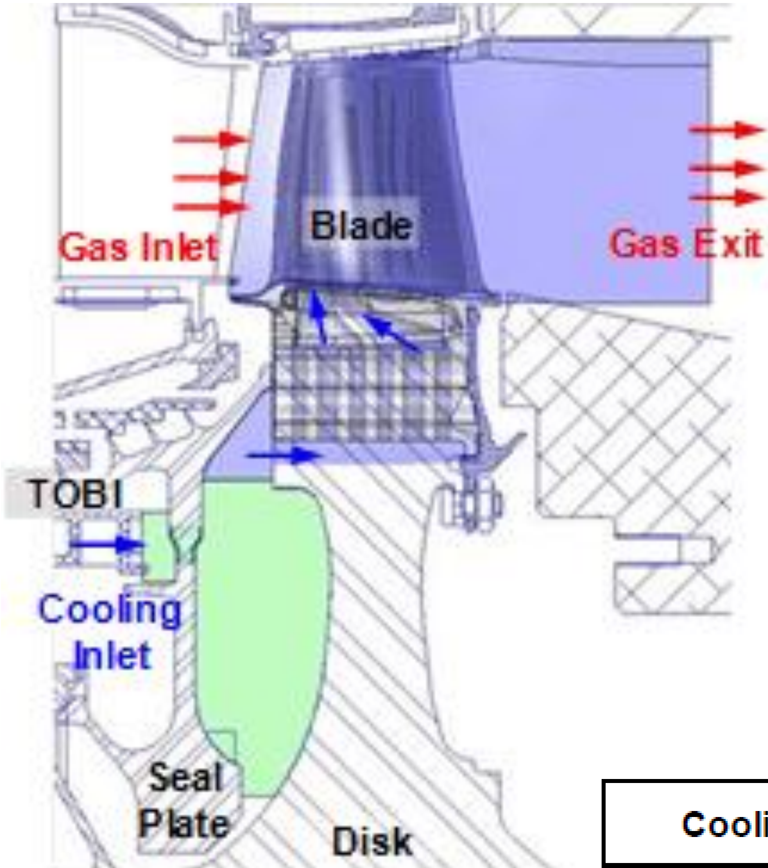
Numerical Set Up and Boundary Conditions



- ANSYS CFX 14.0
- Steady State RANS
- Turbulence model
  - Turbulence intensity factor of 15%.
  - Shear stress transport (SST) turbulence model with automatic wall function.
  - Sensitivity study completed for 4 turbulence models: SA, k-ε, RNG and SST w/ transition.
- Heat transfer
  - Total energy and viscous work term
- Wall function
  - Automatic
- Static structures assumed adiabatic

- Boundary Conditions

Cooling Flow	Hot Gas	
Inlet	Inlet	Exit
Tt; Mass flow rate; Flow angles	Tt(r); Pt(r); Flow angles(r)	Ps(r)
From engine cycle sheet	From Fine_Turbo steady approach	

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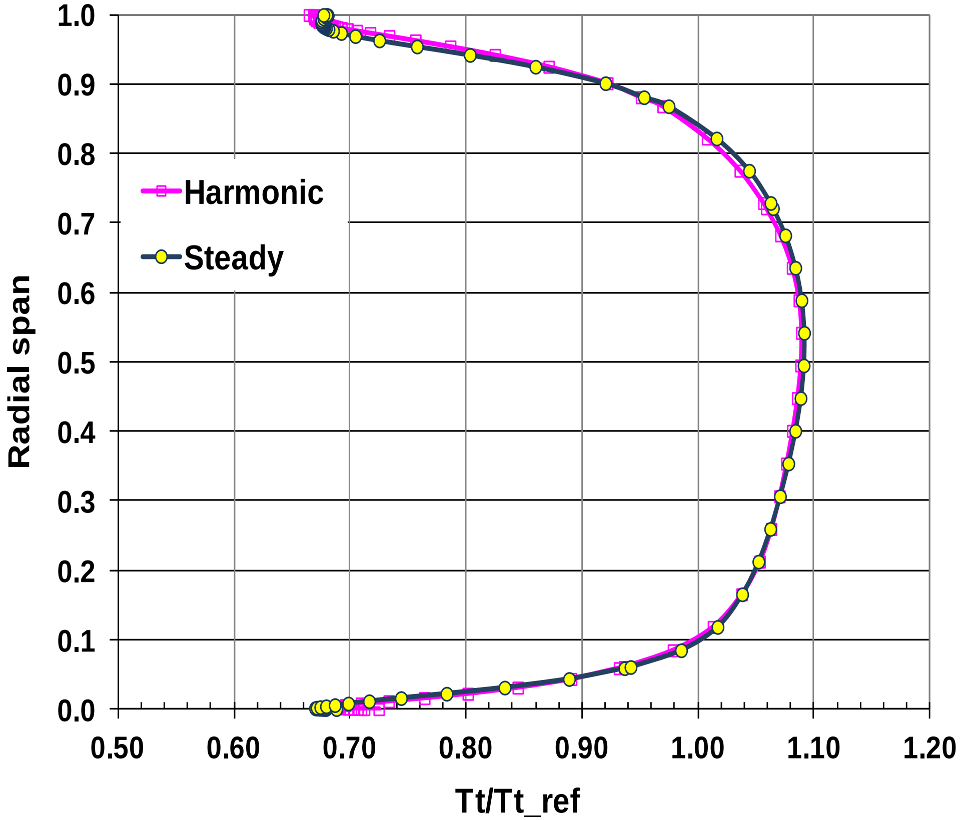
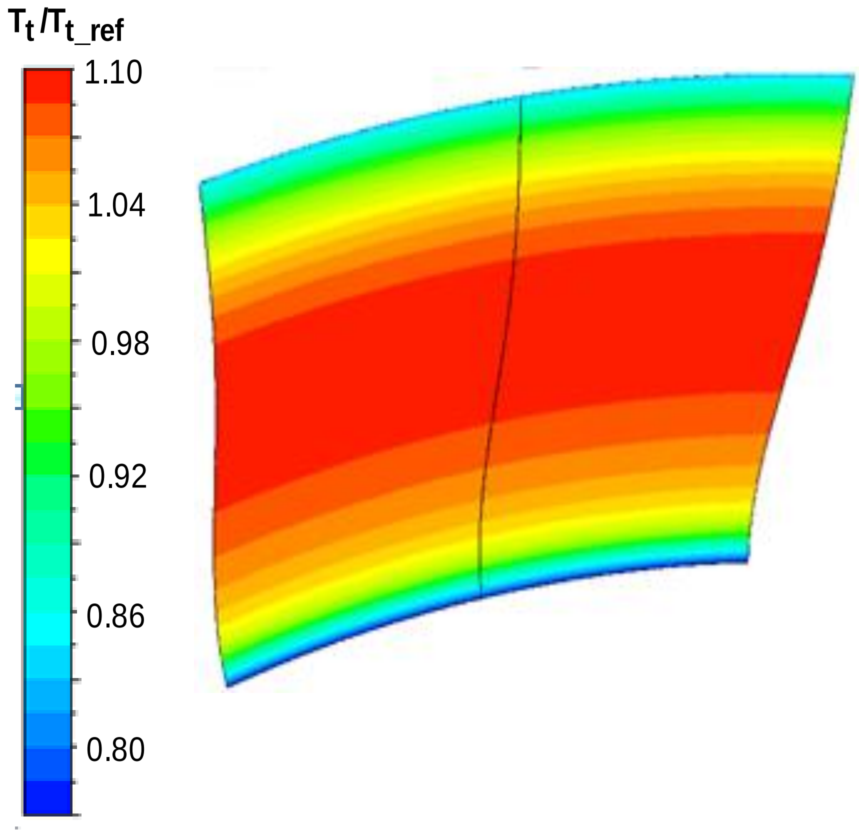
Numerical Set Up and Boundary Conditions

