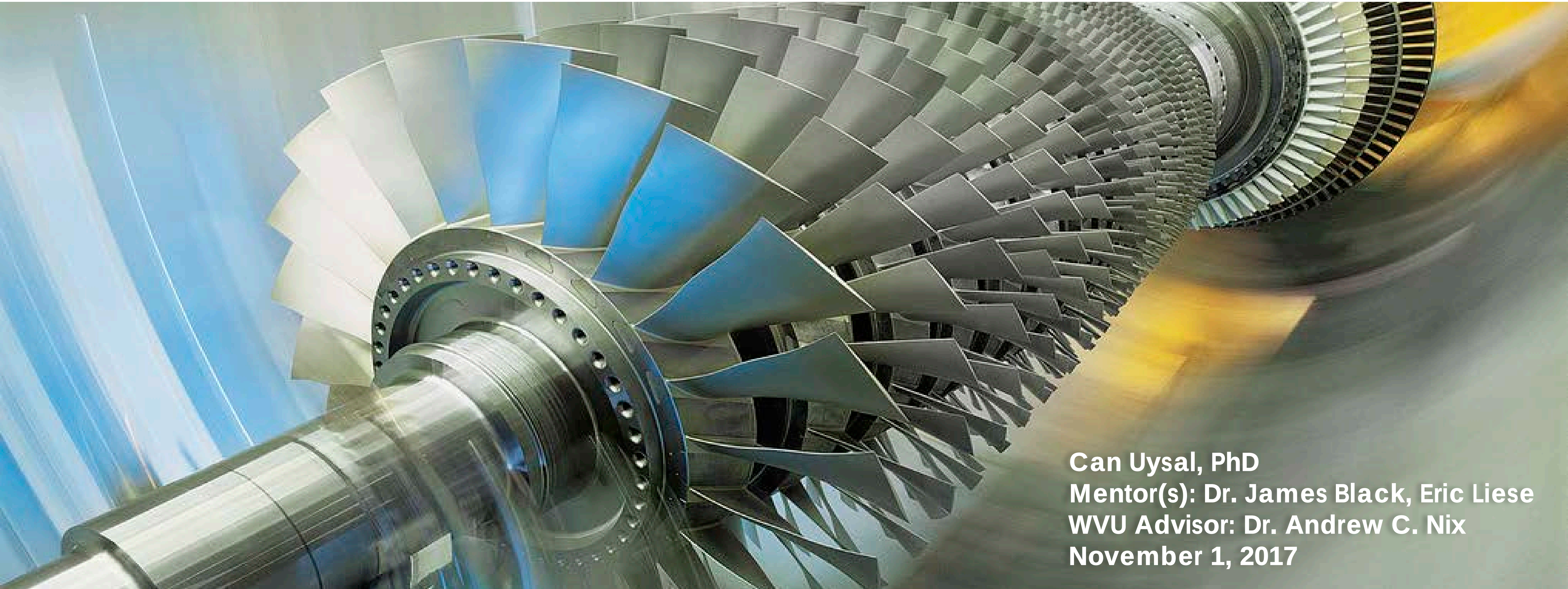
Cooled Gas Turbine Model

An Analytical Model to Investigate the Effects of Different Cooling Techniques on Gas Turbine Performance



Can Uysal, PhD
Mentor(s): Dr. James Black, Eric Liese
WVU Advisor: Dr. Andrew C. Nix
November 1, 2017

Schedule

- Introduction
- Theory and Development
- Cooled Turbine Model (CTM)
- Cooled Gas Turbine Model (CGTM)
- Sensitivity Analysis with CGTM
- The Effect on Performance from Different Blade Cooling Configurations

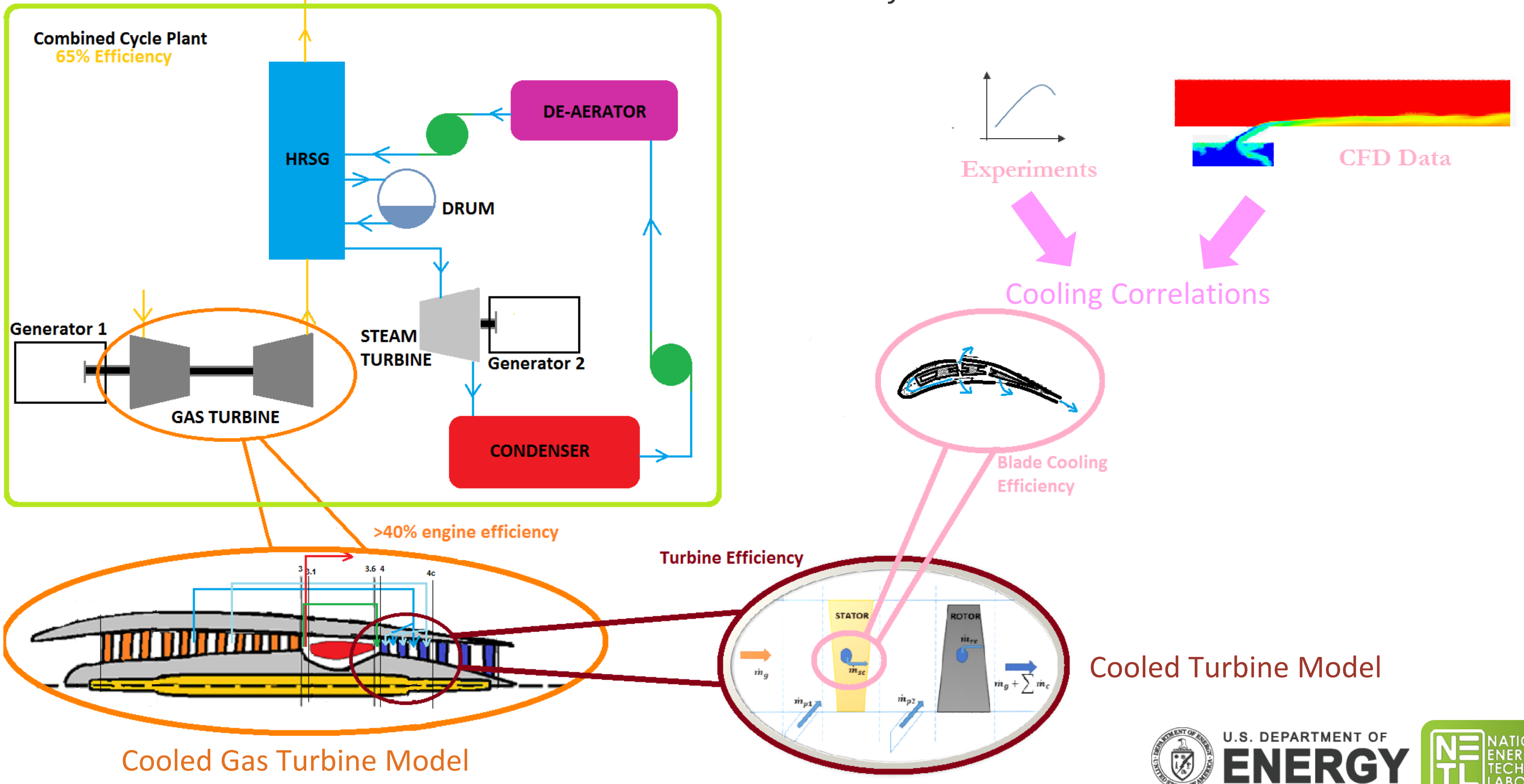
Introduction

- **Project aims to develop an aerothermal engine model that is capable of evaluating the impact of**
  - Different cooling configurations
  - Seal Designs
  - Purge Configurations
  - Material properties
  - Thermal Barrier Coatings

- **Ultimate goal is to be able to identify and evaluate cooling technologies that will lead to >40% gas turbine efficiency to support CC efficiency of 67%.**
- **The model will also have the capability of analyzing the effects of pressure gain combustion, supercritical CO_2 turbines and cooling of the coolant flow on engine performance**

Introduction

The location of Cooled Gas Turbine Model in Combined Cycle Performance Calculations

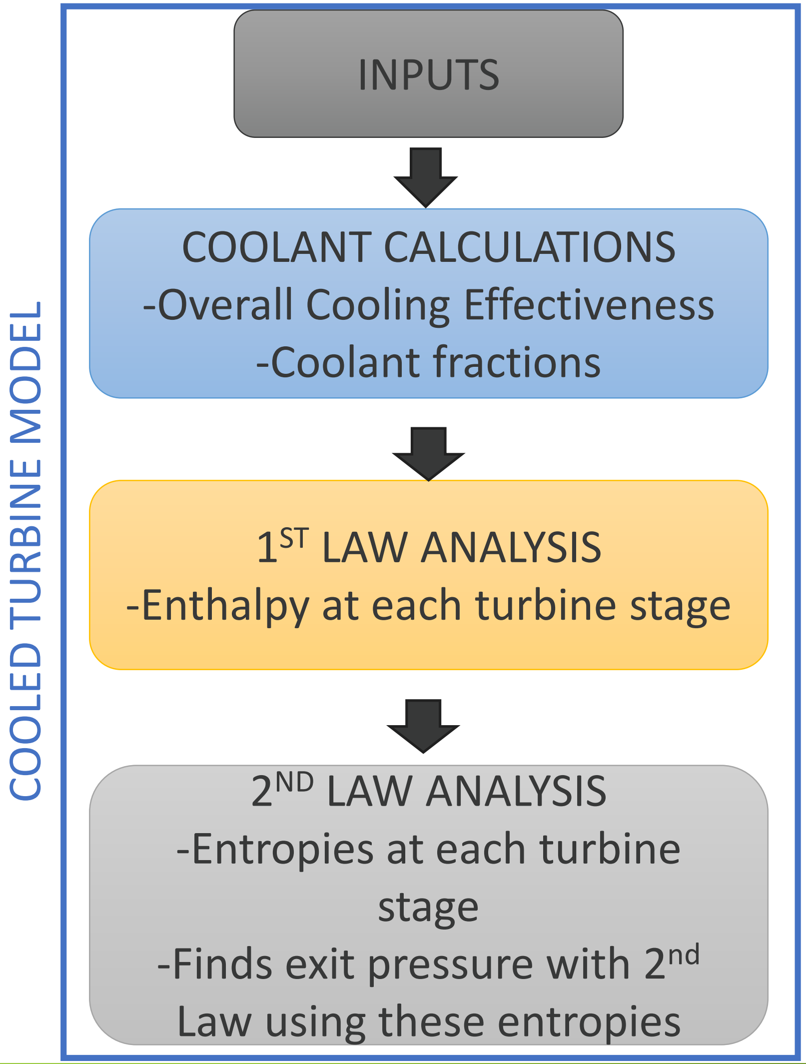


Cooled Turbine Model

Theory

Literature Review of similar models indicate a general flowchart of such a model should include 3 major sections:

