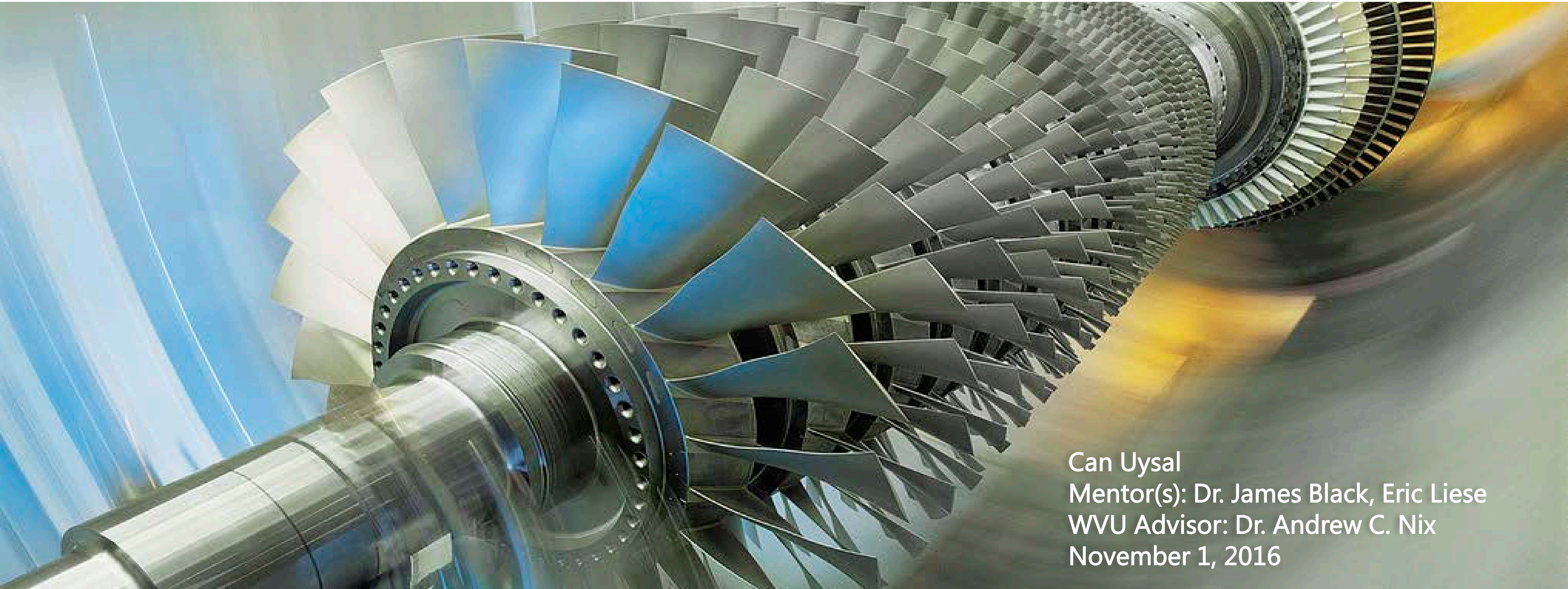
Cooled Gas Turbine Model

A Thermodynamic Model to Quantify the Impact of Cooling Improvements on Gas Turbine Efficiency



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Schedule

- Introduction
- Theory and Development
- Cooled Turbine Model (CTM)
- Cooled Gas Turbine Model (CGTM)
- Sensitivity Analysis with CGTM
- Conclusions and Future Work