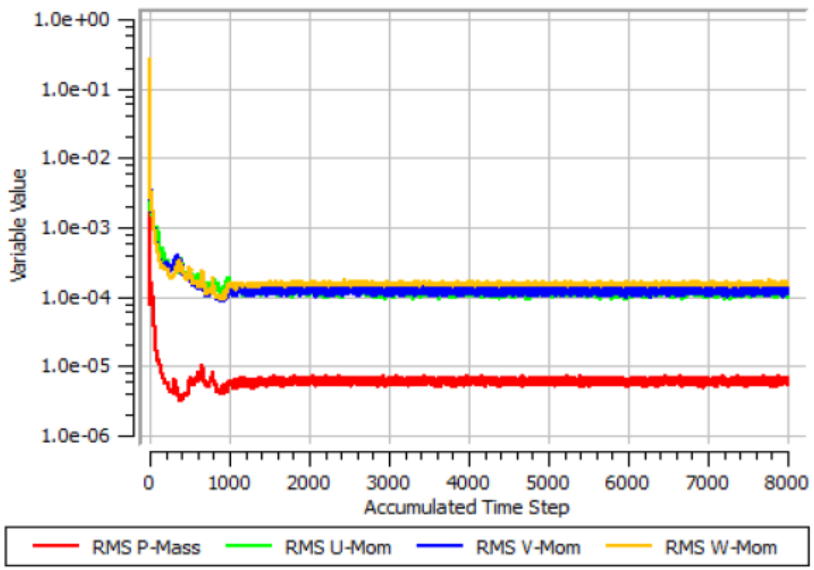


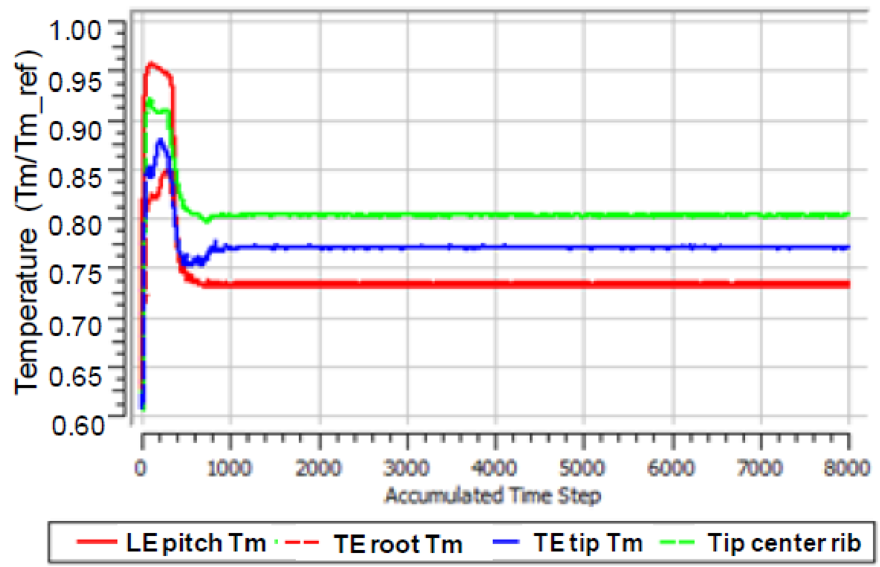


- Inlet total gas temperature obtained using Fine Turbo.
- Harmonic and mixing plane yielded similar absolute radial total temperature profiles.

Mixing Plane Tt(r) is Used

Model Convergence





- CHT steady state solution achieved
  - RMS residuals between 10^{-4} and 10^{-5}
  - Mass flow imbalance ≤ 0.05% of core flow.
  - Blade temperatures at different locations stable.