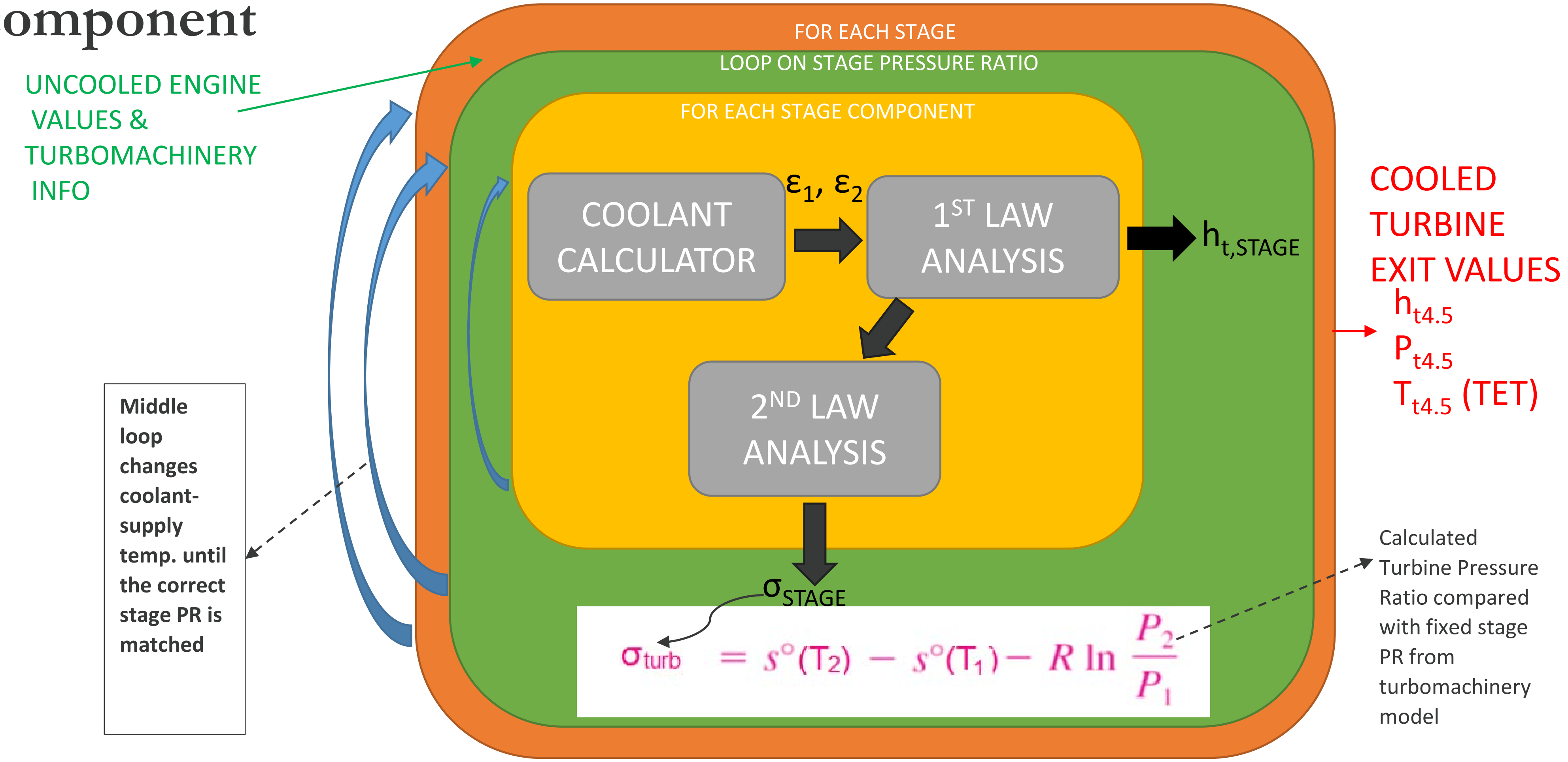
1. Cooling Flowrates should be calculated based on cooling technology
2. 1st Law Analysis using these flowrates will give enthalpy drop
3. 2nd Law Analysis using information from previous sections will give exergy information



Cooled Turbine Model

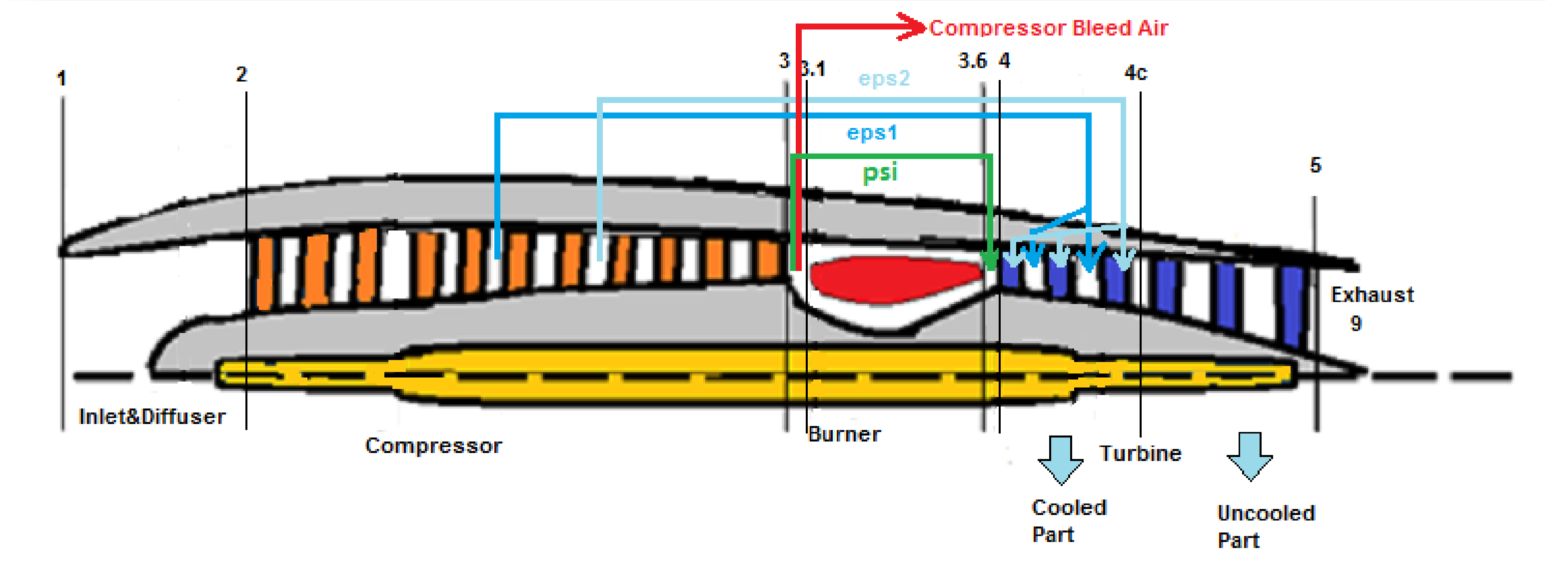
Development

- The **cooled turbine model** repeats the previous analysis at each stage, for each component



Cooled Gas Turbine Model (CGTM)

- Cooled Gas Turbine Model calculations use uncooled engine on-design and turbomachinery design section results
- CGTM uses methane combustion thermodynamic property tables generated by using REFPROP[1] and GASEQ Software[2]



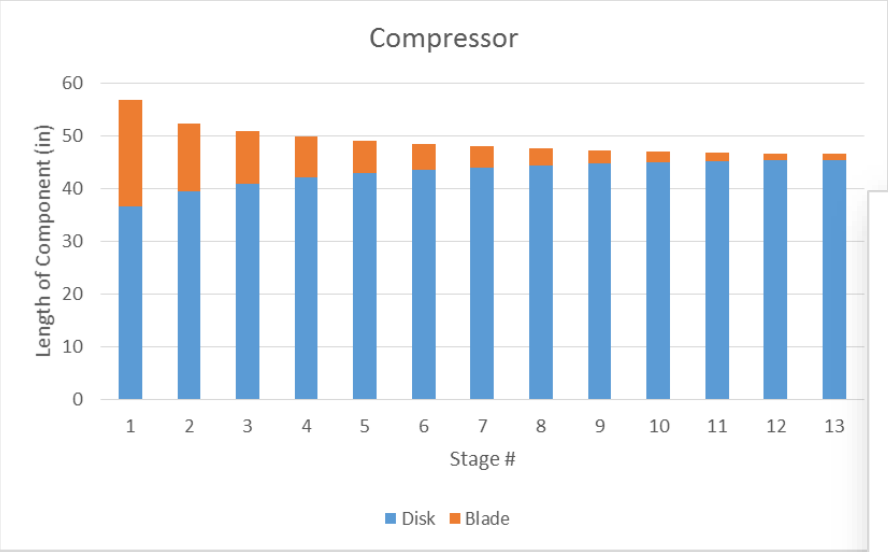
eps1=coolant fraction used for stator cooling eps2=coolant fraction used for rotor cooling psi= coolant fraction used for transition cooling

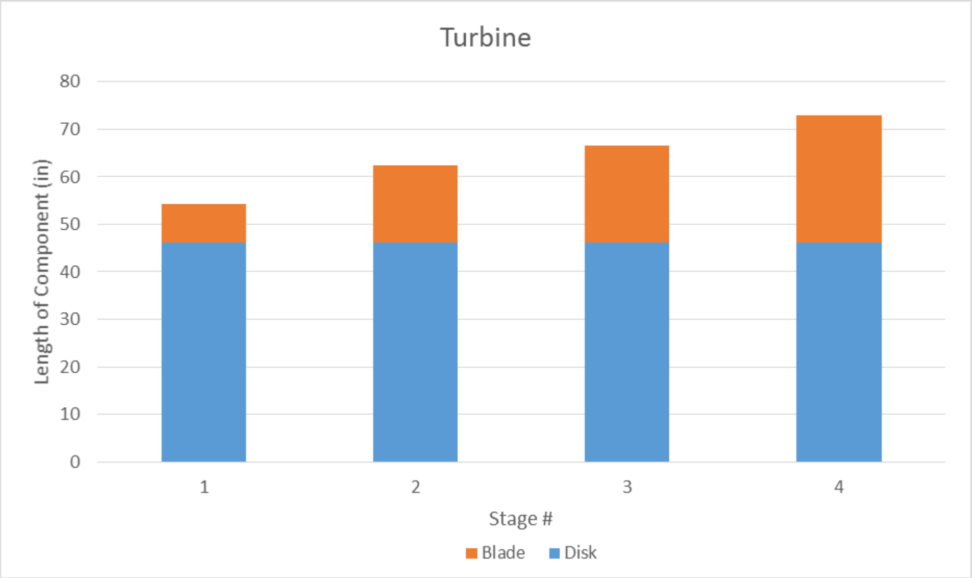
[1] National Institute of Technology (NIST), REFPROP Software using Standard Reference 23, Version 8.0
[2] GASEQ Software-Chemical Equilibria in Perfect Gases by Chris Morley, <http://www.gaseq.co.uk>