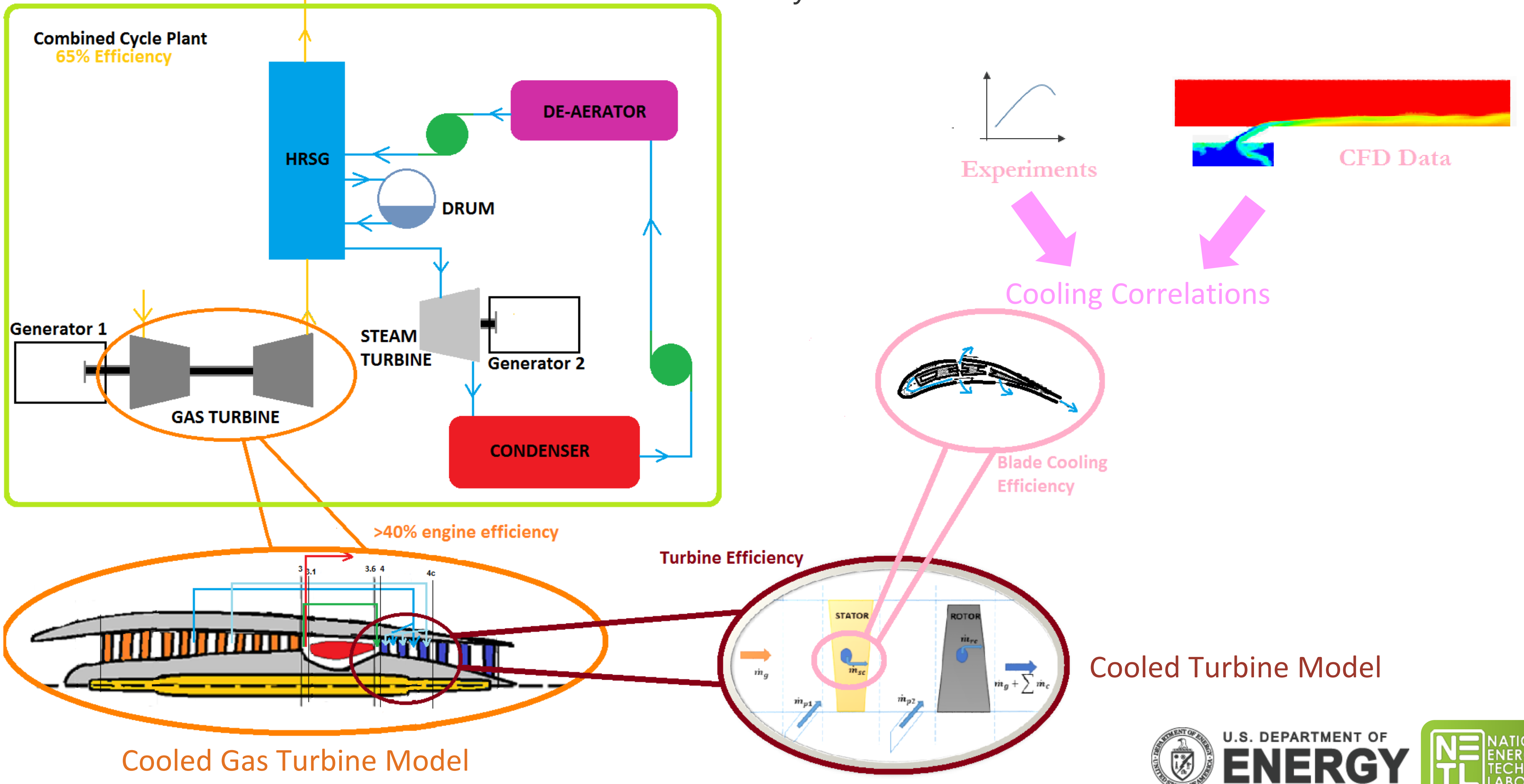
Introduction

- **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 65%.**
- **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



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Introduction

Project phases and completion dates are as follows:

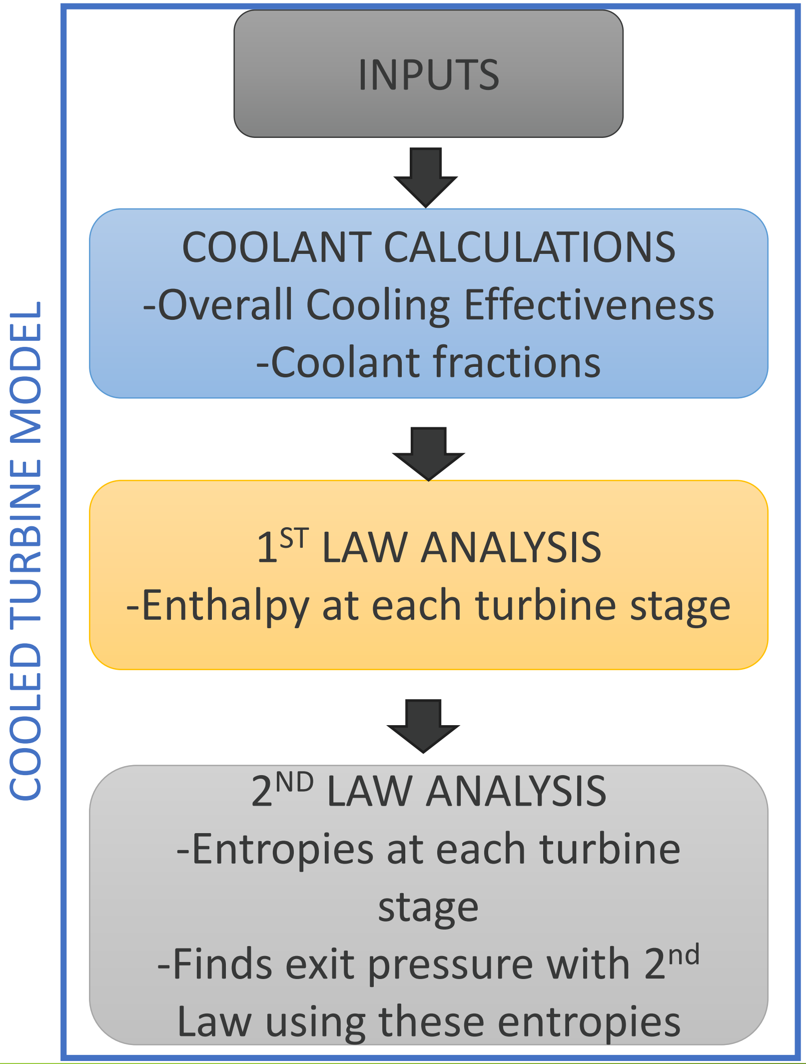
1. Literature Review & Determining the Model Flowcharts (02/19/2016)
2. Cooled Turbine Model Development & Validations (04/24/2016)
3. CGTM Development (06/30/2016)
4. CGTM Validations (08/31/2016)
5. General Sensitivity Analysis on Cooling Parameters (10/04/2016)
6. Adding Correlation Models to use Experimental/CFD Data in CGTM (Internal/External Cooling methods) (11/15/2016)
7. Detailed Sensitivity Analysis (12/16/2016)