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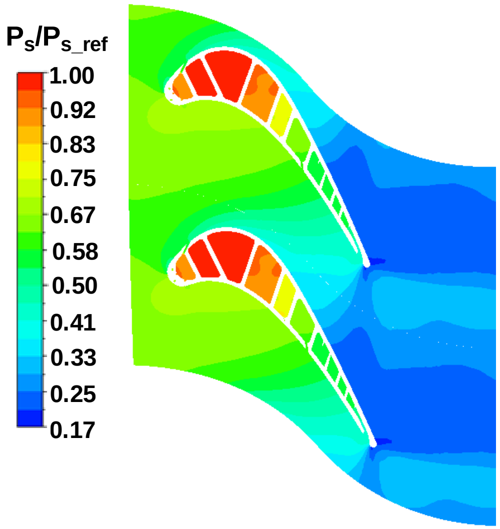
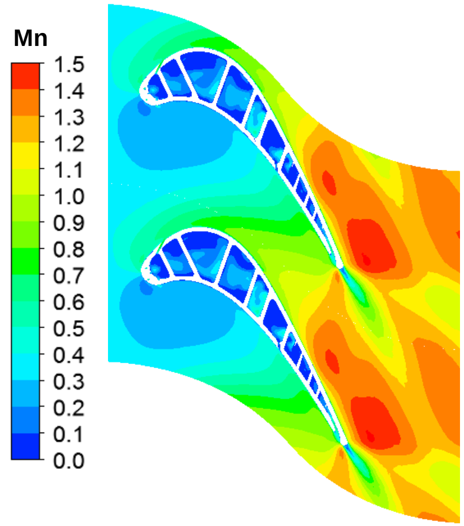
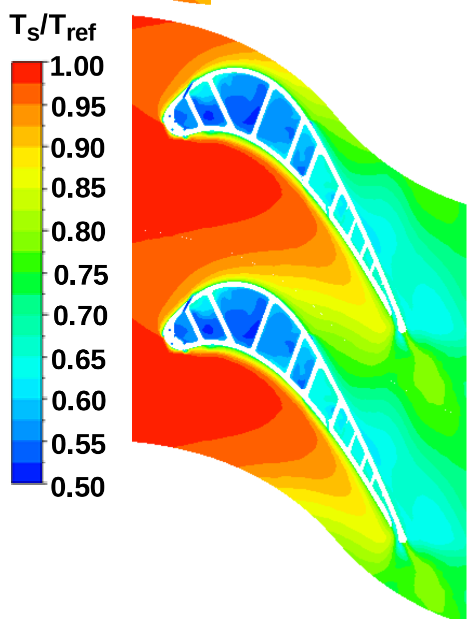
Results – External Gas Flow

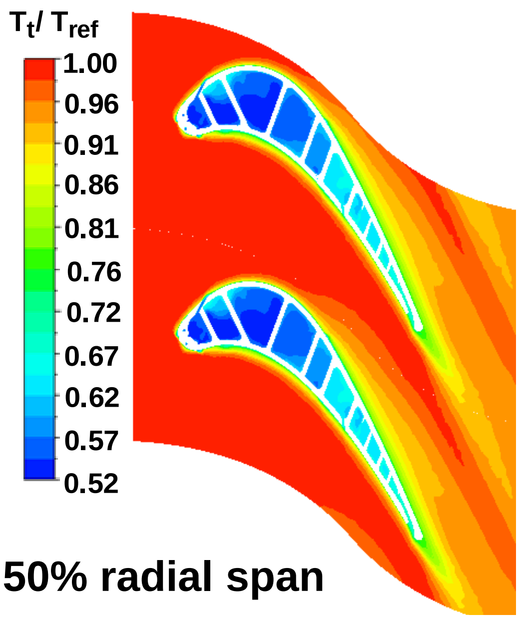




50% radial span

- Low pressure region in the throat due to supersonic flow.