Cooled Gas Turbine Model

Generating Turbomachinery Data

CGTM calculates some of the essential turbomachinery information for cooling analysis such as stage velocity triangles, stage entry/exit flow angles, number of stages, stage pressures and temperatures





Cooled Gas Turbine Model

Validations

- Model is calibrated with three H-class gas turbines: Siemens SGT6-8000H, General Electric GE7HA.02, and Mitsubishi Heavy Industries M501J
- Cycle calculations and component performance results were validated with GasTurb12 Software via tests compares the outputs of two programs side-by-side for specified engine parameters and tests compare the response of two programs to the same input parameter varied in a predetermined range
- Number of stages, blade heights and disk dimensions were used in turbomachinery design section validation with available public data for the selected gas turbines
- Power, Heat Rate, Exhaust Temperature, and number of stages were used with engine parameters to match the real engine data

Cooled Gas Turbine Model

Calibrations

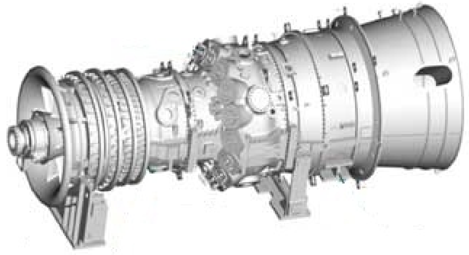
SGT6-8000H	CGTM	Published Value [1]
Power	296 MW	296 MW
Thermal Efficiency	40.0 %	40.0%
Heat Rate	8526 Btu/kWh	8530 Btu/kWh
Exhaust Temperature	1159 ^{0}F	1160 ^{0}F

[2]

GE7HA.02	CGTM	Published Value [1]
Power	347 MW	346 MW
Thermal Efficiency	42.2 %	42.2%
Heat Rate	8084 Btu/kWh	8080 Btu/kWh
Exhaust Temperature	1153 ^{0}F	1153 ^{0}F

[3]

M501J	CGTM	Published Value [1]
Power	327 MW	327 MW
Thermal Efficiency	41.0 %	41.0 %
Heat Rate	8325 Btu/kWh	8325 Btu/kWh
Exhaust Temperature	1178 ^{0}F	1176 ^{0}F

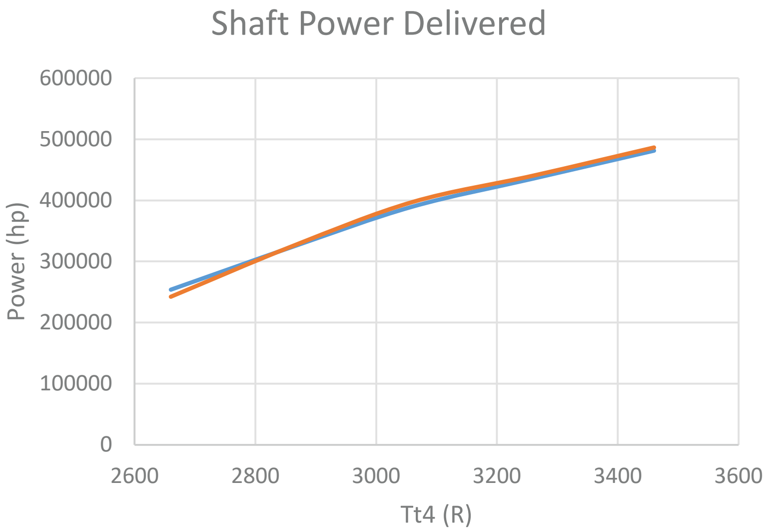


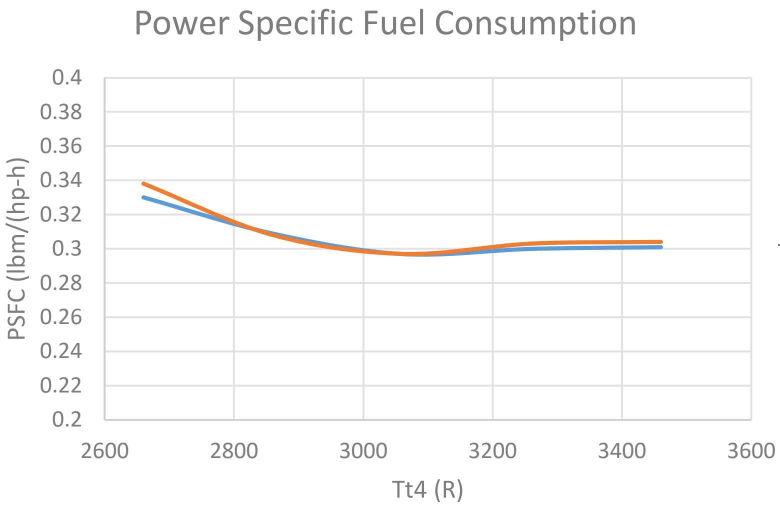
[4]

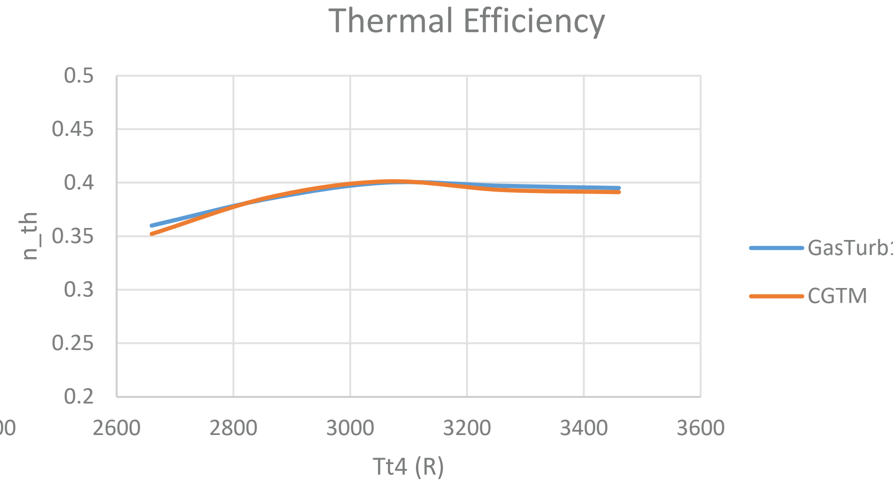
[1] Gas Turbine World, "2015 Performance Specs", 31st Edition, January-February 2015, Volume 45, No.1, Pequot Publishing Inc.
[2] Siemens Global Website-Pressebilder, retrieved from http://www.siemens.com/press/de/pressebilder/?press=/de/pressebilder/2016/power-gas/im2016010336pgde.htm&content[]=PG
[3] GE Power, "GE7HA.01/02 Gas Turbines (60Hz) Fact Sheet 2016", retrieved from https://powergen.gepower.com/products/heavy-duty-gas-turbines/7ha-gas-turbine.html on 08/16/2016
[4] De-Centralized Energy Journal, 2010, "Gas Turbines Breaking the 60% Eff. Barrier", Vol.11, Issue 3, retrieved from <http://www.decentralized-energy.com/articles/print/volume-11/issue-3/features/gas-turbines-breaking.html>

Cooled Gas Turbine Model

Validations







Sample Test Results for a generic H-Class engine scenario

Parameter	Definition	GasTurb12*	CGTM	Unit	%Difference
m_c	Total Coolant Flow Fraction (charged)	14.0	14.0	%	-
η_{cH}	Compressor Isentropic Eff.	0.840	0.827	-	1.57
f	Burner fuel-to air ratio	0.02796	0.02813	-	0.61
η_{tH}	Turbine Isentropic Eff.	0.928	0.921	-	0.75
π_{tH}	Turbine Pressure Ratio	0.0567	0.0563	-	0.71
P_{t9}/P_0	Exhaust Pressure Ratio	1.03	1.04	-	0.97
PWSD	Shaft Power Delivered	417266	421998	hp	1.13
PSFC	Power Specific Fuel Consumption	0.296	0.298	lbm/(hp.hr)	0.68
η_{th}	Thermal Efficiency	40.2	40.0	%	0.50
HR	Heat Rate	8508	8537	Btu/kWh	0.34

[*] GasTurb12 Software by GasTurb GmbH c/o Institute of Jet Propulsion and Turbomachinery Templergraben 55, 52062 Aachen, Deutschland

Ainley, D.G., (1957), "Internal Air Cooling for Turbine Blades: A General Design Survey", Aeronautical Research Council Reports and Memo. 3013