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

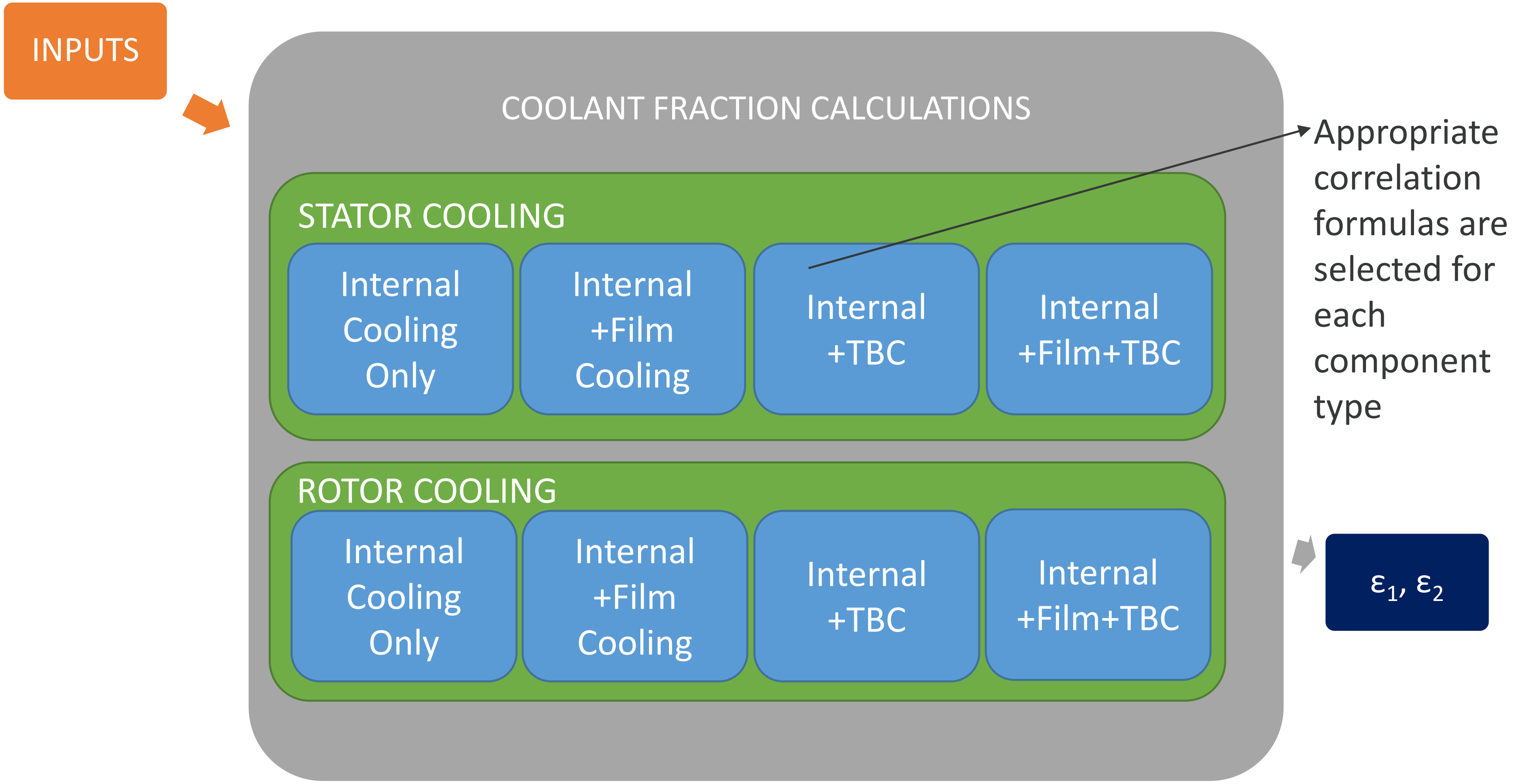
Theory

- **Young and Wilcock's model[1] was chosen for this model for the following reasons:**
  - It gives a detailed and complete thermodynamic analysis of a cooled turbine
  - Rotor equations include the rotational effects and stage loading (important for correct enthalpy calculations)
  - 2nd Law Analysis is done in a compact form that includes all loss factors for better exergy analysis
  - Used and cited by several recent advanced modelling research work (Lallini et al.[2] , Horlock et al. [3], Torbidoni et al. [4] etc.)
  - Easy to implement in a modelling algorithm
- **The flowchart of the model is determined according to this resource**

[1] Young, J.B., and Wilcock, R.C., (2002), "Modelling the Air-Cooled Gas Turbine: Part 2-Coolant Flows and Losses", ASME 2001 GT-392
[2] Lallini V., Janikovic j., Pilidis P., Singh R., and Laskaridis P., (2012), "A Calculation Tool of a Turbine Cooling Air Schedule for General Gas Turbine Simulation Algorithms", J. of Turbomachinery, Vol.134
[3] Horlock, J.H., and Torbidoni L., (2008), "Calculations of Cooled Turbine Efficiency", ASME GT2006-90424
[4] Torbidoni L., and Horlock J.H. (2005), "A New Method to Calculate Coolant Requirements of a High Temperature Gas Turbine Blade", Journal of Turbomachinery, Vol. 127, pp.191-199