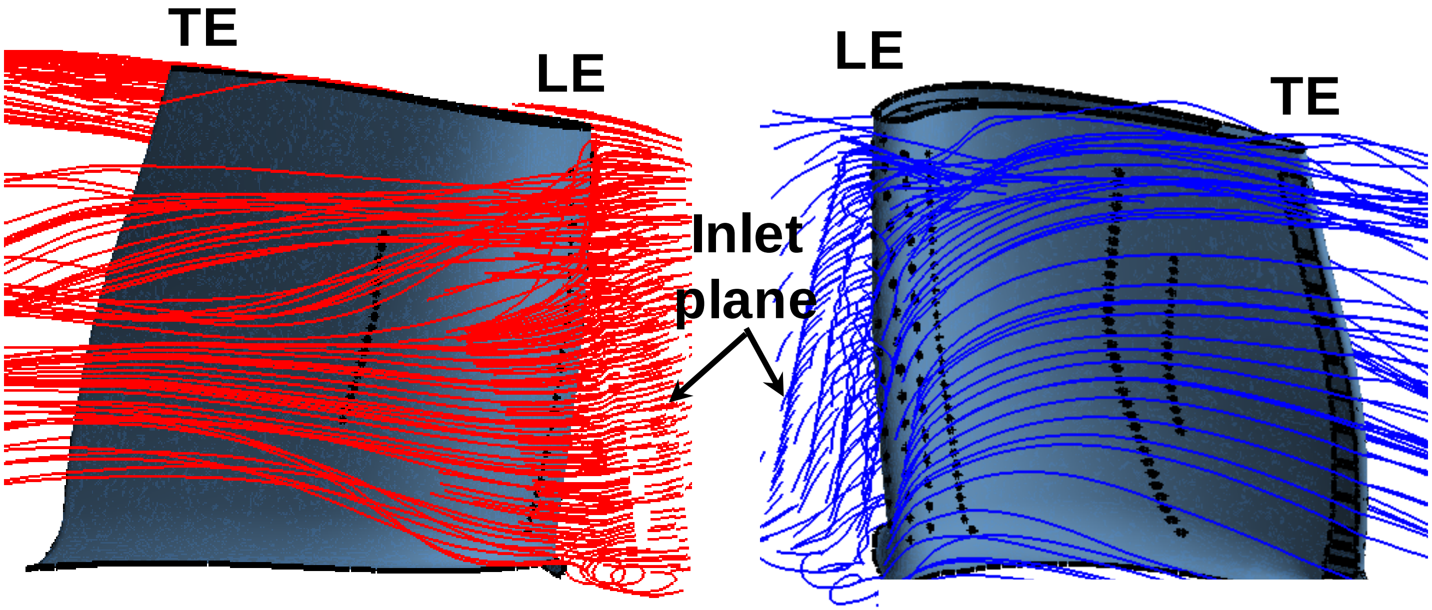


50% radial span

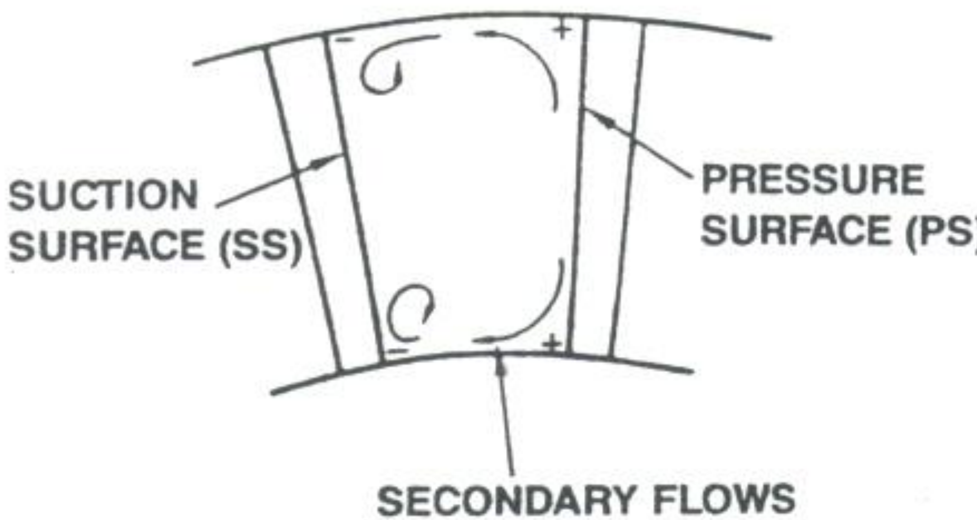
- Migration of hot gas towards the pressure side due to flow accelerating on the suction side.
- Low temperature layer covering most of suction side.

Why is suction side so cool relative to pressure side?

Results – External Gas Flow



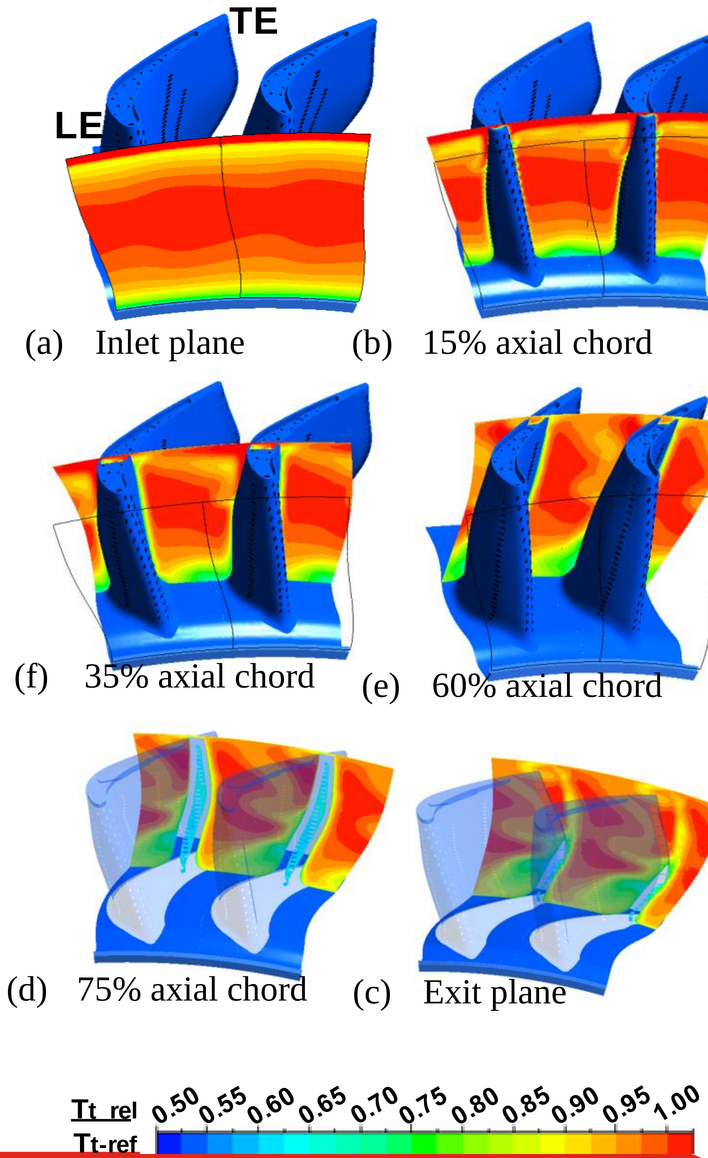
- Secondary flow vortices roll the end wall flows from hub and shroud toward mid-span in suction side.
- These vortices also disperse the flow to the entire span on pressure side.