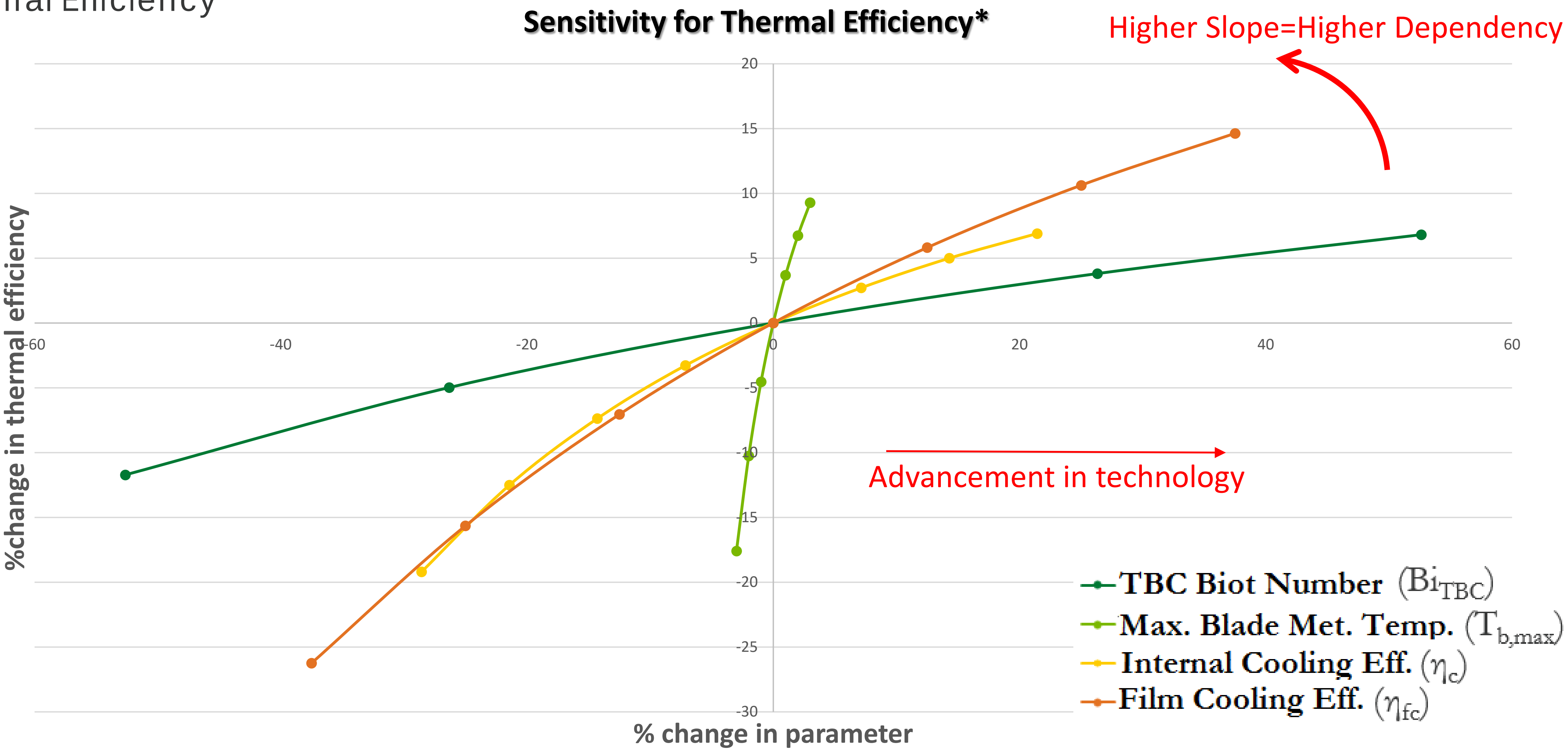
Sensitivity Analysis

- **Sensitivity analysis on some general cooling input parameters of CGTM is made by using following variables:**
  - ➢ Blade Metal Material Properties (through reducing Bi_m and increasing max. allowable metal temperature($T_{b,max}$))
  - ➢ Thermal Barrier Coating Material Properties (through Bi_{TBC})
  - ➢ Internal Cooling Efficiency (η_c)
  - ➢ Film Cooling Efficiency (η_{fc})
- **The effects of changing these parameters on gas turbine key performance parameters (power, heat rate, thermal efficiency) were analyzed separately**
- **Sensitivities of the performance parameters on these cooling variables are found and a sensitivity chart is obtained for each performance parameter**
- **Details of this part is in ASME GT-63480* paper presented in ASME TurboExpo 2017**

[*] Uysal, S. C., Liese, E.C., Nix, A.C., and Black, J.B., (2017),"A Thermodynamic Model to Quantify the Impact of Cooling Improvements on Gas Turbine Efficiency", GT2017-63480, TurboExpo 2017, Charlotte, NC

Sensitivity Analysis

Thermal Efficiency



[*] Uysal, S. C., Liese, E.C., Nix, A.C., and Black, J.B., (2017),"A Thermodynamic Model to Quantify the Impact of Cooling Improvements on Gas Turbine Efficiency", GT2017-63480, TurboExpo 2017, Charlotte, NC

The Effect on Performance from Different Blade Cooling Configurations

Introduction

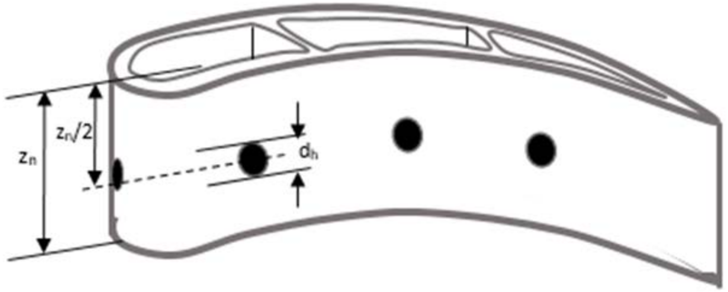
- In this section, an advanced coolant calculation algorithm is developed by combining the "heat-exchanger" method from Ainley[*] and Consonni[**] , with the existing semi-empirical method of CTM
- Values for $\overline{St_{in}}$ and $\overline{\varepsilon_{fc}}$ are calculated from different correlations and experimental/CFD data, respectively and used in an iterative calculation procedure on internal cooling effectiveness
- Users are allowed to specify a blade cooling configuration (both internal and external) to see the impact on engine performance
- New algorithm is modelled as a "coolant calculator" that replaces the existing one with the same outputs, but without changing the cooled turbine 1st Law and 2nd Law Analysis modules

[*] Ainley, D.G., (1957), "Internal Air Cooling for Turbine Blades: A General Design Survey", Aeronautical Research Council Reports and Memo. 3013
[**] Consonni S.,(1992) "Performance Prediction of Gas/Steam Cycles for Power Generation", PhD Dissertation to Princeton University, Center for Energy and Environmental Studies

The Effect on Performance from Different Blade Cooling Configurations

Development of the Advanced Coolant Calculator-Assumptions

1. Cooling flow is equally divided between the pressure and suction sides
2. Blade curvature and compressibility effects are negligible
3. No flow and temperature variations along the radial direction (i.e. adjacent blade strips)
4. Cross-flow effects between adjacent strips are negligible
5. All internal cooling segments will have the same ε_c so that the coolant heating within the blade is same for all internal segments.
6. Coolant fraction required by the film cooling is supplied entirely by the internal cooling.



Element of analysis (repeated from hub to tip)

7. Average adiabatic film cooling effectiveness for the blade strip can be obtained by the Seller's Method
8. Average internal cooling Stanton number can be found by a weighted average based on the chord length fractions of each applied internal cooling method
9. Pressure losses in the cooling channels are included in the performance calculations by the entropy loss term for internal friction

[*] Uysal, S. C., (2017), "Analytical Modelling of the Effects of Different Gas Turbine Cooling Techniques on Engine Performance", PhD Dissertation, West Virginia University, ProQuest Publishing, Ann Arbor, MI

The Effect on Performance from Different Blade Cooling Configurations

Methodology

- The NTU equation obtained by Consonni** is transformed in this algorithm to calculate the coolant fraction with «known» NTU

$$\frac{\dot{m}_c}{\dot{m}_g} = \left(\frac{4\bar{S}t_{in}\vartheta_i n_p (\frac{H}{d})}{NTU} - 1 \right) \frac{1}{(1+Bi_m)} \frac{\alpha_h}{C_g} \frac{St_g}{\bar{S}t_{in}} \frac{c_{p,g}}{c_{p,cl}}$$

- Where NTU is known from re-arranging the result of the heat exchanger analysis by Ainley*, with $\varepsilon_{c,ext}$ calculated by using the ε_c and 1D HT scheme

$$NTU = -ln\left(1 - \varepsilon_{c,ext} \frac{T_{m,ext} - T_{tcl,in}}{T_{tg*} - T_{tcl,in}}\right)$$

- The value of $T_{m,ext}$ is dependent on the cooling technology applied and can be found from using the Biot number and effectiveness definitions:

$$\begin{cases} T_{m,ext} = Bi_m\left(T_{tg*} - T_w\right) + T_{m,int} & no\ TBC \\ T_{m,ext} = \dfrac{Bi_m T_w + Bi_{TBC} T_{m,int}}{(Bi_m + Bi_{TBC})} & with\ TBC \end{cases}$$

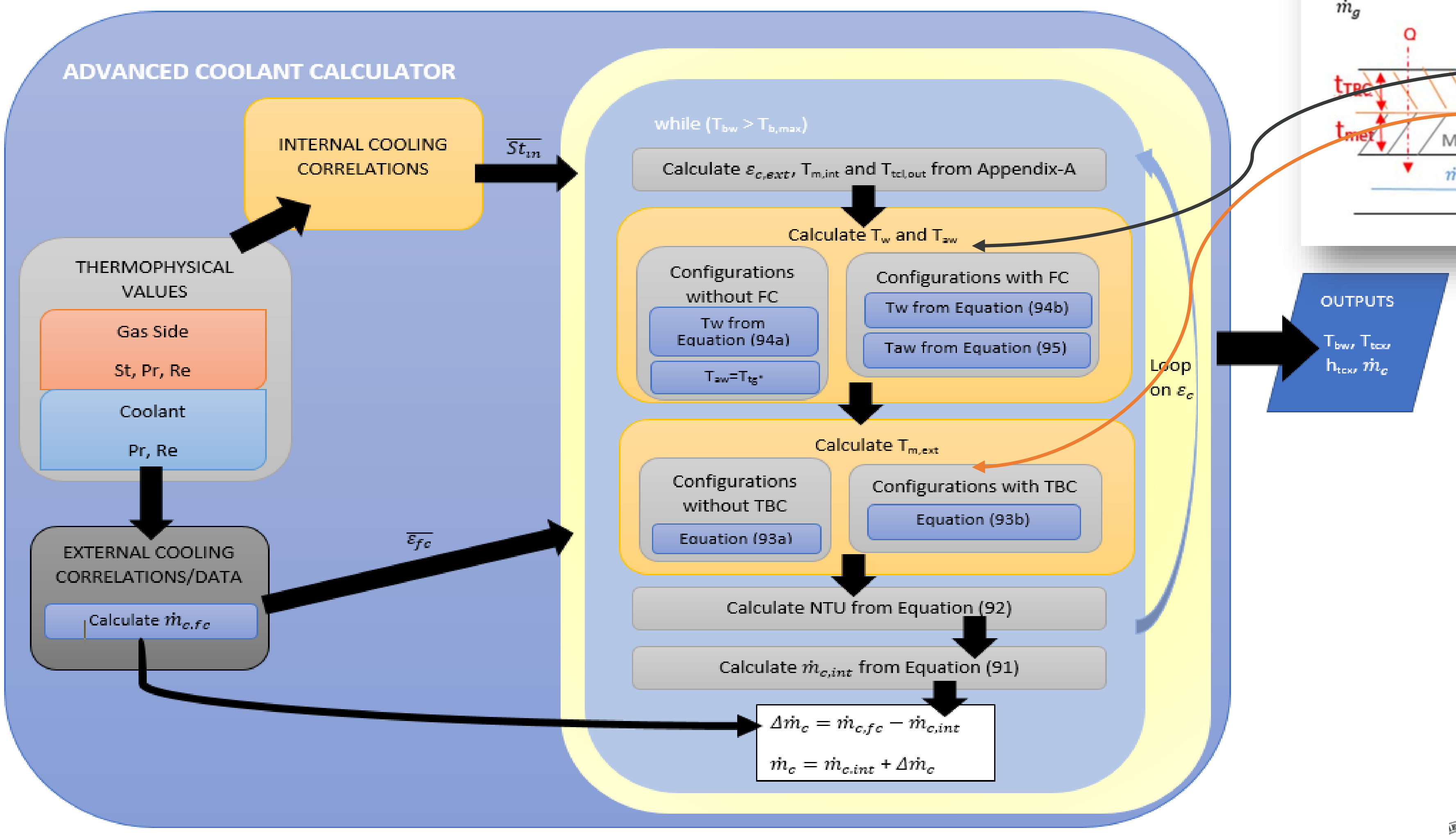
- The outer wall temperature T_w is dependent on the application of film cooling