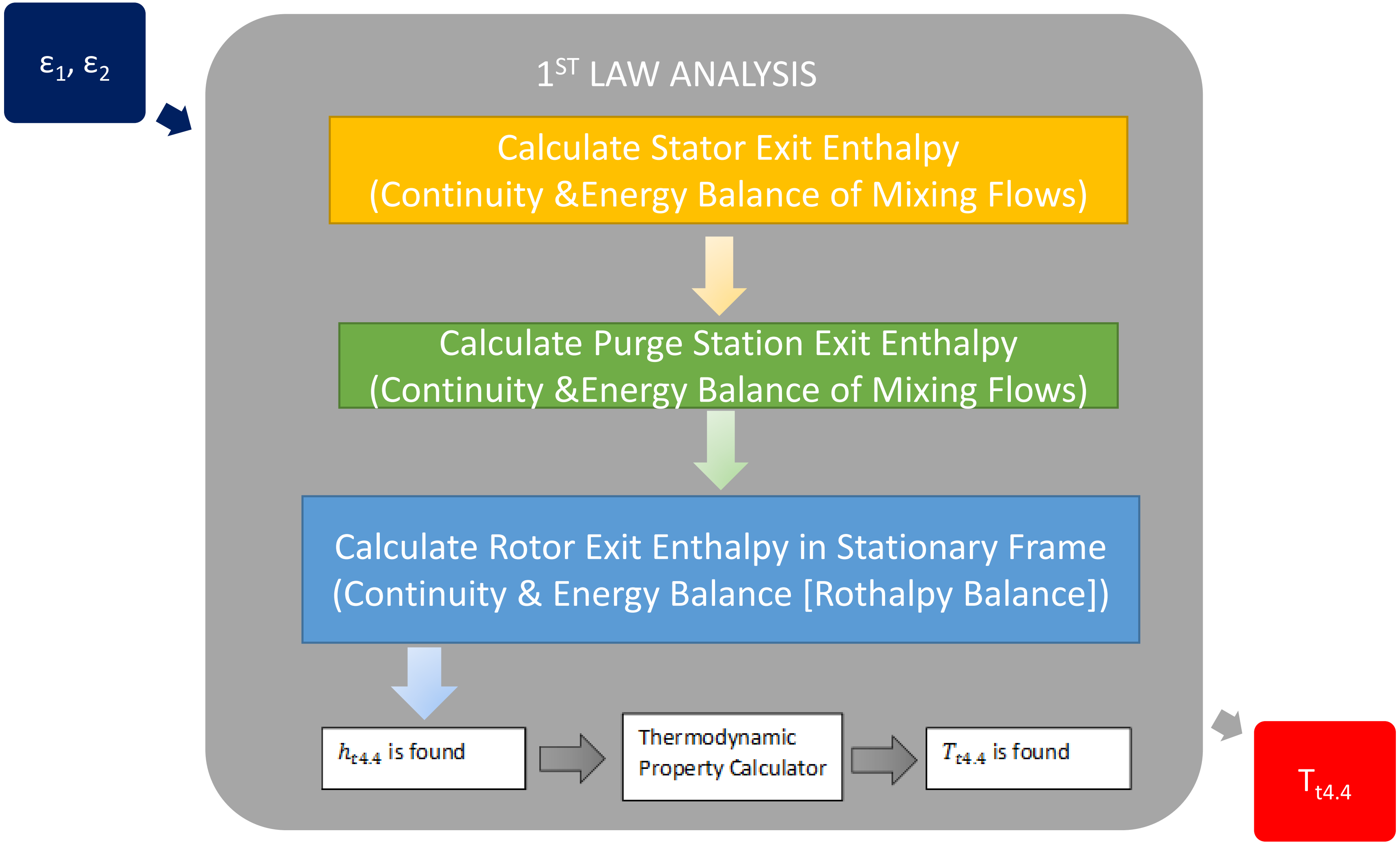
Cooled Turbine Model

Development



Cooled Turbine Model

Development



Cooled Turbine Model

Development

$T_{t@each\ stage}$

2ND LAW ANALYSIS

STATOR/ROTOR

$$\dot{\sigma}_{S/R} = \dot{\sigma}_{basic} + \dot{\sigma}_{cool}$$

Uncooled

$$\dot{\sigma}_{s/r,basic} = (\dot{m}_{4.1} + \dot{m}_{sc})R_{4.1}(1 - e_t)\ln(\frac{1}{\Pi_{tH}})$$

Cooled

$$\dot{\sigma}_{s/r,cool} = \dot{\sigma}_{s,tbc} + \dot{\sigma}_{s,met} + \dot{\sigma}_{s,int} + \dot{\sigma}_{s,ext}$$

TBC conduction | Metal conduction | Internal Cooling | External Cooling

$$\dot{\sigma}_{s,int} = \dot{\sigma}_{s,intQ} + \dot{\sigma}_{s,intF}$$

Internal HT | Internal Frictions

$$\dot{\sigma}_{s,ext} = \dot{\sigma}_{s,extQ} + \dot{\sigma}_{s,extMIX}$$

Convective HT | Mixing

$$\dot{\sigma}_{s,extMIX} = \dot{\sigma}_{s,mixQ} + \dot{\sigma}_{s,mixKE}$$

Mixing HT | Mixing K.E.

Model by Young et al.*

PURGE(S)

Use mixing flows entropy balance

$$\dot{\sigma}_{STAGE} = \dot{\sigma}_{STATOR} + \sum \dot{\sigma}_{PURGE,i} + \dot{\sigma}_{ROTOR}$$