Secondary flows impact film cooling effectiveness

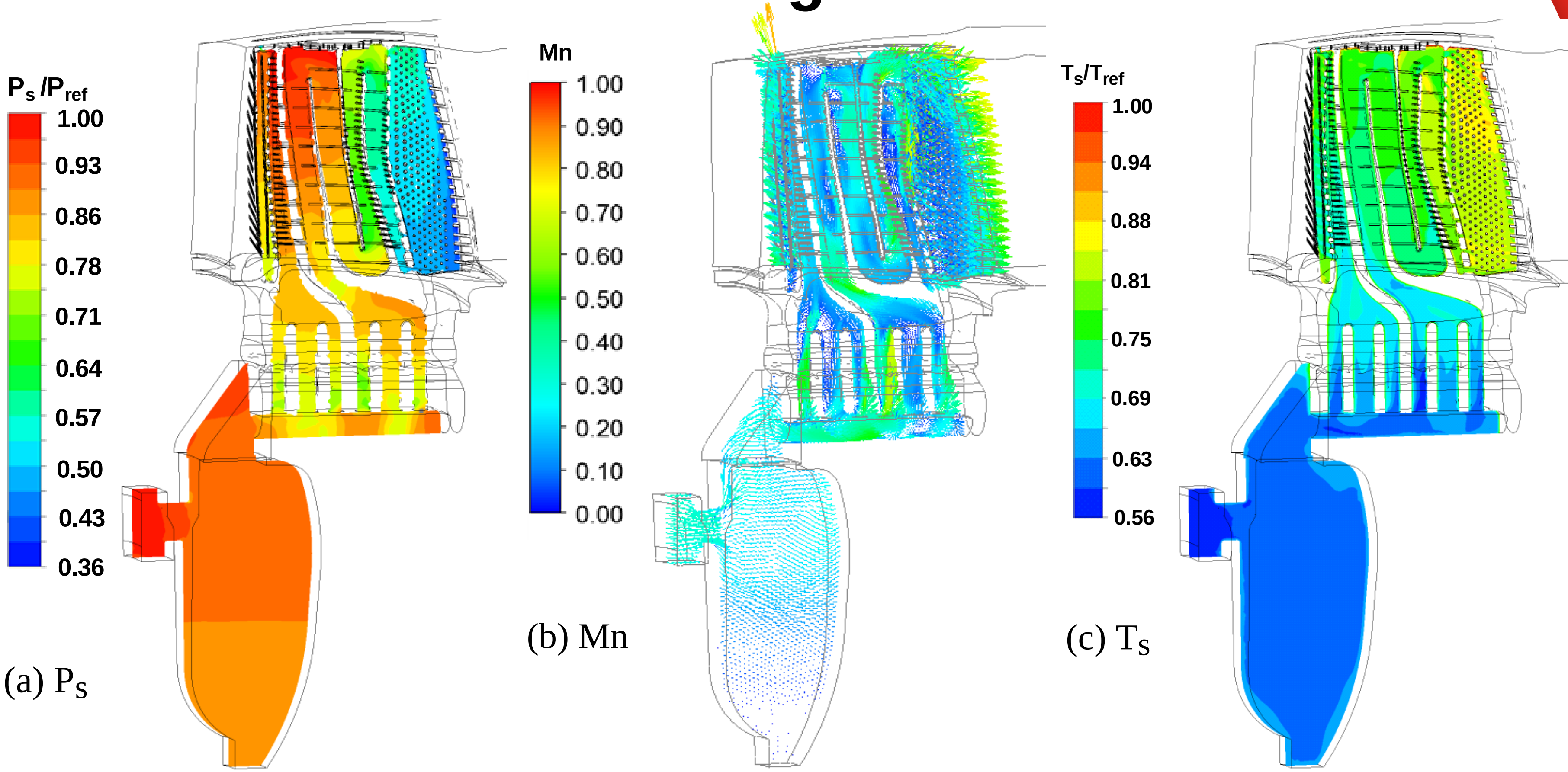
Results – External Gas Flow

- Secondary flow vortices gradually roll blade hub and tip cooling flows as flow progresses from the blade leading edge towards the trailing edge.
- The cool flow migration causes the trailing edge metal temperature radial gradient to worsen.
- Temperature gradients are directly promotional to stress.



TE durability will suffer due to secondary flow effects

Results – Internal Cooling Flows



- Pressure drop due to entrance losses compensated by pumping effect.
- Recirculation zones detected inside the blade core, seal plate cavity and Tangential on board ejector (TOBI). This will adversely affect heat transfer and cause pressure loses.
- Cooling air temperature increases as it travel through the serpentine. The cooling air temperature in the trailing edge region might not be adequate.

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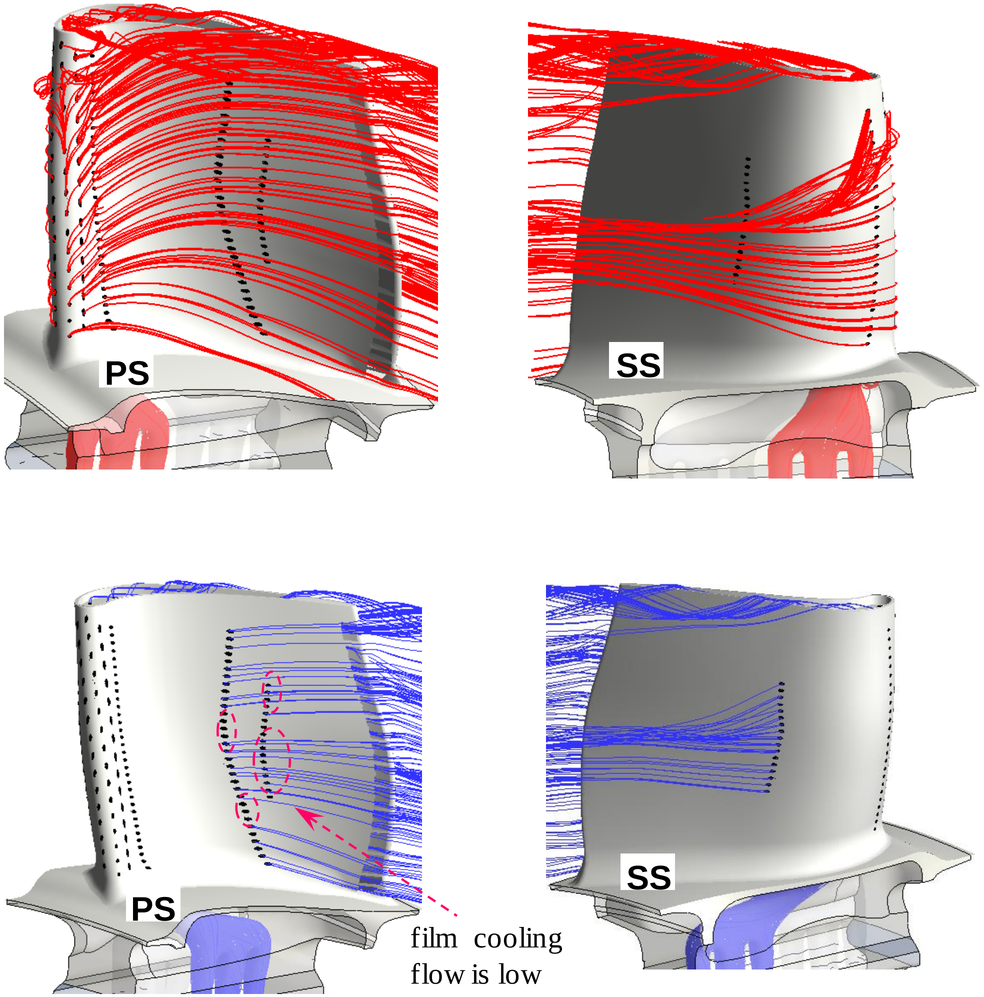
Results – Internal Cooling Flows