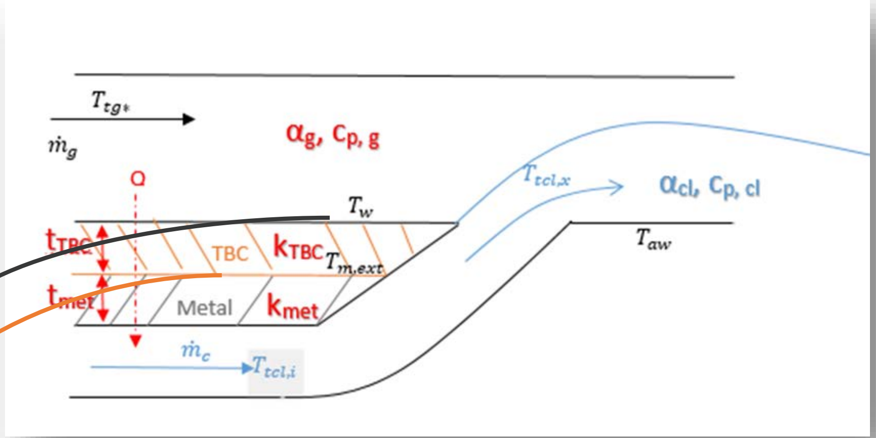
$$\begin{cases} T_w = T_{tg*} - \dfrac{T_{tcl,out} - T_{tcl,in}}{Bi_m}\left(\dfrac{1}{\varepsilon_{c,ext}} - \dfrac{1}{\varepsilon_c}\right) & no\ Film\ Cooling \\ T_w = T_{taw} - \dfrac{T_{tcl,out} - T_{tcl,in}}{Bi_m}\left(\dfrac{1}{\varepsilon_{c,ext}} - \dfrac{1}{\varepsilon_c}\right) & with\ Film\ Cooling \end{cases}$$

[*] Ainley, D.G., (1957), "Internal Air Cooling for Turbine Blades: A General Design Survey", Aeronautical Research Council Reports and Memo. 3013
[**] Consonni S.,(1992) "Performance Prediction of Gas/Steam Cycles for Power Generation", PhD Dissertation to Princeton University, Center for Energy and Environmental Studies

The Effect on Performance from Different Blade Cooling Configurations

Algorithm

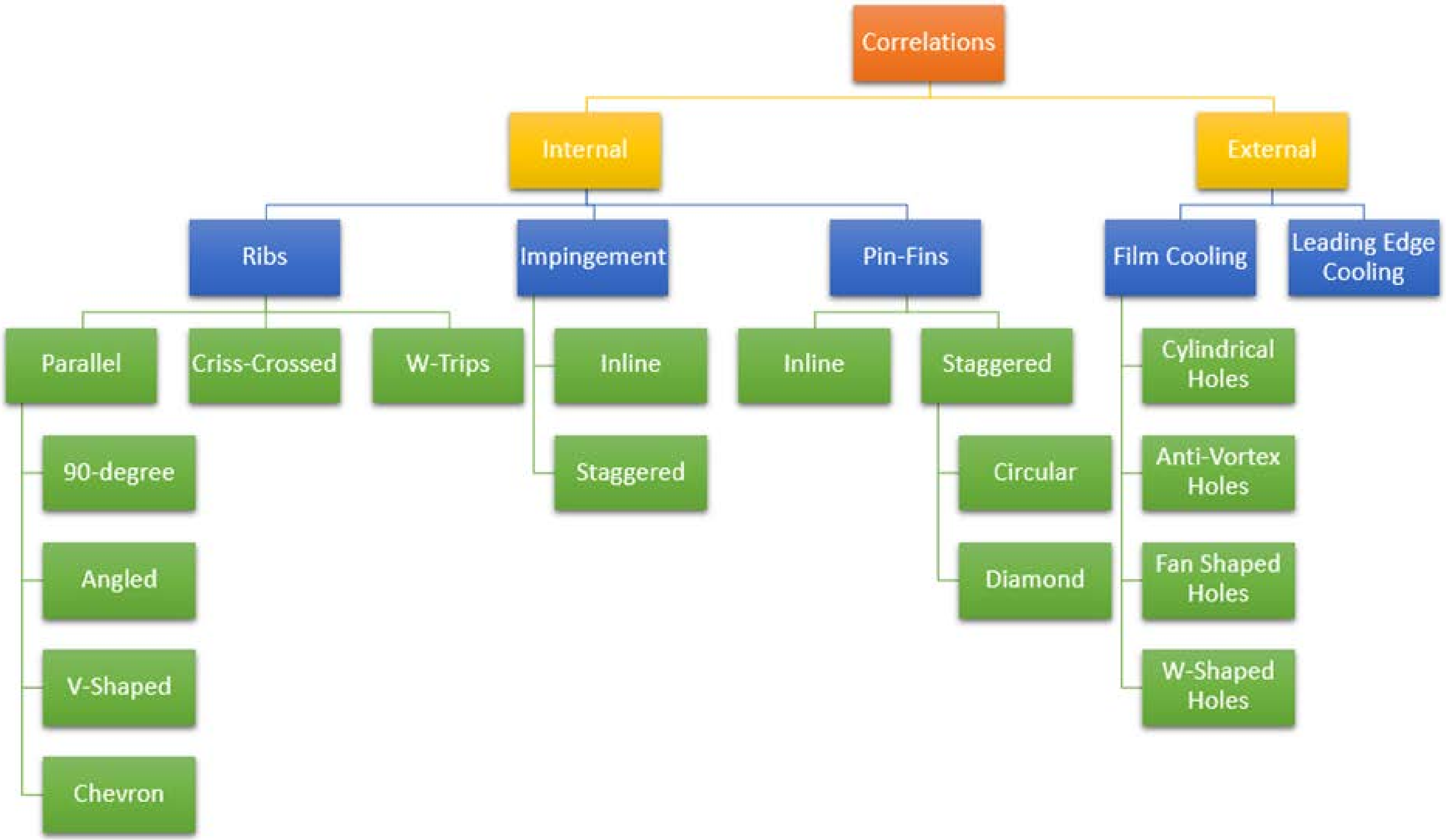




[*] Uysal, S. C., (2017), "Analytical Modelling of the Effects of Different Gas Turbine Cooling Techniques on Engine Performance", PhD Dissertation, West Virginia University, ProQuest Publishing, Ann Arbor, MI

The Effect on Performance from Different Blade Cooling Configurations

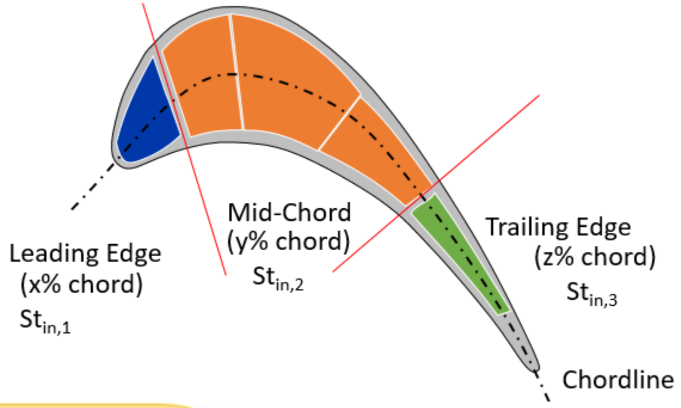
Internal and External Cooling Correlations

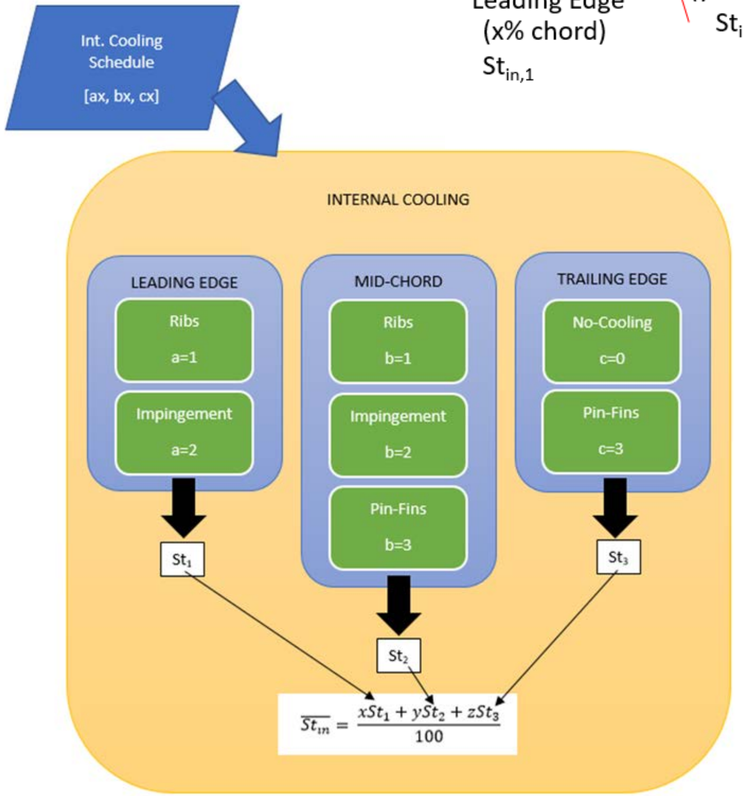


The Effect on Performance from Different Blade Cooling Configurations

Internal Cooling Subsytem

- User enters an internal cooling schedule indicating cooling types: $[LE, MC, TE]_{1x3}$
- Algorithm picks the regarding correlation for each blade segment and calculates a local Stanton number
- Local Stanton numbers are then span-averaged by using chord length as a weighting factor to obtain $\overline{St_{in}}$
- This value is then used in the iterative coolant calculation procedure