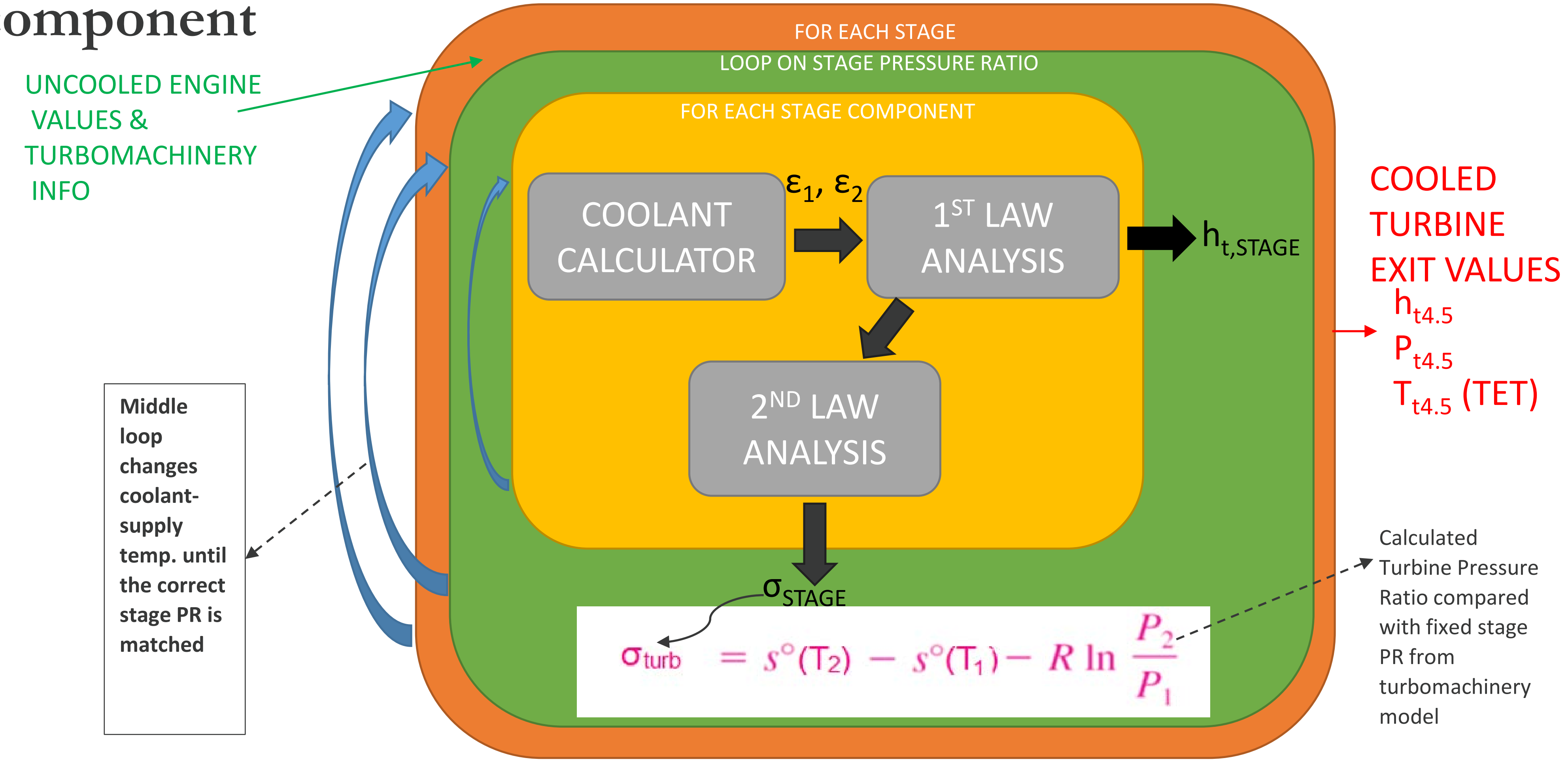
$\dot{\sigma}_{STAGE}$

[*] Young, J.B., and Wilcock, R.C., (2002), “Modelling the Air-Cooled Gas Turbine: Part 2-Coolant Flows and Losses”, ASME 2001 GT-392

Cooled Turbine Model

Development

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



Cooled Turbine Model

Validation

Coolant Calculations and 1st Law Analysis sections are validated with the example case data given by Young et al.*

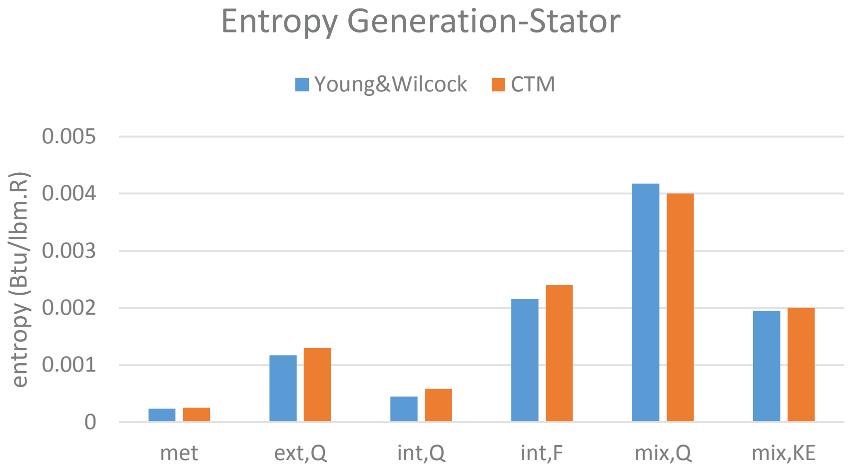
Parameter	CTM Result	Young et al.
Stator		
Cooling Fraction	0.145	0.145
Exit Total Temperature (K)	1598	1603
Rotor		
Cooling Fraction	0.050	0.049
Exit Total Temperature (K)	1484	1487

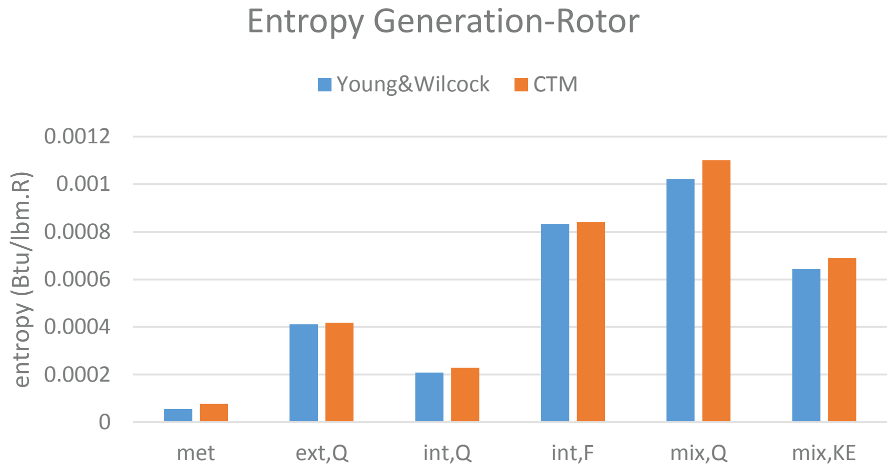
[*] Young, J.B., and Wilcock, R.C., (2002), "Modelling the Air-Cooled Gas Turbine: Part 2-Coolant Flows and Losses", ASME 2001 GT-392

Cooled Turbine Model

Validation

Entropy terms from Young et al.* example case is used for 2nd Law Analysis algorithm validation





Same trend obtained for both stators and rotors:

$$\dot{\sigma}_{MIX,Q} > \dot{\sigma}_{int,F} > \dot{\sigma}_{MIX,KE} > \dot{\sigma}_{ext,Q} > \dot{\sigma}_{int,Q} > \dot{\sigma}_{met}, \dot{\sigma}_{tbc}$$