- Secondary flow vortices disrupt the cooling effectiveness from the film cooling. This effect is mainly seen on the suction side.

- Last row of cooling flows on the pressure side seem to have some ingestion.

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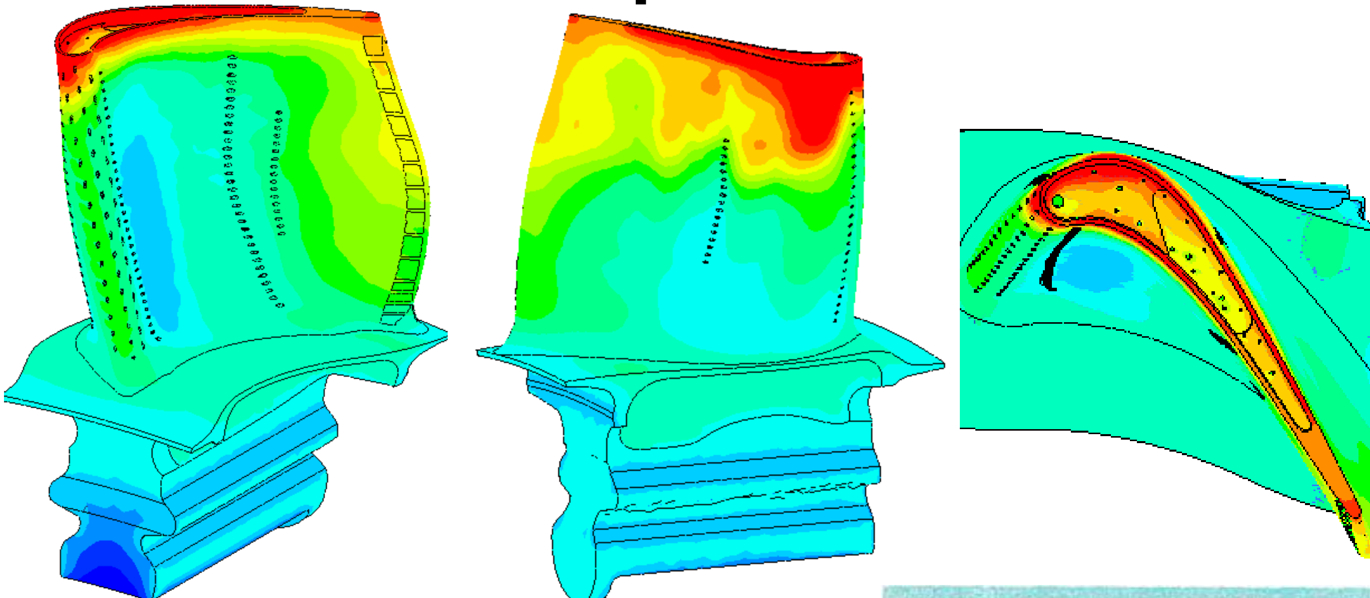
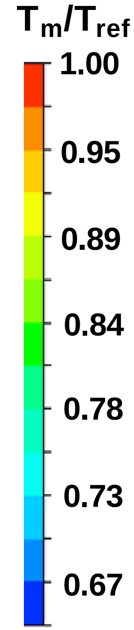
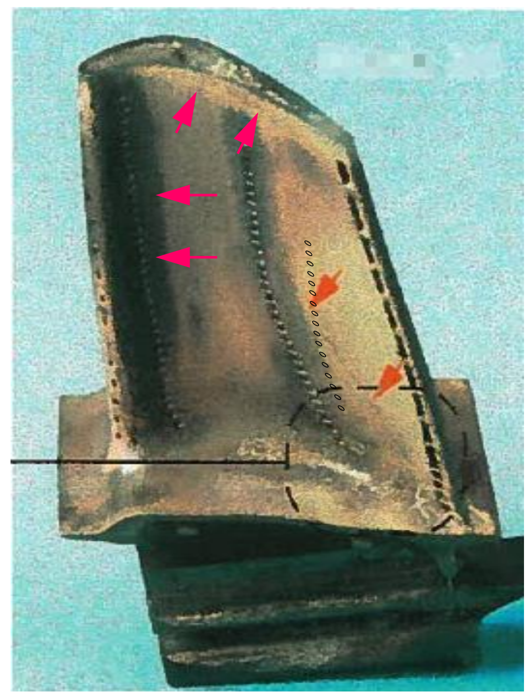
Results – Metal Temperatures





- Blade tip hot due to cooling flow rolling over from pressure side to suction side. Also, internal flow recirculation affected some zones.
- Trailing edge too hot due to last row of pressure side cooling holes not providing adequate cooling.
- Heat tinting field experience validate these results.