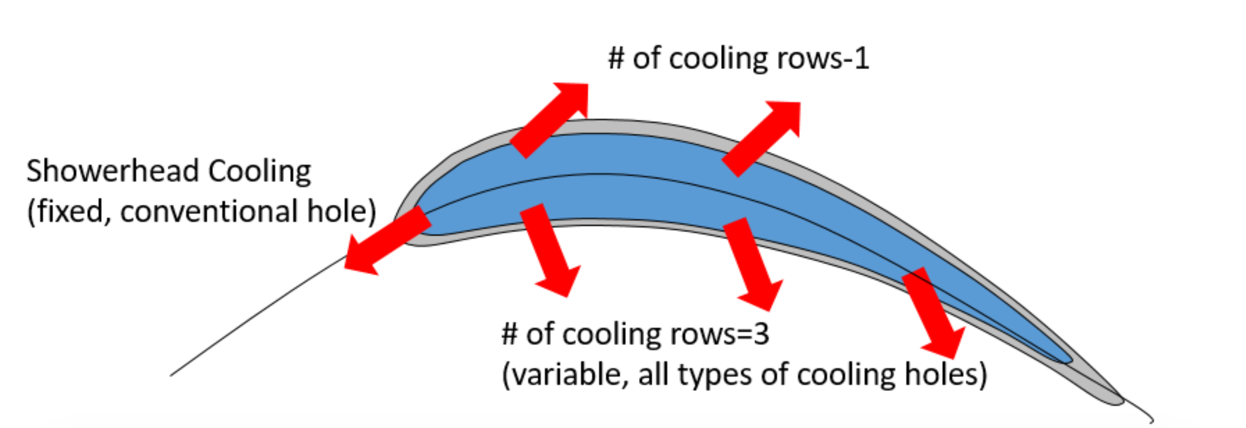


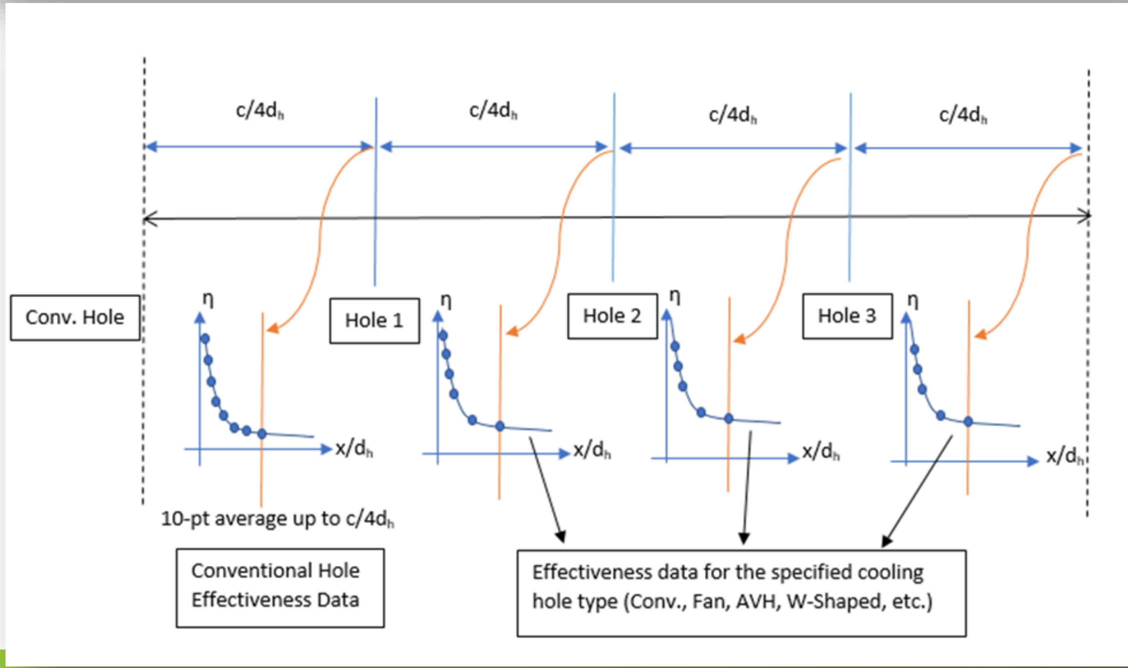
The Effect on Performance from Different Blade Cooling Configurations

External Cooling Subsystem

- In the external cooling sub-system, the film cooling efficiencies that are obtained either through experiments or CFD is used to obtain blade average adiabatic film cooling efficiency ($\overline{\varepsilon_{fc}}$)
- Based on the number of cooling hole rows, algorithm distributes the holes over the chord evenly
- After distributing the holes over the chord, algorithm picks the corresponding span averaged effectiveness data set (from experiment or CFD) for the specified hole type and blowing ratio
- Effectiveness data is read up to the x/d location that corresponds to the location of the next cooling hole
- Algorithm calculates an average span-averaged adiabatic film cooling effectiveness value by using Seller's Method*

$$\bar{\eta}_{ad,pressure/suction} = \sum_{i=1}^{\#of\ cooling\ rows} \eta_{f,i}\left[\prod_{j=0}^{i-1}(1-\eta_{f,j})\right]$$





The Effect on Performance from Different Blade Cooling Configurations

Determining the Analysis Inputs

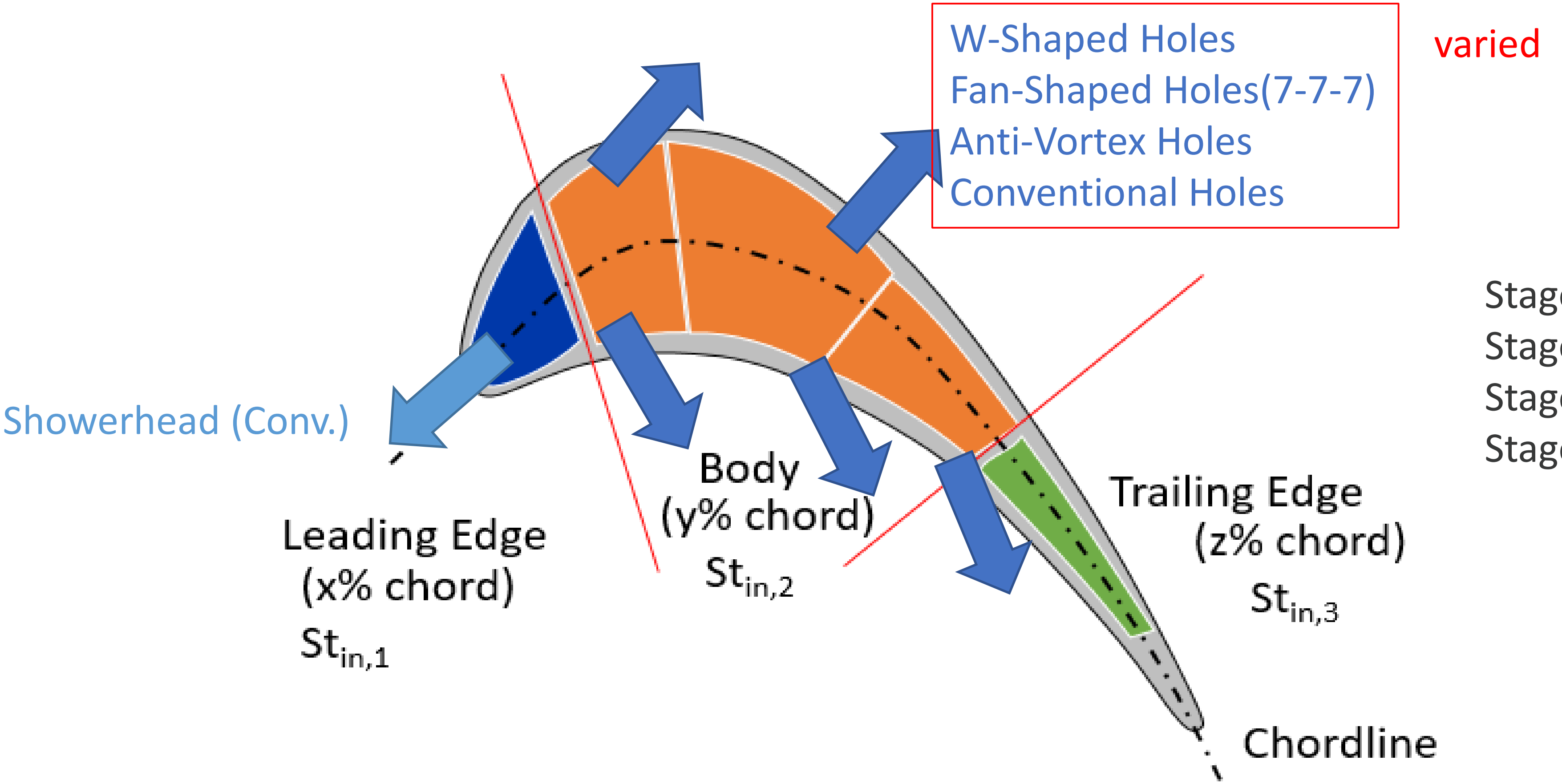
- With the existing internal and external cooling correlations and CFD data built-in to the advanced coolant calculator, it is possible to analyze 1024 logical blade cooling configurations
- To determine the analysis cases, the blade internal cooling configurations were determined from the configurations mostly used in recent advanced gas turbines: LE→ Impingement, Mid-Chord → Ribs, TE→ Pin-Fins
- The effect of the effects of film cooling hole type, mid-chord internal cooling type, trailing edge internal cooling type, and the number of film cooling rows were analyzed
- The base cooling analysis inputs used for this analysis are determined from typical values used in advanced blades from Town et al.* and Consonni**

Cooling Analysis Inputs for with advanced coolant calculator		
Engine Type	*Aero-Engine*	*Ind. Gas Turbine*
Blade Metal Biot Number (Bi_m)	0.15	0.16
TBC Biot Number (Bi_{tbc})	0.35	0.37
Maximum Allowable Blade Metal Temperature ($T_{b,\ max}$) [^{0}R]	2100	2000
Purge Fractions [%]	0.2 and 0.1	0.5 (for both stations)
Cooling Configuration	Internal + Film + TBC	Internal + Film + TBC (on first two stages) Internal+ TBC (on last stages)
Film Cooling Effective Injection Angle (deg)	[varied]	[varied]
Film Cooling Blowing Ratio (BR)	1.0	1.0
Film Cooling Hole Type	[varied]	[varied]
Film Cooling Hole Diameter (d_h) [in]	0.03	0.06
Film Cooling Rows (# of FC rows)	2	3
Film Cooling Hole Vertical Spacing (z_n) [per d_h]	3	3
Internal Cooling Configuration	[Impg., Ribs, Pin-Fin]	[Impg., Ribs, Pin-Fin]
Blade Chord Percentile for each Internal Cooling Type (%)	[%20, %40, %20]	[%20, %40, %20]
Blade Chord Length (stator, rotor) [in, in] *	0.7, 0.9	(2.98,3.00), (5.97,6.00), (6.84, 6.86),(8.34,8.36)
Blade Height (stator, rotor) [in, in] *	2.08, 2.601	(8.96, 8.98), (17.9, 18.1), (20.5, 20.6), (25.0, 25.1)

[*] Town, J., Straub, D., Black, J., Thole, K., and Shih, T., (2017), "State-of-the-Art Cooling Technology for a Rotor Blade", ASME GT2017-64728, Charlotte, NC
[**] Consonni S.,(1992) "Performance Prediction of Gas/Steam Cycles for Power Generation", PhD Dissertation, Princeton University, Center for Energy and Environmental Studies