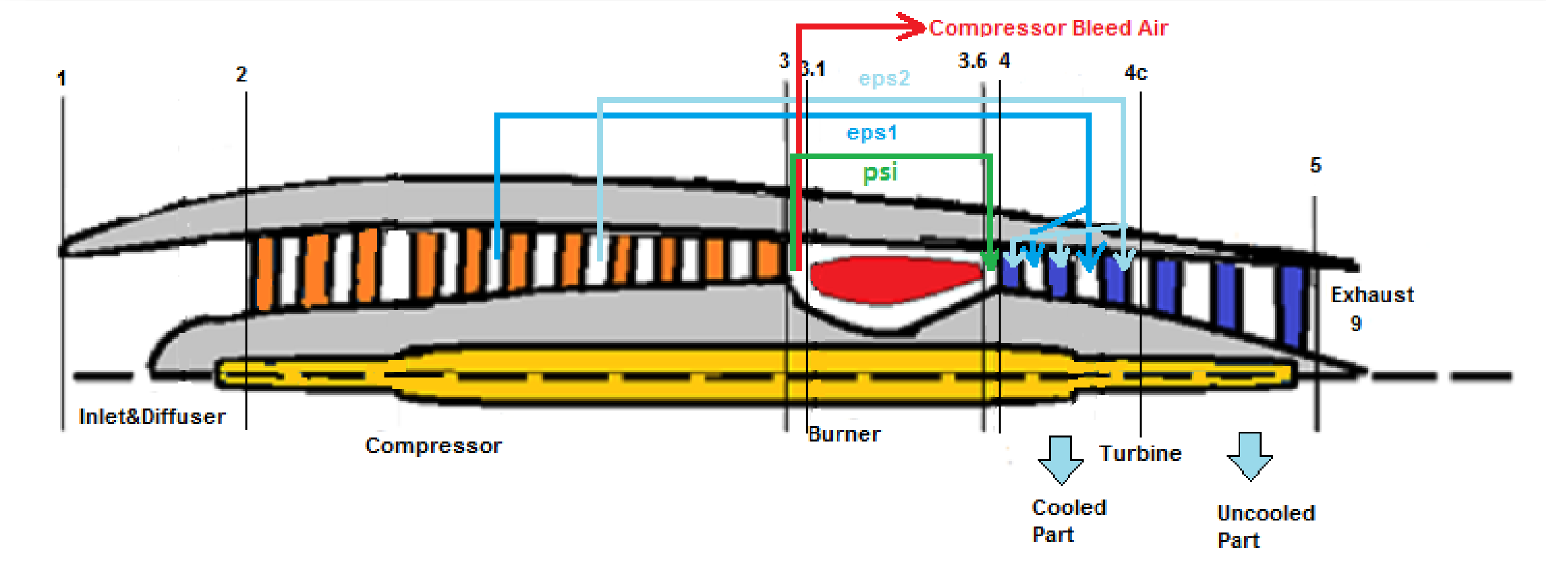
(Mixing HT > Internal Friction & BL Friction > Mixing KE > External HT > Internal HT > Conduction HT)

Higher Entropy Rate ($\dot{\sigma}$) → Higher Exergy ($\Phi = T_0\dot{\sigma}$) → More deviation from max. theoretical turbine work ($W_{actual} = W_{isentropic} - \Phi$) → Less Turbine Efficiency ($\eta_{turb,actual} < \eta_{turb,\ isentropic}$)

[*] Young, J.B., and Wilcock, R.C., (2002), "Modelling the Air-Cooled Gas Turbine: Part 2-Coolant Flows and Losses", ASME 2001 GT-392

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

Input List

- **Inputs related to cooling analysis are listed as follows:**

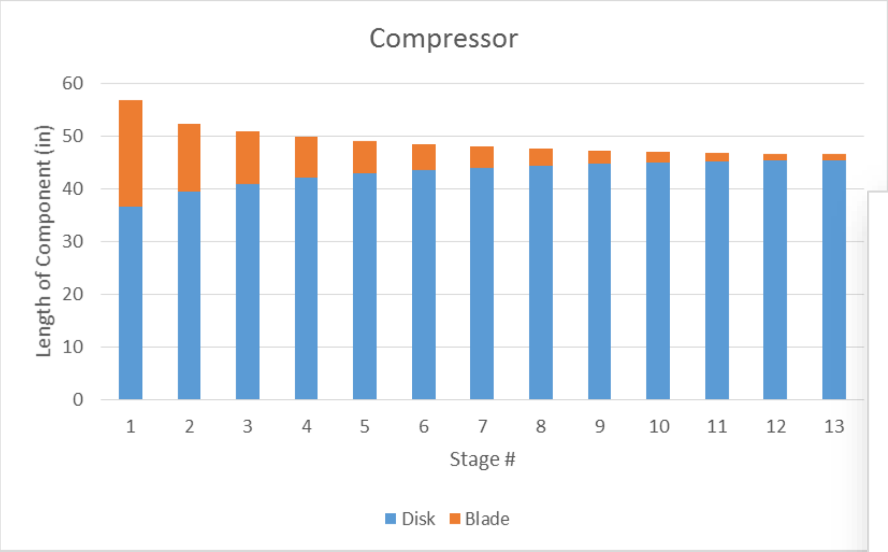
Parameter	Definition
Bi_m	Biot Number (metal) [hot side based]
Bi_{tbc}	Biot Number (TBC) [hot side based]
$T_{b,max}$	Maximum Blade Metal Temperature
η_{fc}	Adiabatic Film Cooling Effectiveness
η_c	Internal Cooling Effectiveness
$purge_1$	Pre-stage purge fraction
$purge_2$	Intermediate stage purge fraction
$[Schedule]_{4xn*}$	Cooling Schedule matrix indicating which cooling technology applied to each cooled component

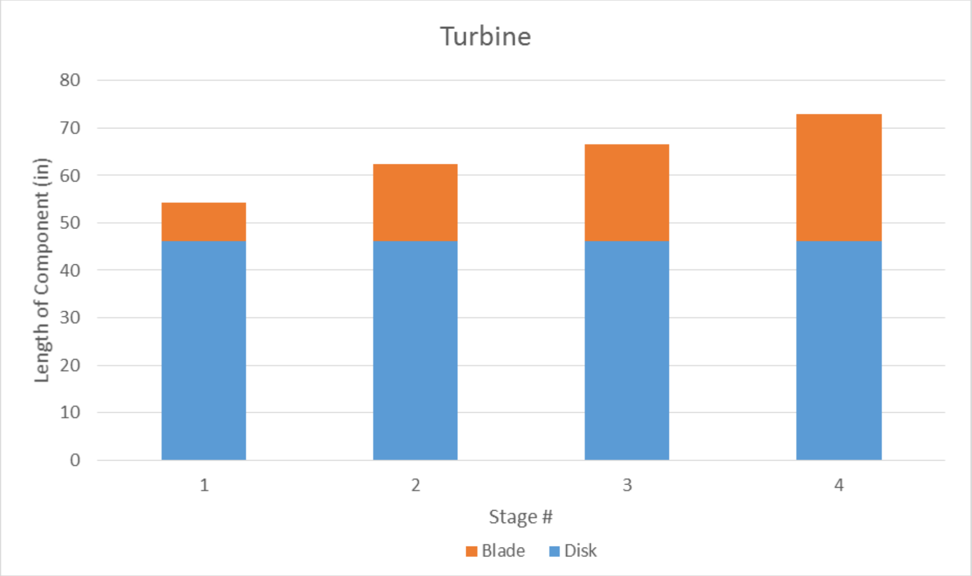
*n= #of cooled stages

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

- **Validations carried out 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**
- **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