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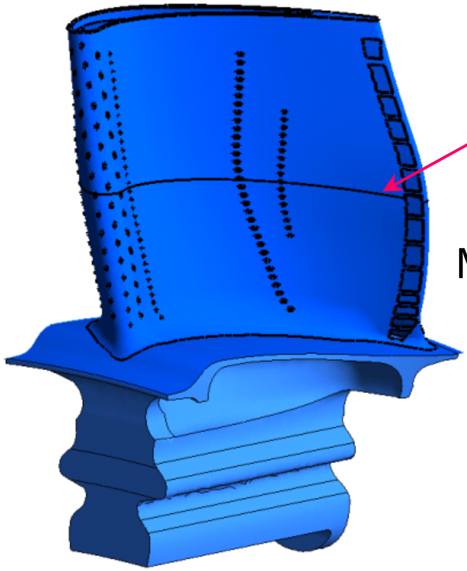
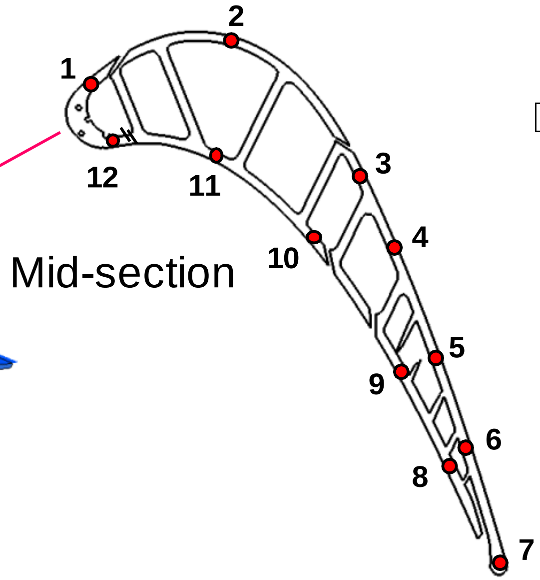
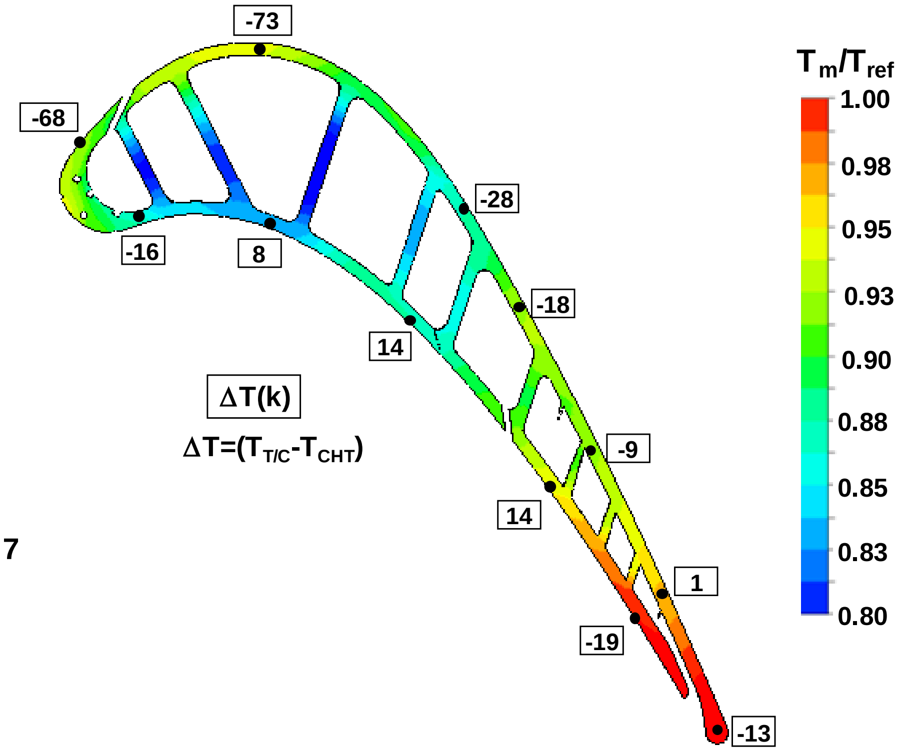
Results – Comparison Against TC Data







- Three blades instrumented at 50% radial span. 7 TCs on the suction side and 5 TCs on the pressure side. Blade to blade variation within 2%.
- Results within 20K (~50F) except the locations 1, 2, 3 on the suction side where ΔT_m can be as high as 73K (~140^{o}F).