The Effect on Performance from Different Blade Cooling Configurations

The Effect of Different Film Cooling Geometries on Engine Performance

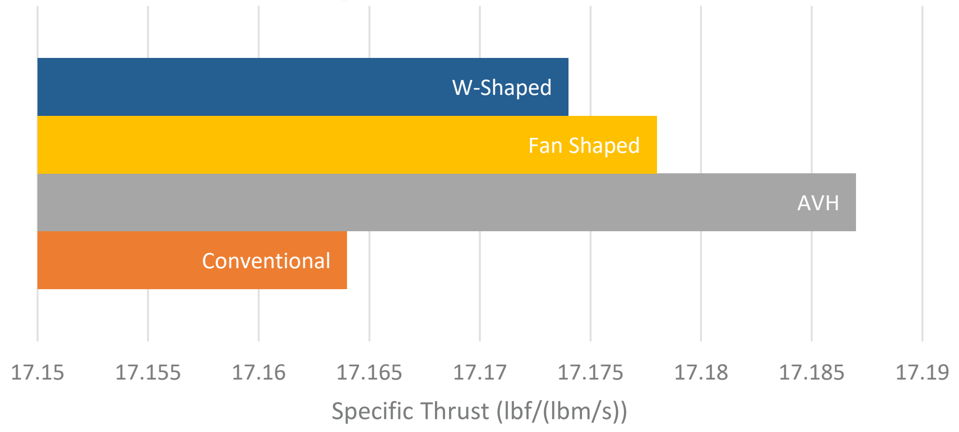


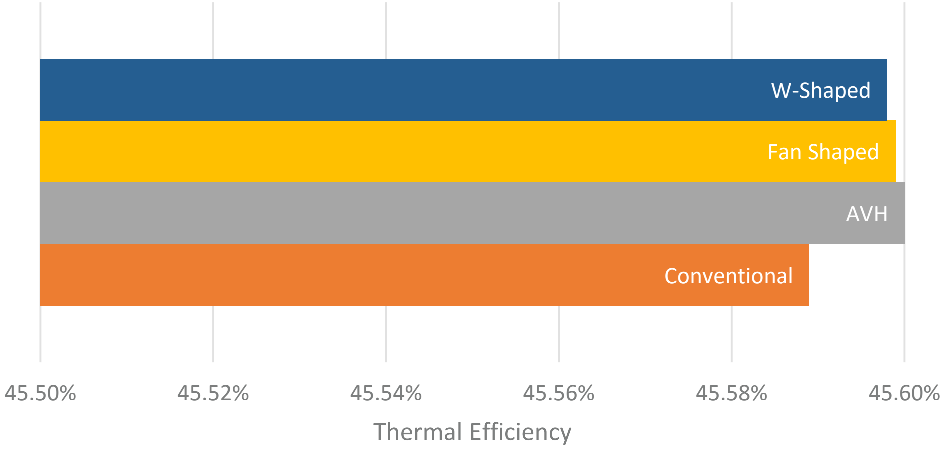
Stage 1: Int.+ TBC+ Film Cooling
Stage 2: Int.+ TBC+ Film Cooling
Stage 3: Int. + TBC
Stage 4: Int. Cooling Only

The Effect on Performance from Different Blade Cooling Configurations

The Effect of Different Film Cooling Geometries on Engine Performance

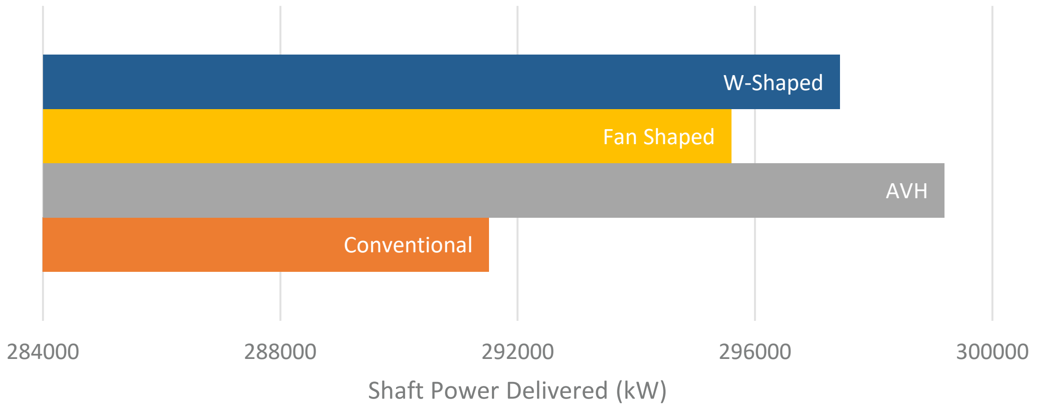
- **Aero-Engine***

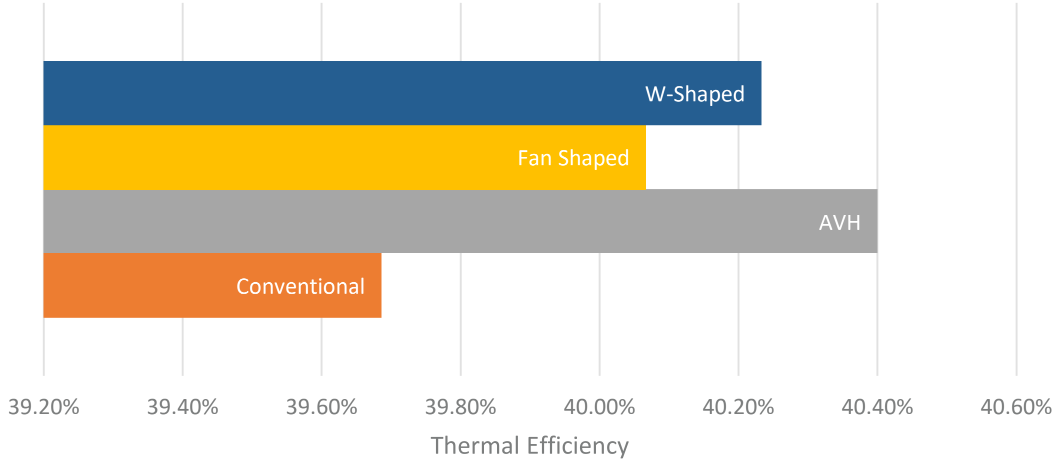




AVH>Fan Shaped>W-Shaped>Conventional

- **Industrial GT***





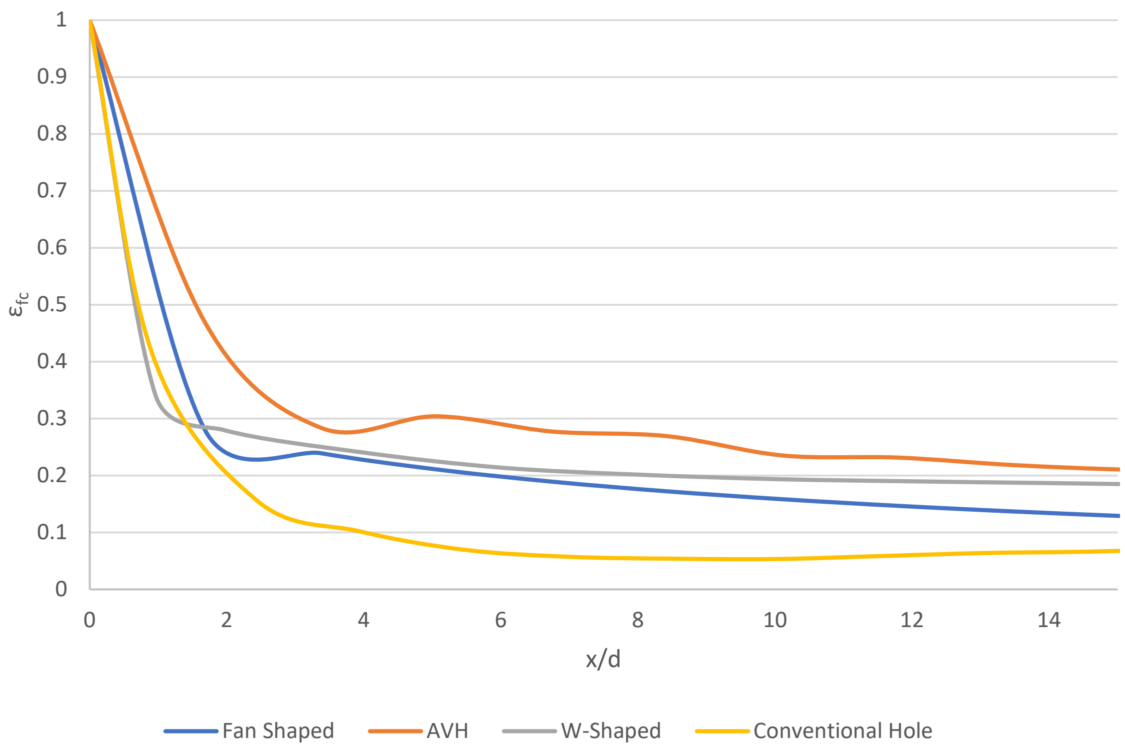
AVH>W-Shaped>Fan Shaped>Conventional

[*] Uysal, S. C., (2017), "Analytical Modelling of the Effects of Different Gas Turbine Cooling Techniques on Engine Performance", PhD Dissertation, West Virginia University, ProQuest Publishing, Ann Arbor, MI

The Effect on Performance from Different Blade Cooling Configurations

The Effect of Different Film Cooling Geometries on Engine Performance

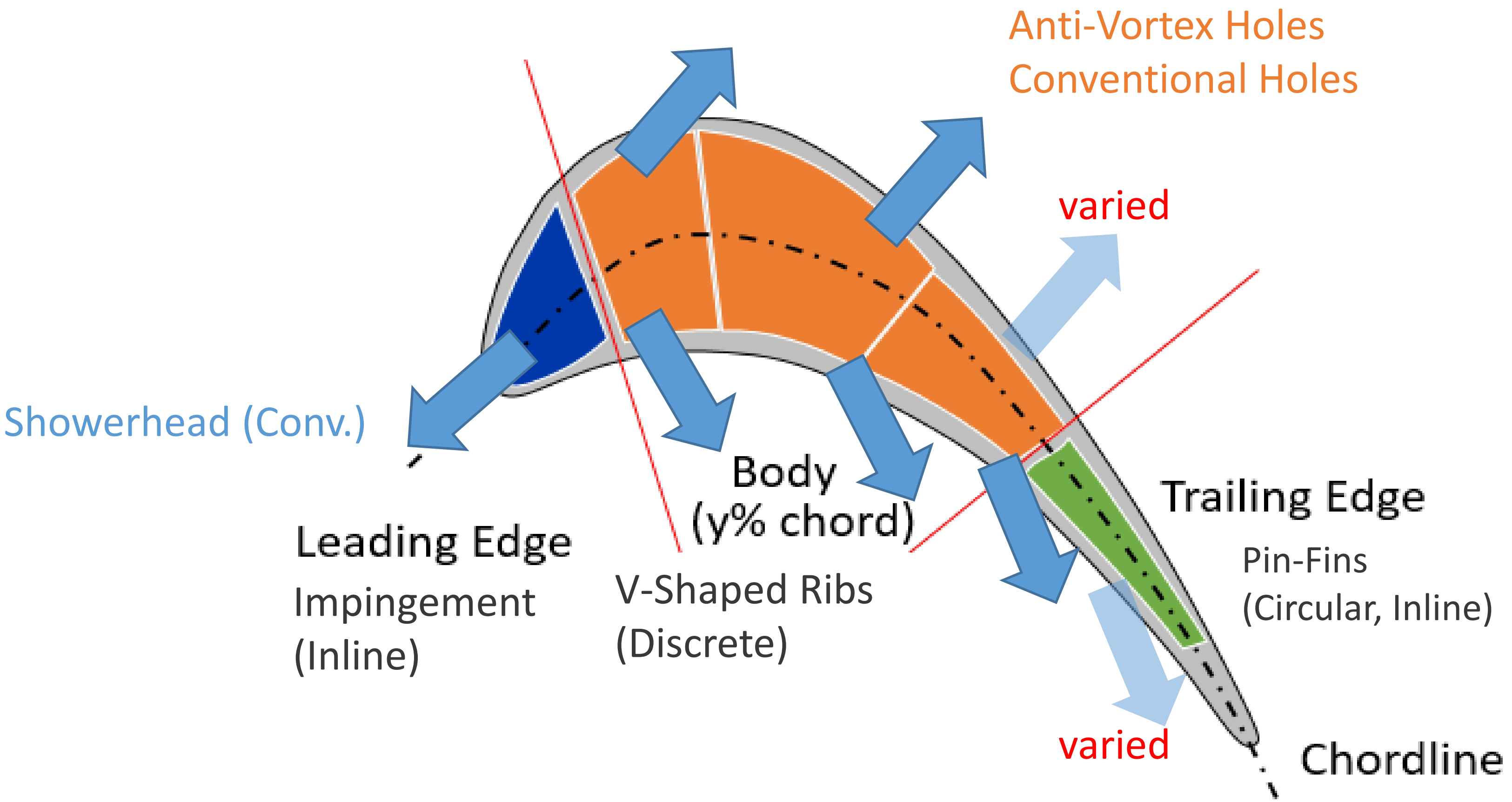
- The method that gives the highest film cooling effectiveness reduces the adiabatic wall temperature most, which also improves the internal cooling flow effectiveness through reducing the coolant heating
- The performance trends are in both engines are in parallel to the film cooling effectiveness performance of the compared methods
- For the industrial GT, due to having longer chord length than the aero-engine GT blade, max. x/d location for FC data is different; causes the difference in performance rankings of the fan shaped and W-Shaped holes