Validations

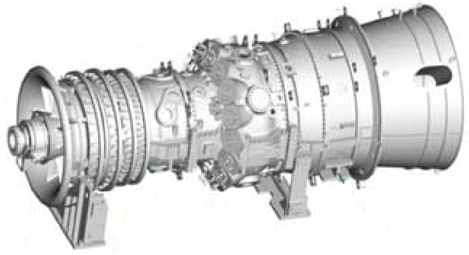
SGT6-8000H	CGTM	Published Value [1]
Power	296 MW	296 MW
Thermal Efficiency	40.0 %	40.0%
Heat Rate	8526 Btu/kWh	8530 Btu/kWh
Exhaust Temperature	1159 ^{0}F	1160 ^{0}F

[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>

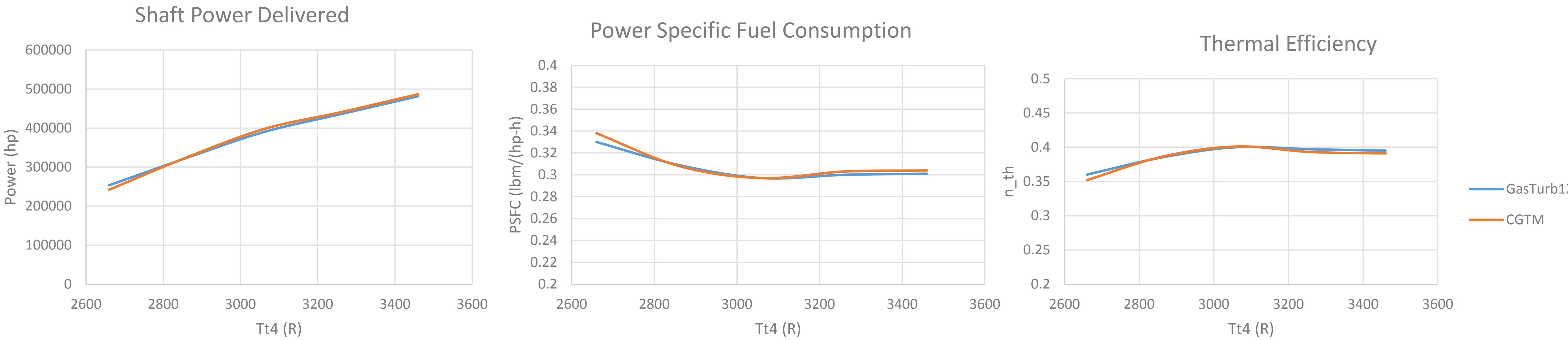
Cooled Gas Turbine Model

Validations

- Cycle calculations were validated with GasTurb12 via case specific tests and continuity tests.
- Case specific tests compares the outputs of two programs side-by-side for specified engine parameters
- Continuity test aims to compare the response of two programs to the same input parameter varied in a predetermined range
- GasTurb12 uses a different cooling analysis model (a pressure loss model) but two programs are made comparable by entering the cooling fractions calculated by CGTM into GasTurb12.

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

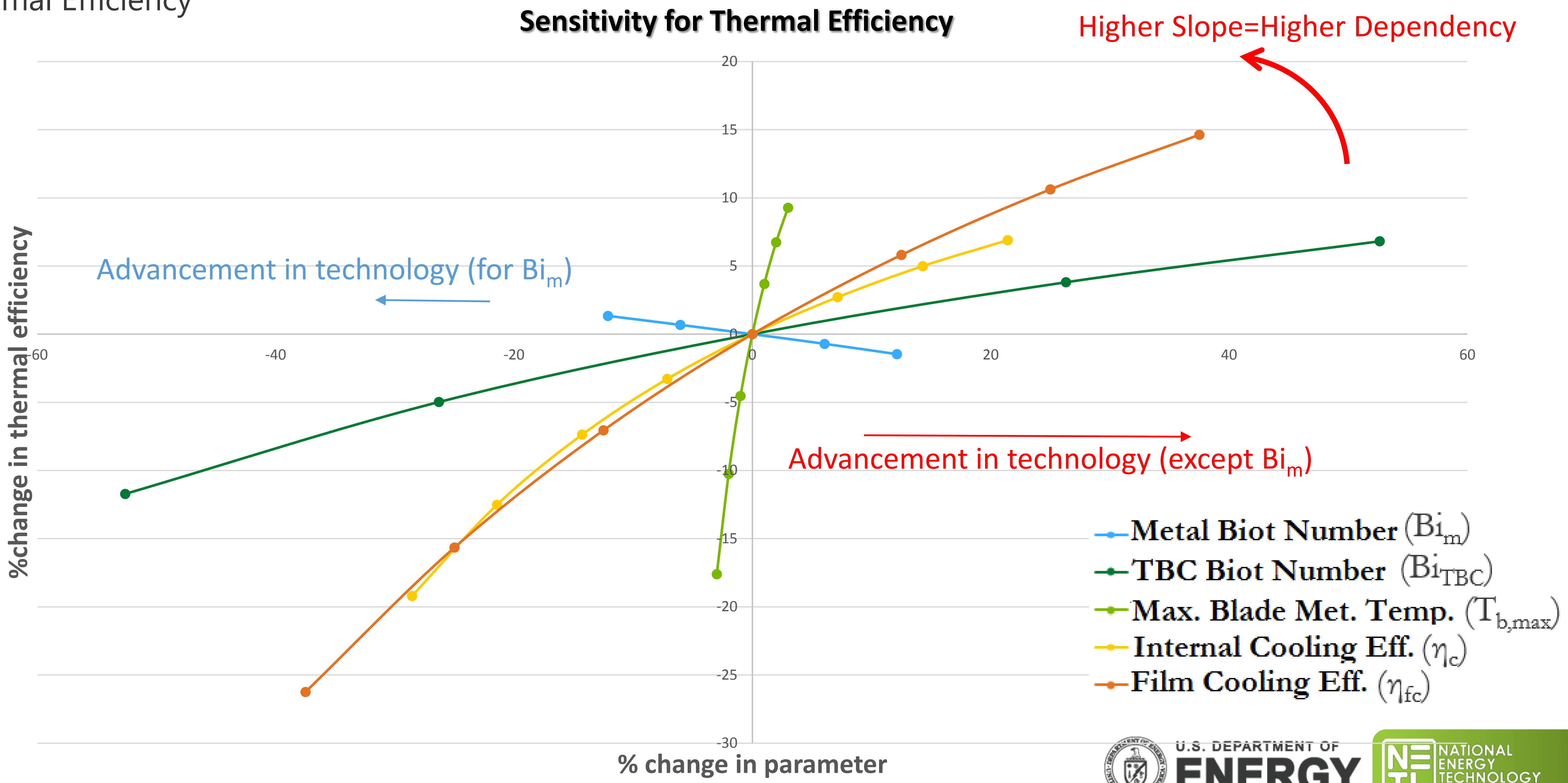
[*] GasTurb12 Software by GasTurb GmbH c/o Institute of Jet Propulsion and Turbomachinery Templergraben 55, 52062 Aachen, Deutschland

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**

Sensitivity Analysis

Thermal Efficiency



Sensitivity Analysis

Thermal Efficiency

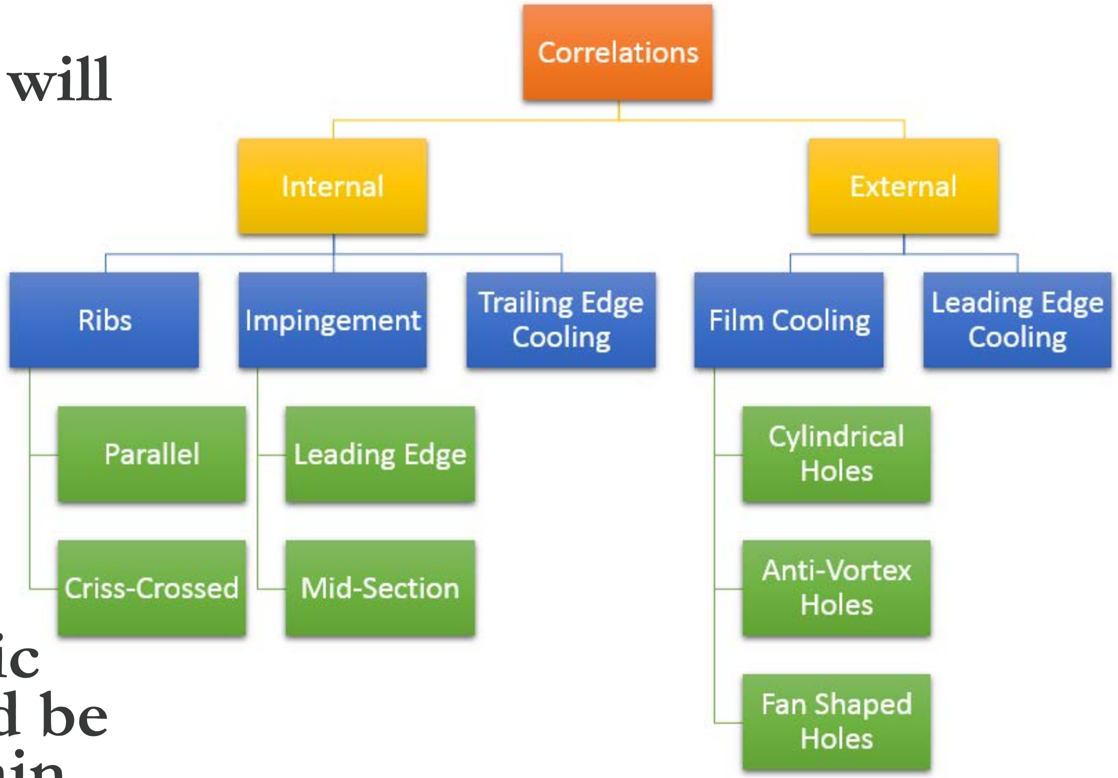
- Increasing the maximum blade temperature through advanced blade materials will have the highest impact to increase thermal efficiency
- Advancements in film cooling techniques will have higher impact than advancements in internal cooling techniques and TBC materials
- Reducing metal Biot number through reduced metal conduction rates has the lowest impact
- The magnitudes of the effects are directly related to how much a cooling technique can reduce the required coolant flowrates as its efficiency is increased
- Reducing the coolant flowrates will reduce turbine losses, increase compressor performance and engine power, resulting in higher thermal efficiency
- In the case of changing two or more technology parameters simultaneously, cross-effects through loss parameters could result in a lower increase in thermal efficiency

Conclusions

- A cooled turbine model is developed that also calculates losses coming from cooling techniques
- The cooled turbine model is integrated into the Cooled Gas Turbine Model that calculates gas turbine performance parameters
- Models were validated with published data and commercial software
- CGTM is used in a parameter sensitivity analysis to understand which cooling technology has the highest potential to reach >40% GT efficiency
- For a fixed blade material, improving film cooling technologies has the highest impact on increasing GT efficiency

Future Work

- With the addition of cooling technology specific correlations to the model, CGTM will be able to be used in comparisons for different internal and external cooling techniques
- The model can be used in optimization algorithms to determine what a cooling parameter should be to satisfy a desired engine performance
- Additional sensitivity studies and optimization studies will give more specific information on what advancements should be done in a certain cooling technique to attain higher performance



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