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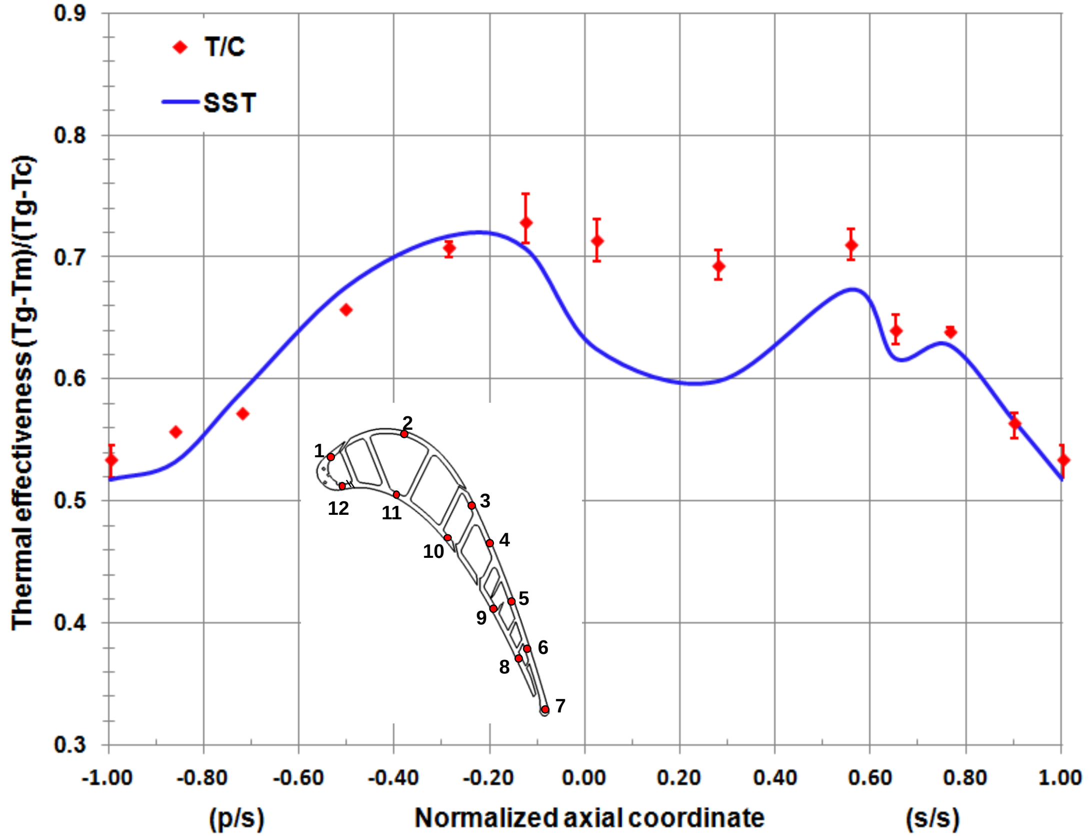
Results – Comparison Against TC Data



- CHT model with SST with transition does an adequate job predicting metal temperatures except on a few points on the suction side.

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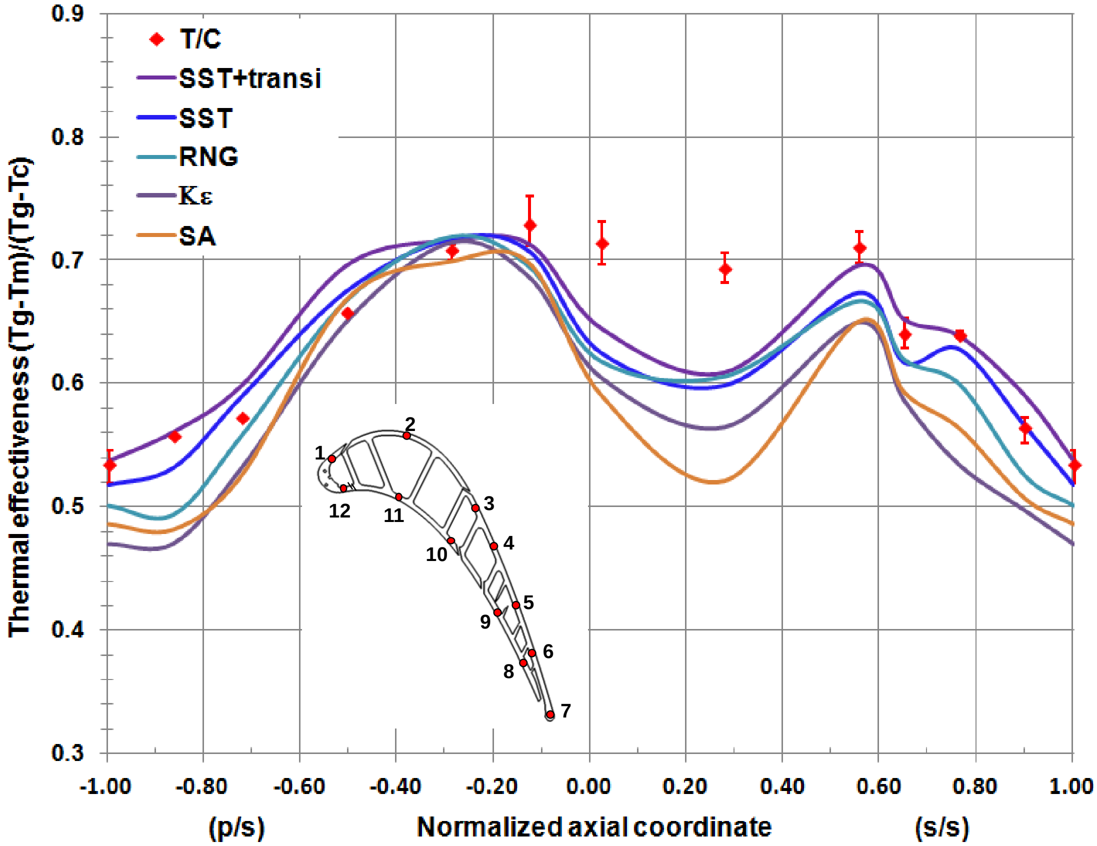
Results – Sensitivity to other Turbulent Models



- All models fail to adequately predict metal temperatures for a few points on the suction side.SA being the worst.
- Best model to predict metal temperatures on LE and TE is SST + Transition. K-ε being the worst in these locations.

Conclusions

- CHT reasonably predicts metal temperature for a filmed cooled blade. However, the metal temperature accuracy might not meet the life prediction requirements.

- Although temperature accuracy may not meet the life prediction requirement, CHT results can still provide detailed guidance for model calibration.

- Therefore, the CHT simulation could be a valuable design and analysis tool during the preliminary analysis or trade-off studies.

- Further investigation:
  - Investigate potential issues with combustor profile.
  - Explore different turbulence models with better fluid flow transition prediction capability.
  - Apply an unsteady inlet boundary condition for the CHT simulation to obtain the blade temperature response.

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Thank you !

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