[*] Uysal, S. C., (2017), "Analytical Modelling of the Effects of Different Gas Turbine Cooling Techniques on Engine Performance", PhD Dissertation, West Virginia University, ProQuest Publishing, Ann Arbor, MI

The Effect on Performance from Different Blade Cooling Configurations

Analysis-The Effect of the Number of Film Cooling Rows

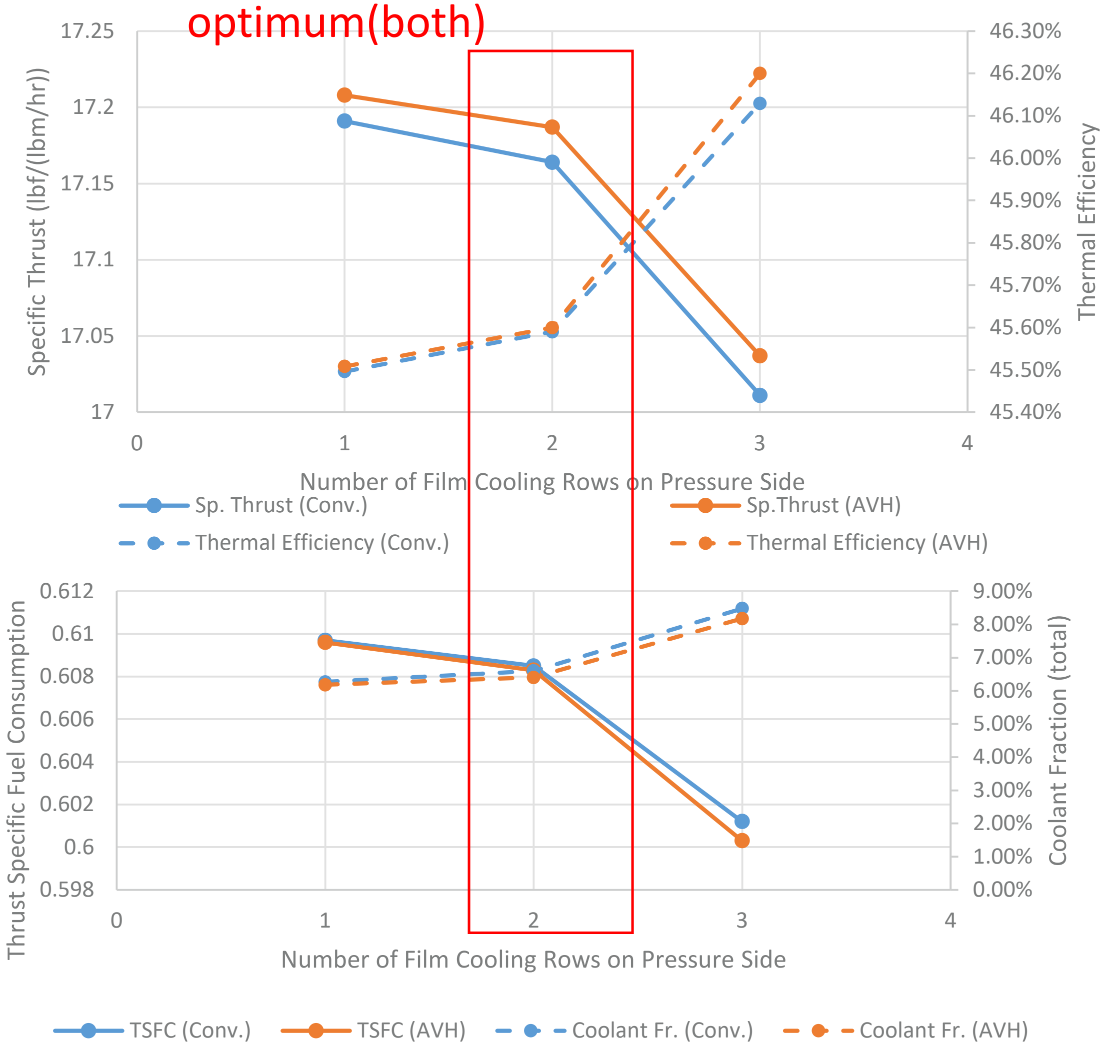


Stage 1: Int.+ TBC+ Film Cooling
Stage 2: Int.+ TBC+ Film Cooling
Stage 3: Int. + TBC
Stage 4: Int. Cooling Only

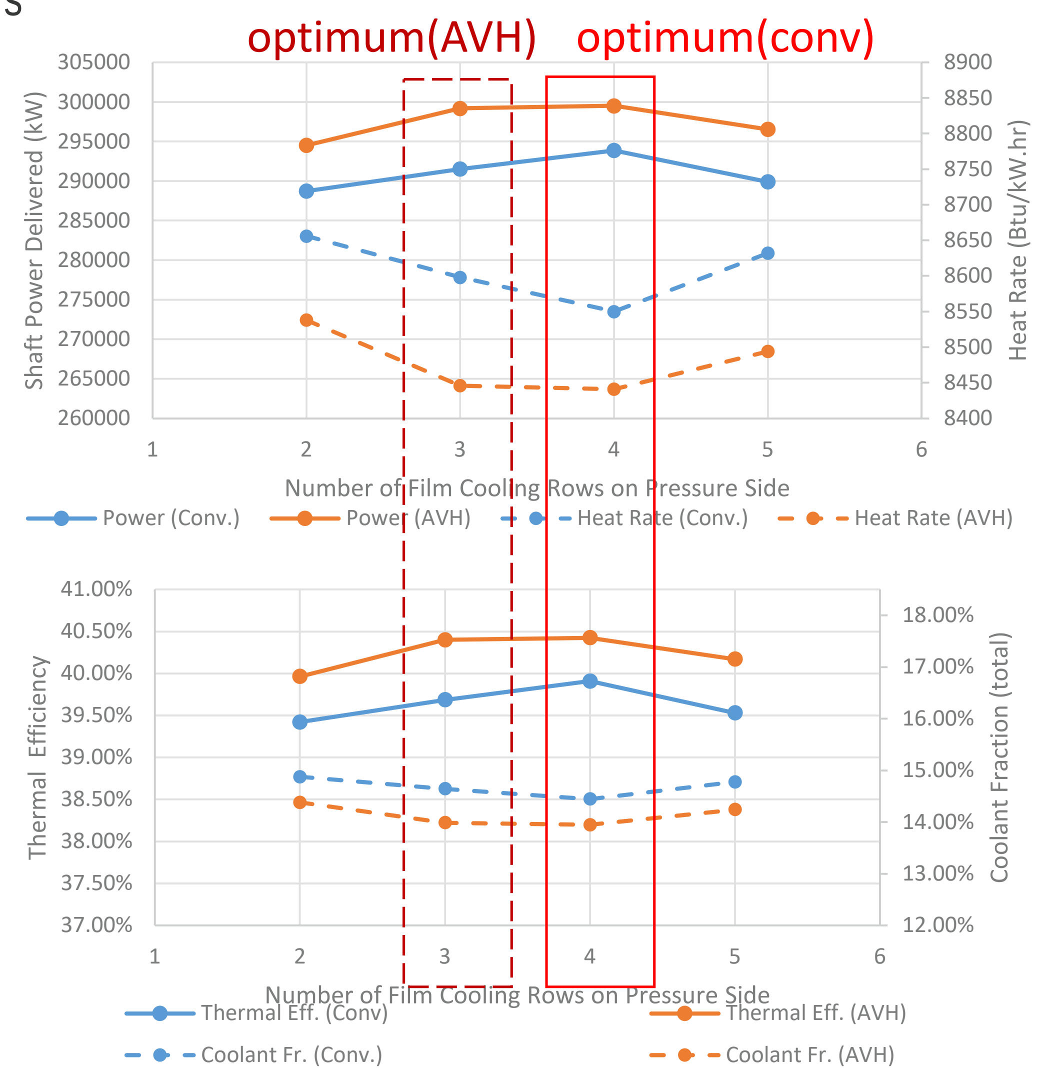
[*] Uysal, S. C., (2017), "Analytical Modelling of the Effects of Different Gas Turbine Cooling Techniques on Engine Performance", PhD Dissertation, West Virginia University, ProQuest Publishing, Ann Arbor, MI

The Effect on Performance from Different Blade Cooling Configurations

Analysis-The Effect of Number of Film Cooling Holes



Aero-Engine*



Industrial GT*

*# of FC hole rows on Suction Side is 1 less than Pressure Side

Conclusions

- For a fixed blade material, improving film cooling technologies has the highest impact on increasing GT efficiency
- An advanced coolant calculation algorithm, giving the users the ability to analyze the impact on engine performance from different cooling configurations, developed by using the heat-exchanger method by Consonni and Ainley
- The impact of using different film cooling configurations were analyzed for two different engines; the results showed that the performance impact of the W-Shaped holes are better for industrial gas turbines due to the differences in blade geometries
- Analysis with the number of film cooling rows showed that different optimal values exist for different engine types but the AVH equipped blades provided highest performance with lowest number of film cooling rows in both cases
- A Cooled Blade Model, which is capable of analyzing blade temperature distributions through a finite element analysis approach, is being developed and will be integrated into CGTM/CEDM

Cooled Gas Turbine Model

An Analytical Model to Investigate the Effects of Different Cooling Techniques on Gas Turbine Performance

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY