2014 University Turbine Systems Research Workshop
Co-organized by Purdue and DoE NETL
21-23 October 2014

Issues in Modelling and Simulation of Turbine Cooling

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DoE – NETL & Ames Laboratory

PURDUE UNIVERSITY

Outline of Talk

Challenges in Modelling and Simulation
- **Rim seals:** *Jason Liu, Adam Weaver*
- **Compound-Angle Film Cooling:** *Zach Stratton*

Design Tools:
- **Unsteady Conjugate Heat Transfer:** *Chien-Shing Lee*
- **Effects of Averaging:** *Chien-Shing Lee*

Summary & Current Work

Rim Seals: Jason Liu & Adam Weaver

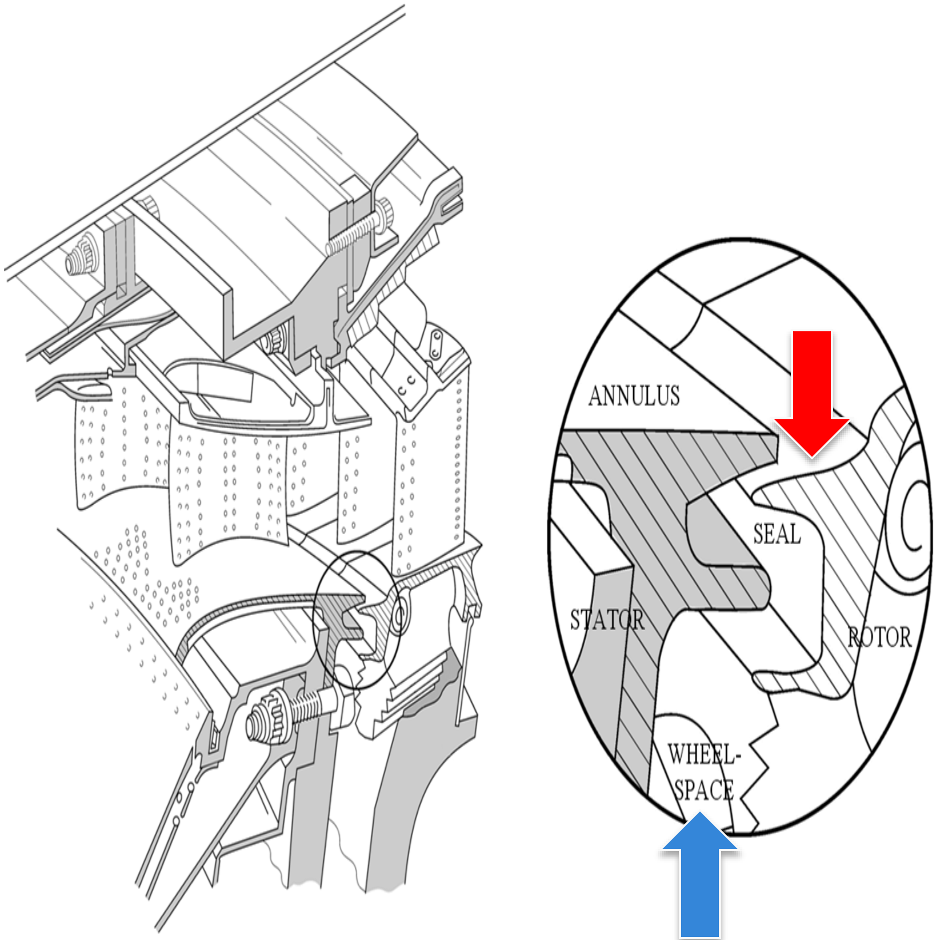
Up to 30% of the air entering the compressor is used for turbine cooling. **One area where reduction may be possible is the rim seals.**

Previous and Current Studies:

- Chupp, Hendricks, Lattime, Steinetz, Aksit
- **Bath: Owens, Lock, Sangan**
- Penn State: Thole

Key Findings by Bath:

- Pressure downstream of stator vanes dominate ingress.
- Rotor blades play no role on ingress.
- CFD can accurately predict CO_2 injection with sealant flow as a way to measure ingress.



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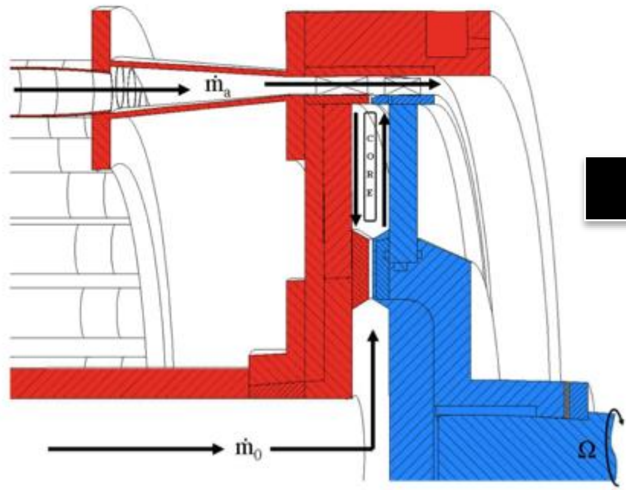

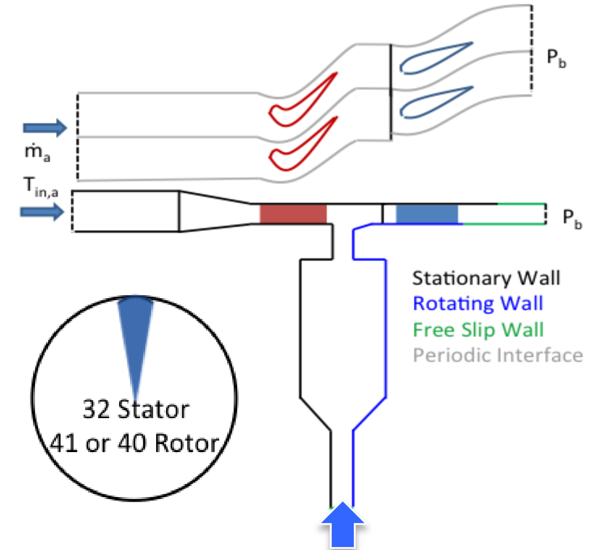

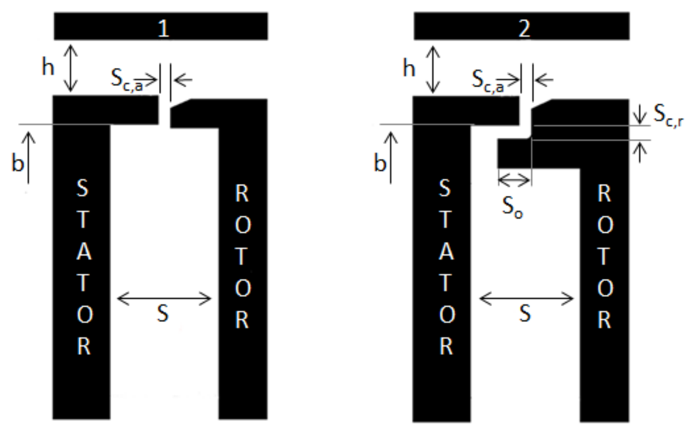

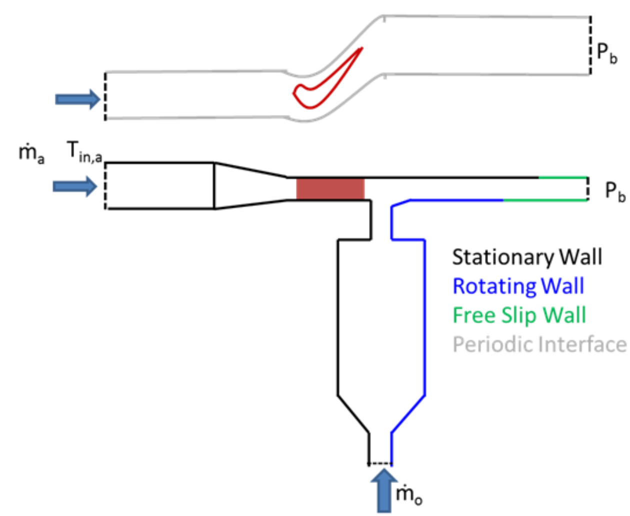

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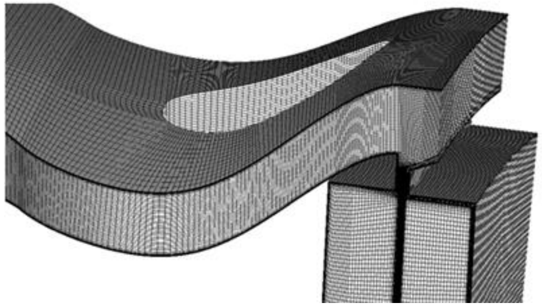
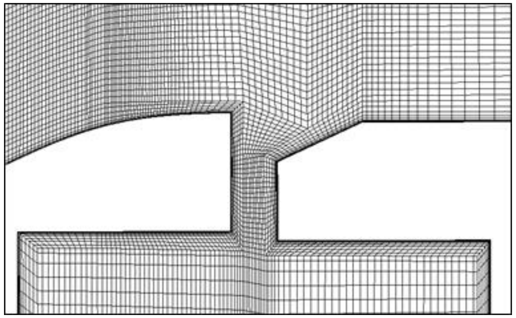
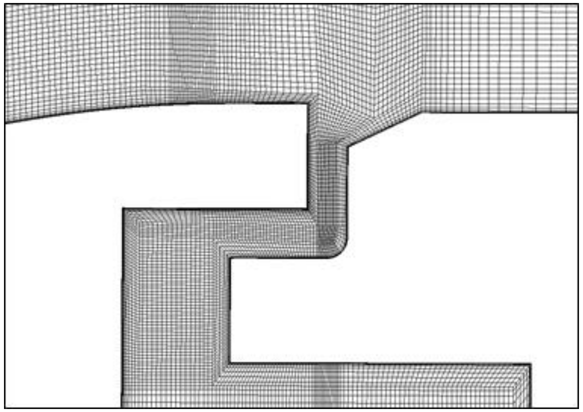
RANS Study of Stator-Rotor:

- **time-accurate** Fourier on 32-41 and 32-40 → 4-5
- **steady-state** without blades on the rotor (inertial frame)







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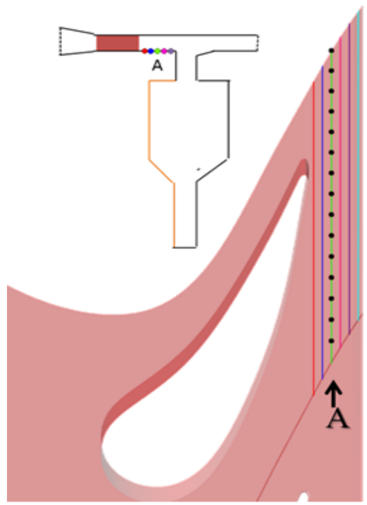
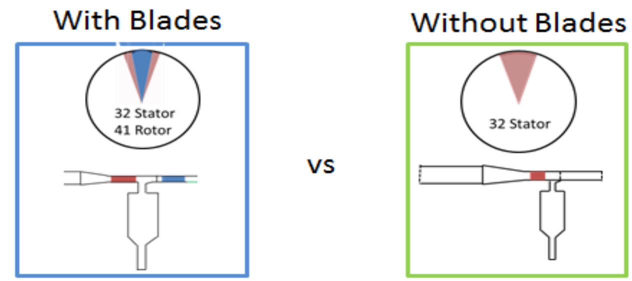
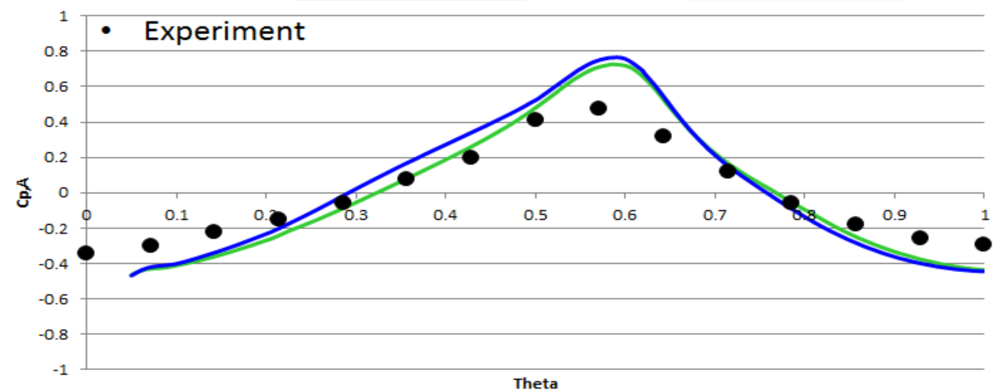
CFD Studies of Stator-Rotor:







- Pressure downstream of the stator relatively independent of the blades on the rotor.
- Thus, blades on rotor could be removed for Bath configuration to get this pressure distribution.
- BUT, still need to assess how well CFD can predict that pressure.

Rim Seals: Jason Liu & Adam Weaver

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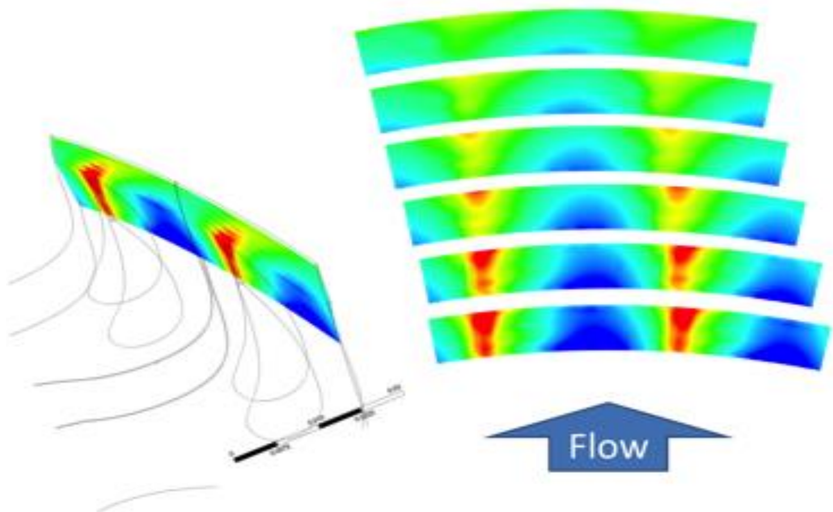
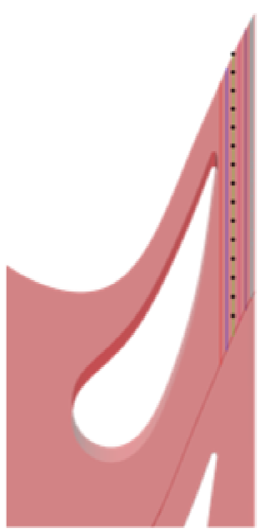
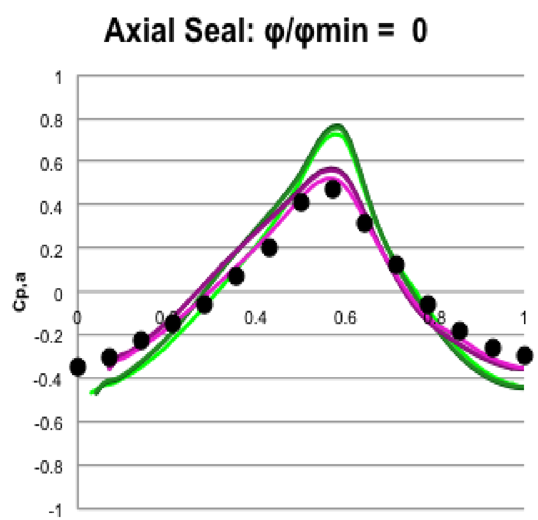
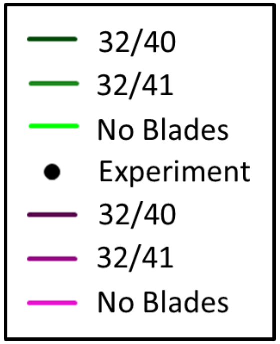
CFD Studies of Stator-Rotor:



- Each plane is 1 mm apart, and probe diameter is 1 mm.
- Magnitude of the peak & trough in P diminishes rapidly downstream of stator vanes.
- CFD can predict pressure distribution to within 5%.







Rim Seals: Jason Liu & Adam Weaver

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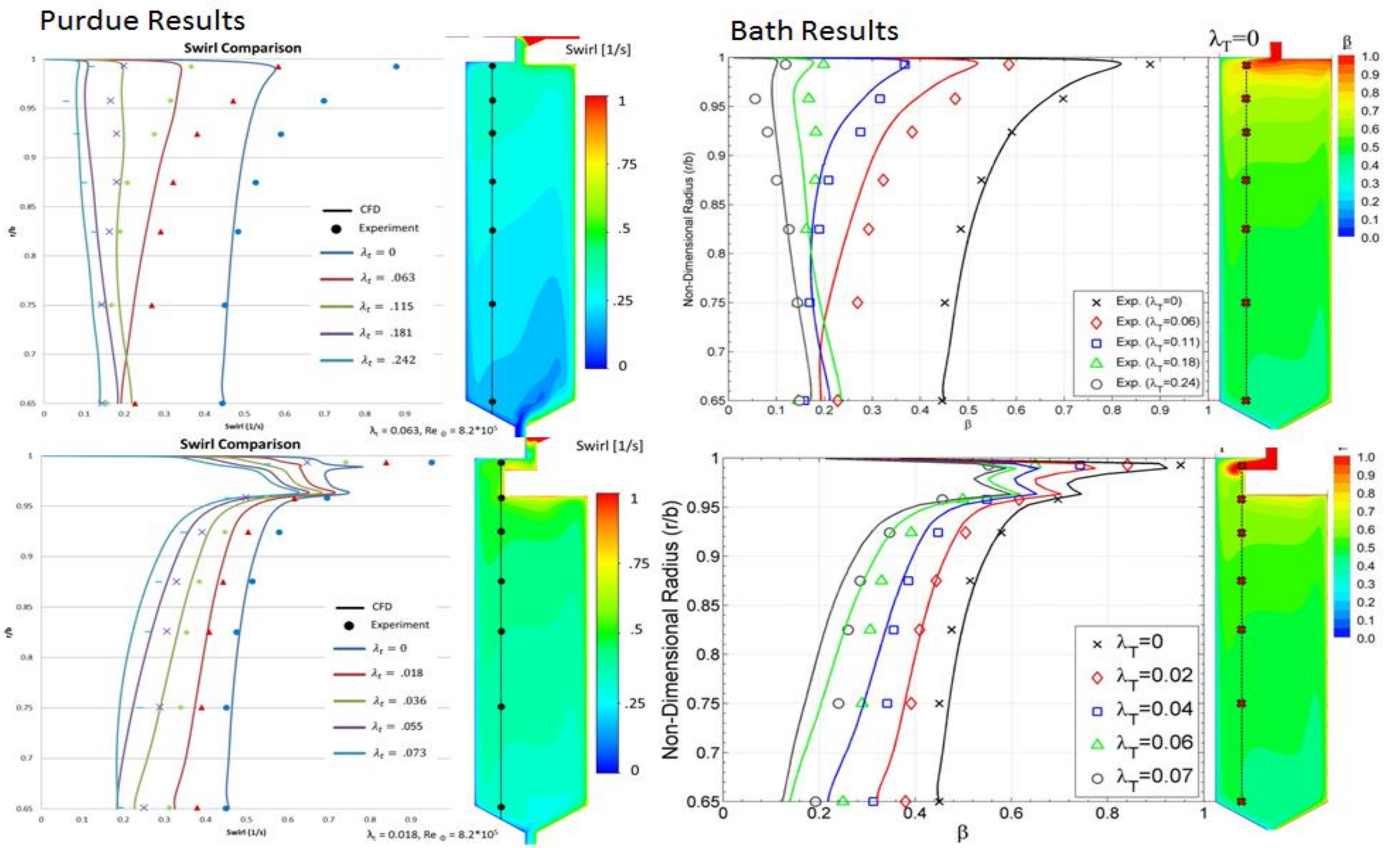
CFD Studies of Stator-Rotor:

By using an inertial frame of reference,

- swirl is predicted reasonably well (esp. at lower radii)
- cannot predict the measured ingress
- do not match the CFD results from Bath.



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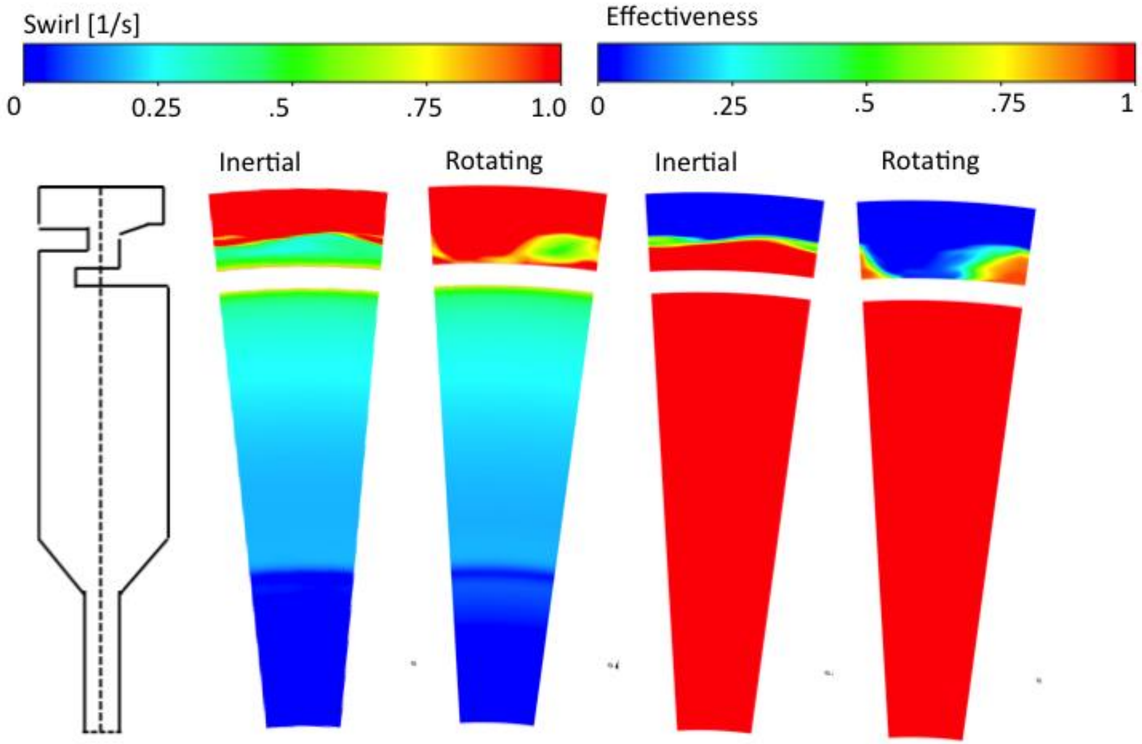
CFD Studies of Stator-Rotor:

- Inertial frame (Purdue) **&** inertial+noninertial+frozen rotor BC (Bath) yield different flow fields. The culprit is in the frozen rotor BC.
- The Bath approach matches experimental data only at 3000 rpm case, which is what was reported.

Thus, the blades on the rotor do play a role on ingress.



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- **Effects of Averaging:** *Chien-Shing Lee*

Summary & Current Work

Compound-Angle Film Cooling: Zach Stratton

Why compound-angle film cooling?

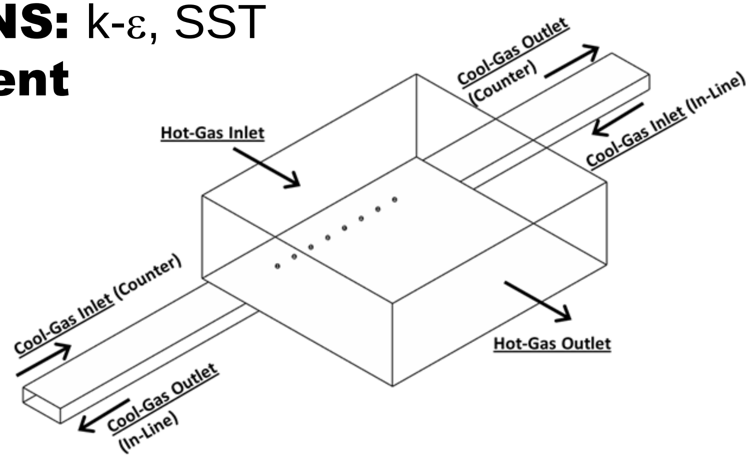
- Higher adiabatic effectiveness over streamwise injected holes [Ligrani]
- Improved lateral spreading [Schmidt]

Objectives:

- What is affect of flow direction in the internal coolant passage?
- Assess k-ε, SST, LES?

Supported by GE and DoE NETL

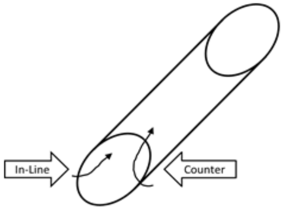
RANS: k-ε, SST
Fluent



Hot Gas (Air)
$T_\infty = 303^oK$
$u = u(y);\ \delta = 2.8d$
$u_\infty = 13.8\ m/s$
Turbulence Intensity = 6%

Cool gas (N_2)
$T_c = 202^oK$
$\dot{m} = 0.02145\ kg/s$
$Re_{d_H} = 35{,}000$

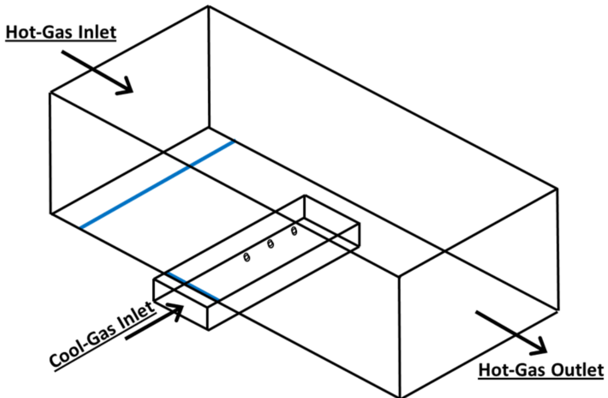
Case	Flow Direction	Blowing Ratio
1a	In-Line	0.5
1b	In-Line	1.0
1c	In-Line	1.5
2a	Counter	0.5
2b	Counter	1.0
2c	Counter	1.5



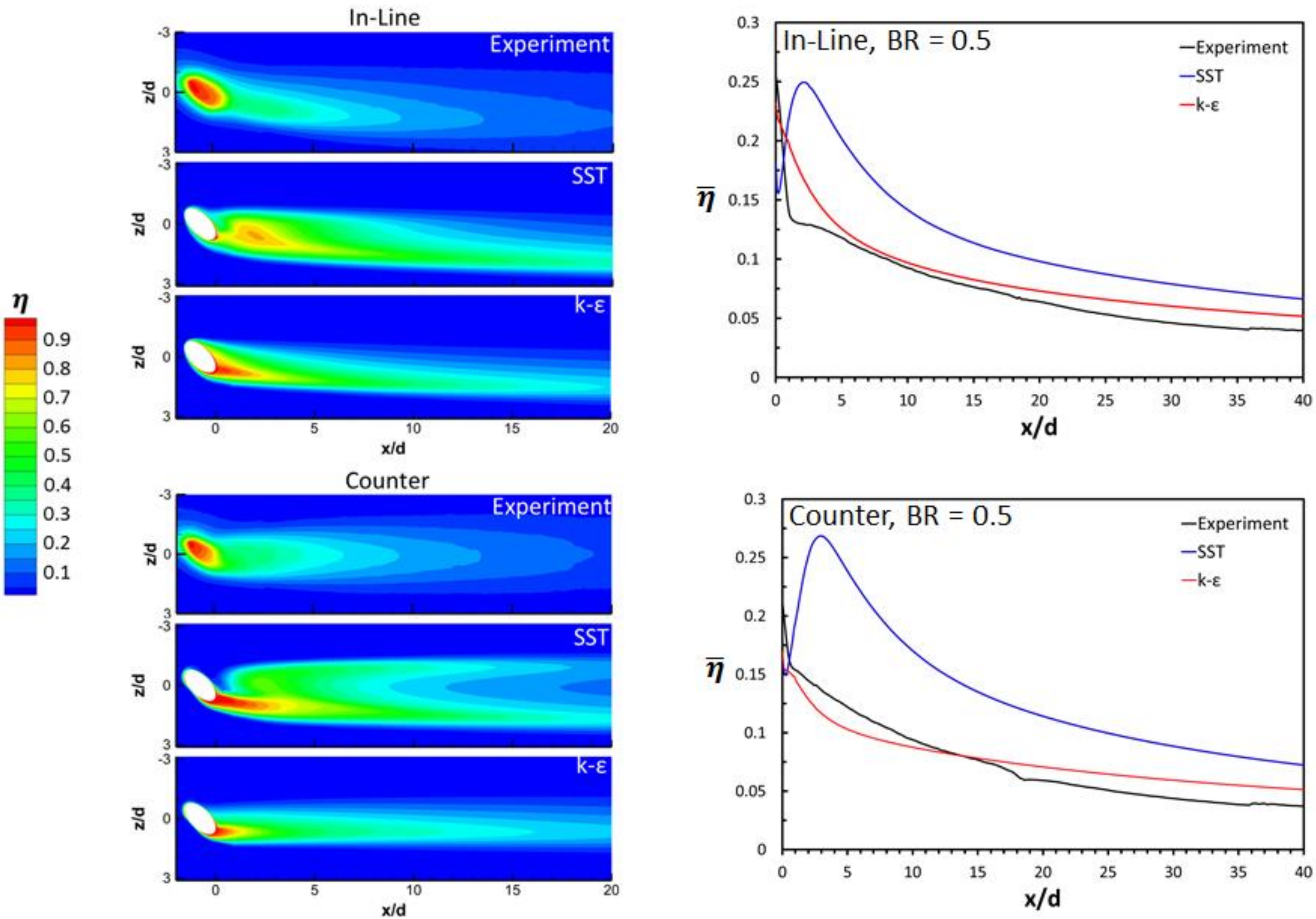
Hole diameter (d) = 5 mm
Hole length = 6d
Hole spacing = 6.25d
Adiabatic walls

LES
PowerFlow

Experimental data: Dave Bogard



Compound-Angle Film Cooling: Zach Stratton



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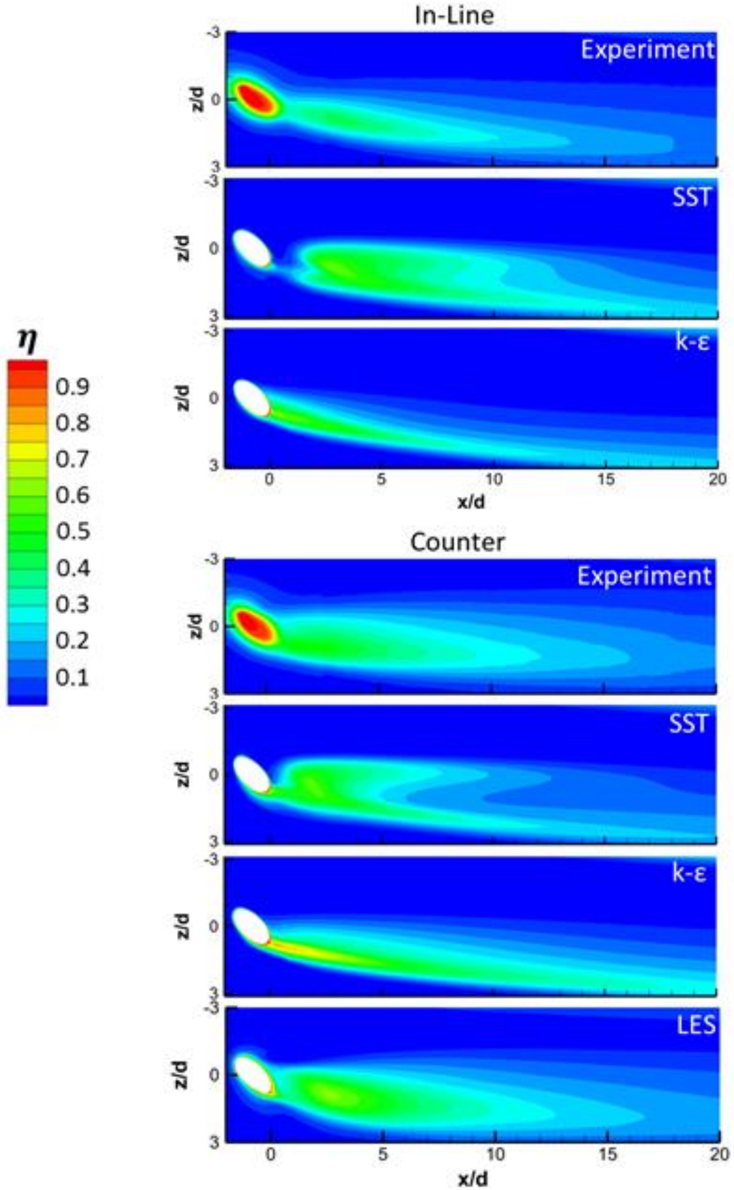
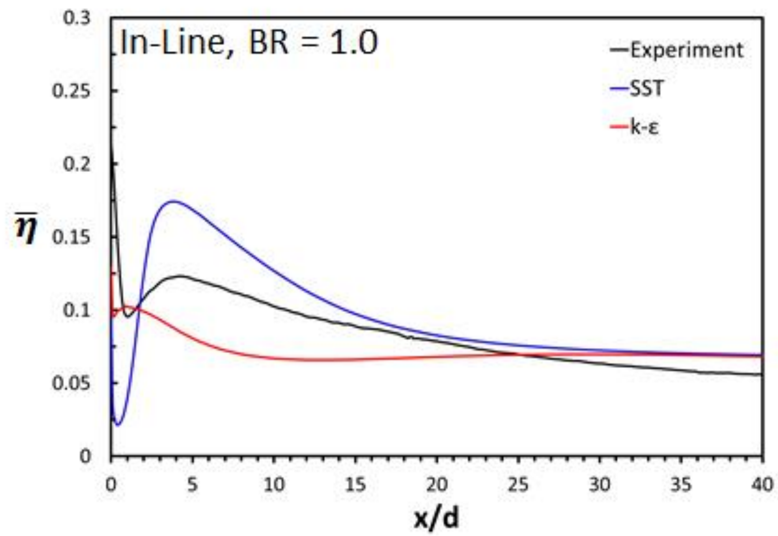
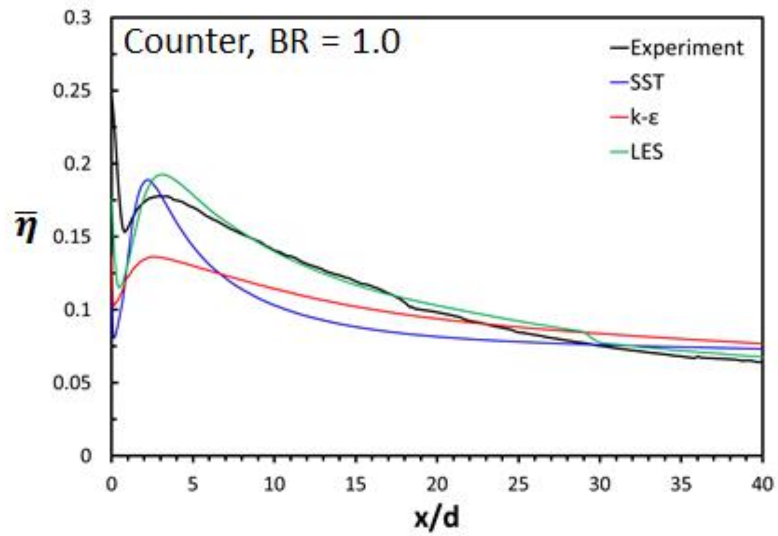
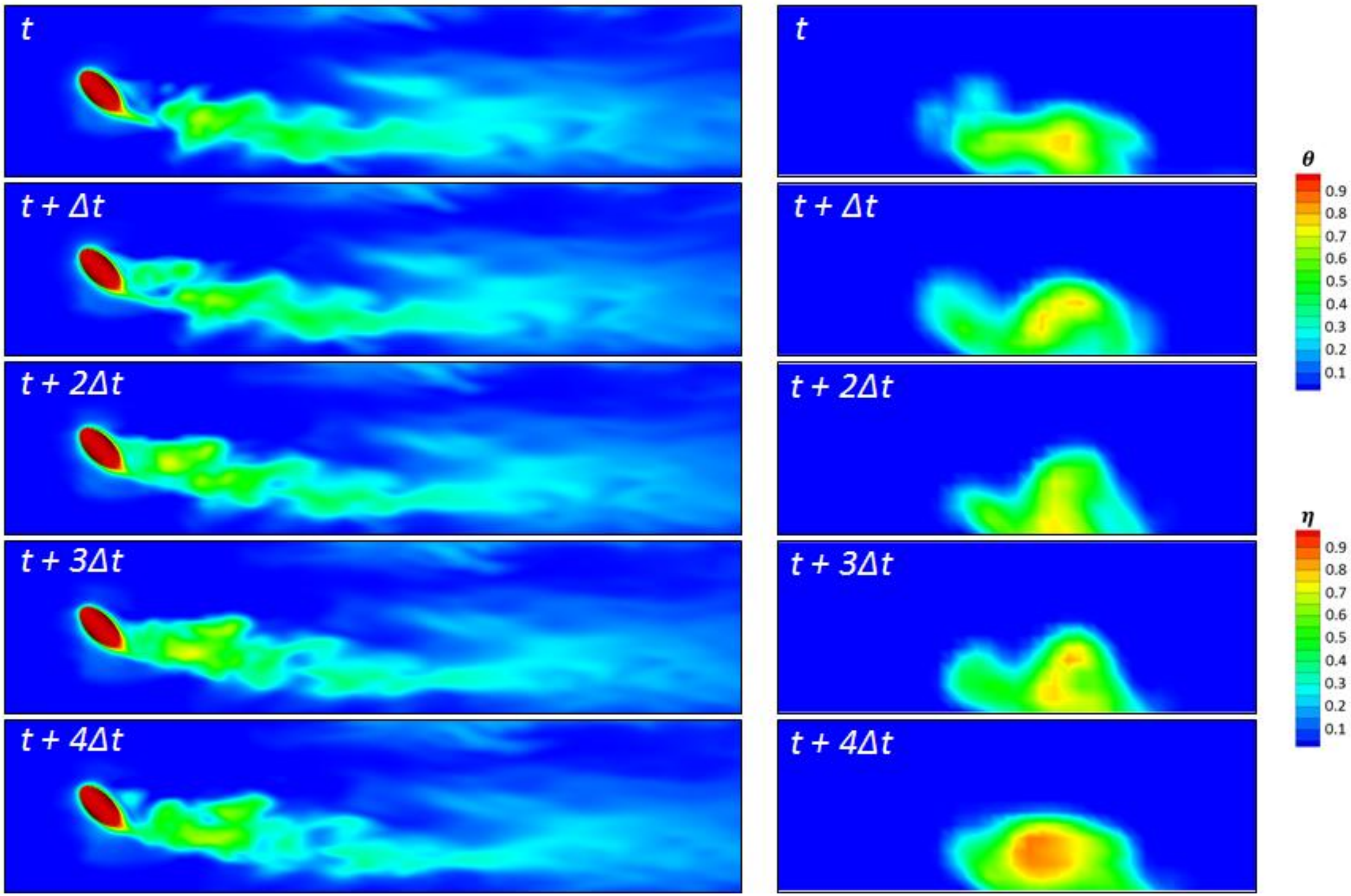






Compound-Angle Film Cooling: Zach Stratton

LES: instantaneous normalized temperature



Compound-Angle Film Cooling: Zach Stratton

Conclusion:

- Separation induces a vortex that causes flow to swirl in the hole.
- Vortex is unsteady causing side-to-side shedding.
- Steady RANS compared poorly with experiment.
- LES was able to predict adiabatic effectiveness with reasonable accuracy, but MUST simulate the trip in the experiment.

Our Current Efforts:

- Examine LES models in the near-wall region for surface heat transfer.
- Examine RANS to LES interface boundary conditions.
- Understand statistics from LES to guide RANS modeling for internal cooling and film cooling.

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Summary & Current Work

Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

One source of failure in GTs is due to **inadequate cooling during transient operations – not startup, but from a lower load state to a higher load state**.

Previous Work:

- Very little work reported that are relevant to gas turbines. Mostly on startup.
- Lee, at al. (2013) showed **the temperature in the material could exceed the maximum permitted during the transients even though the cooling provided is adequate once steady-state is reached.**

Objective:

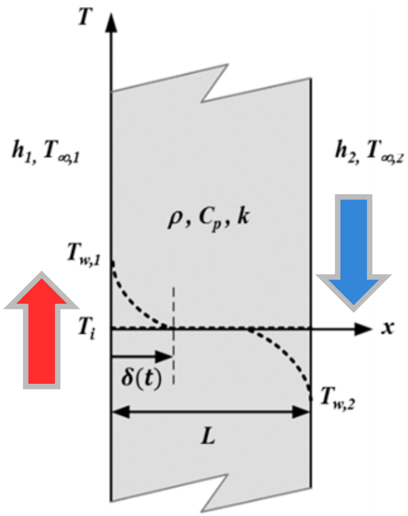
- Develop a model that can be used to guide the design of cooling strategies subjected to sudden changes in heating loads.
- Want to estimate the over temperature, its duration, …

Approach:

- Develop a closed-form approximate solution of unsteady 1-D HT in a flat plate.

Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

Approximate Solution by an Integral Method



$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$T(x,0) = T_i$$

$$-\left.\frac{\partial T}{\partial x}\right|_{x=0} = \frac{h_1(T_{\infty,1} - T_{w,1})}{k}$$

$$-\left.\frac{\partial T}{\partial x}\right|_{x=L} = \frac{h_2(T_{w,2} - T_{\infty,2})}{k}$$

1st time domain:
when conduction from both sides reaches the same point in the plate.

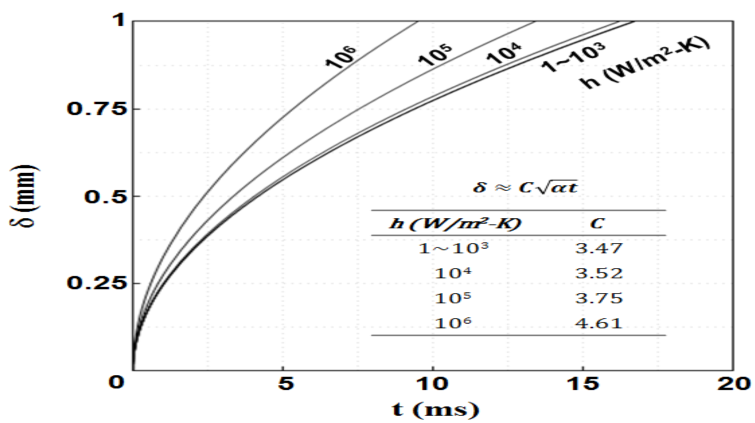
2nd time domain:
from the end of the 1st time domain to the time when the temperature in the plate reach its maximum (referred to as its peak temperature).

3rd time domain:
from the time of the peak temperature to the time when steady state is reached.

1st Time Domain:

$$\int_{T_i}^{T_{w,1}} \left(\frac{2(T_{w,1}-T_i)\left(\frac{h_1(T_{\infty,1}-T_{w,1})}{k}\right)+\frac{h_1}{k}(T_{w,1}-T_i)^2}{\left[\frac{h_1(T_{\infty,1}-T_{w,1})}{k}\right]^3} \right) dT_{w,1} = \frac{4}{3}\alpha t$$

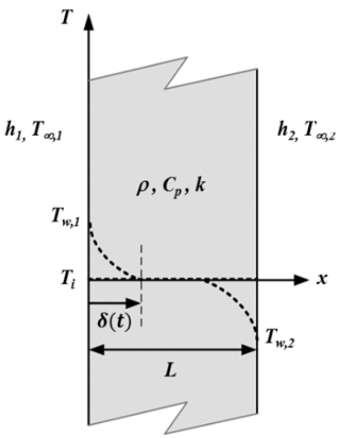
$\delta_1 \approx 3.47\sqrt{\alpha t}$ (Valid for h < 10^4 W/m^2-K)



See IGTI2015-43526 for details.

Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

Approximate Solution by an Integral Method



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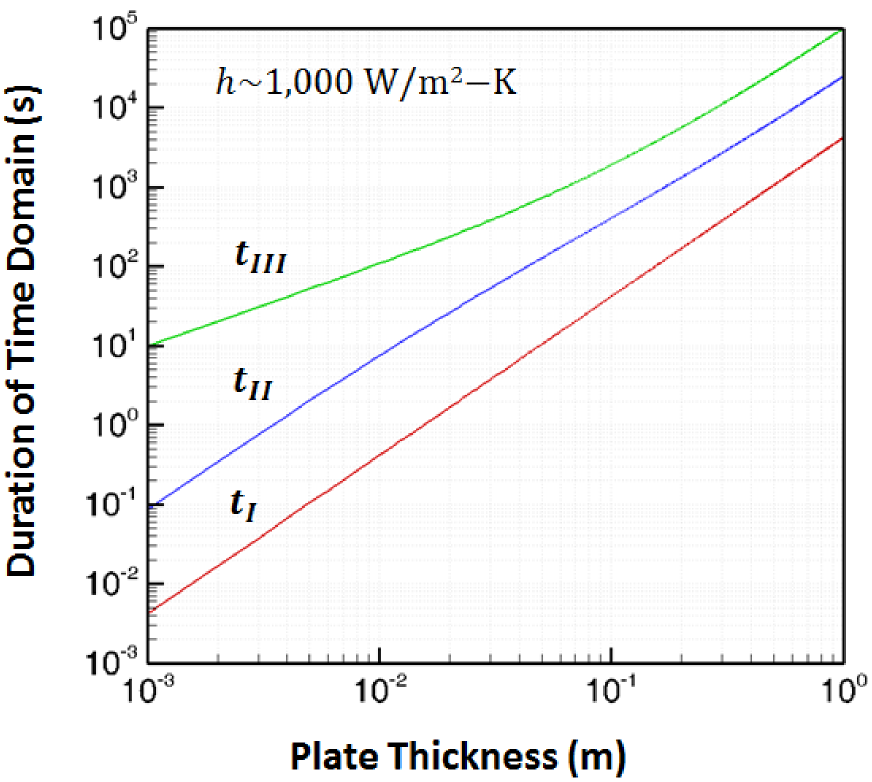


2nd and 3rd Time Domains:

$$\mathbb{T} = \mathcal{C}_1 \mathbb{X}_1 e^{-\frac{t}{\tau_{III}}} + \mathcal{C}_2 \mathbb{X}_2 e^{-\frac{t}{\tau_{II}}} + \mathbb{R}$$

$$\tau_{II,\,III} = \rho\, Cp\, L \left(\frac{48 + 7\frac{h_1 L}{k} + \frac{h_1 L}{k}\cdot\frac{h_2 L}{k} + 7\frac{h_2 L}{k}}{\frac{6k}{L}\left[\left(48 + 20\frac{h_1 L}{k} + 5\frac{h_1 L}{k}\cdot\frac{h_2 L}{k} + 20\frac{h_2 L}{k}\right) \pm 3\sqrt{\left(16 + 4\frac{h_1 L}{k} + \frac{h_1 L}{k}\cdot\frac{h_2 L}{k} + 4\frac{h_2 L}{k}\right)^2 + 16\left(\frac{h_1 L}{k} - \frac{h_2 L}{k}\right)^2}\right]} \right)$$

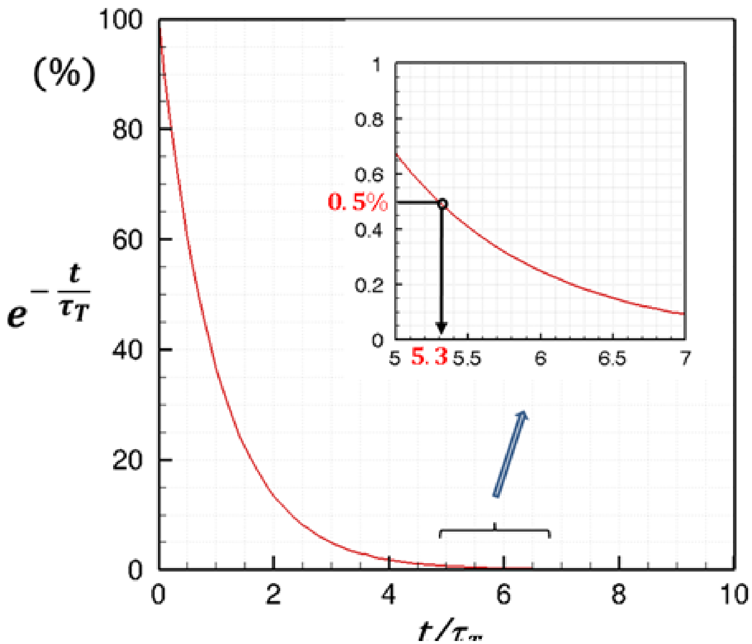
See IGTI2015-43526 for details.

Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

Estimate Duration of Over Temperature:

$$P \cong 5.3\,\tau_T$$

$$\tau_T = \tau_{II} + \tau_{III}$$



Estimate "Maximum" Over Temperature:

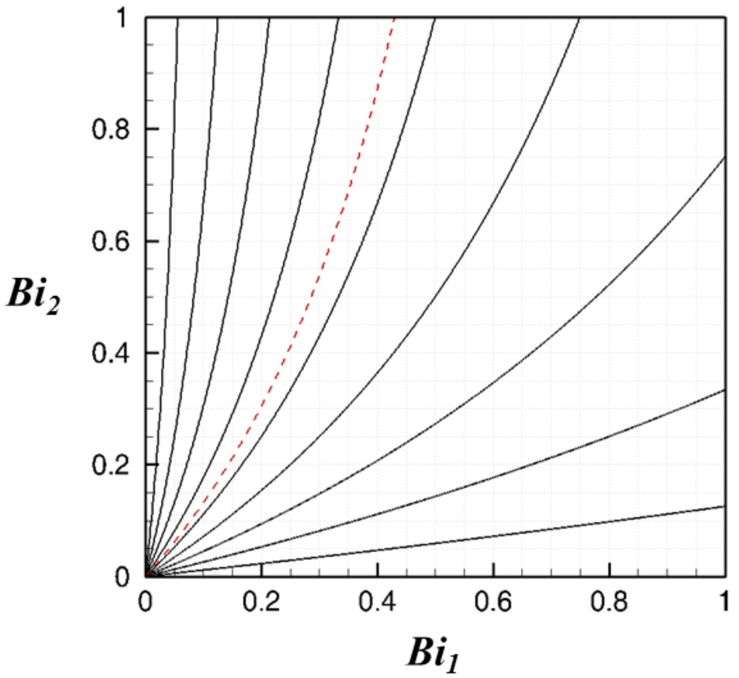
$$\theta_{w,1,max} = \mathcal{M}_1 + \frac{1}{2}\left(\theta_{w,1,i} - \mathcal{M}_1 + \mathcal{M}_2\right)\left(e^{-\mathcal{N}_{II}(Fo_c - Fo_i)}\right) + \frac{1}{2}\left(\theta_{w,1,i} - \mathcal{M}_1 - \mathcal{M}_2\right)\left(e^{-\mathcal{N}_{III}(Fo_c - Fo_i)}\right)$$

See IGTI2015-43526 for details.

Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

What cooling is needed for a given heating load to ensure T_{max} in material does nor exceed acceptable value?

$$\frac{Bi_1(1 + Bi_2)}{Bi_1 + Bi_1 Bi_2 + Bi_2} = \theta_{w,1,i}$$



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Unsteady Conjugate HT: C.S. Lee, T. I-P. Shih

To determine a **precooled wall temperature needed that ensures the max. temperature in a plate never exceeds the max. allowable** throughout the transient process:

$$\theta_{w,1,max} \leq \theta_{max.\,allowable}$$

$$\rightarrow \theta^*_{w,1,i} \leq \frac{\left((2-\mathcal{M}_{2,b})\theta_{max.\,allowable} - \mathcal{M}_1 + \mathcal{M}_{2,c}\right)}{\left(1-\mathcal{M}_{2,a}\right)}$$

where

$$\theta^*_{w,1,i} = \frac{T^*_{w,1,i} - T_{\infty,2}}{T_{\infty,1} - T_{\infty,2}} \qquad \mathcal{M}_1 = \frac{Bi_1(1+Bi_2)}{Bi_1 + Bi_1 Bi_2 + Bi_2}$$

$$\mathcal{M}_{2,a} = \frac{4(Bi_1 - Bi_2)}{\sqrt{(4Bi_1 + Bi_1Bi_2 + 4Bi_2 + 16)^2 + 16(Bi_1 - Bi_2)^2}}$$

$$\mathcal{M}_{2,b} = \frac{(4+Bi_2)^2}{\sqrt{(4Bi_1 + Bi_1Bi_2 + 4Bi_2 + 16)^2 + 16(Bi_1 - Bi_2)^2}}$$

$$\mathcal{M}_{2,c} = \frac{5Bi_1Bi_2^{\,2} - 4Bi_1^{\,2}Bi_2 - 4Bi_1^{\,2} + 12Bi_1Bi_2 + 16Bi_1}{(Bi_1 + Bi_1Bi_2 + Bi_2)\sqrt{(4Bi_1 + Bi_1Bi_2 + 4Bi_2 + 16)^2 + 16(Bi_1 - Bi_2)^2}}$$

In a GT operation:

If maximum allowable = 900°C,

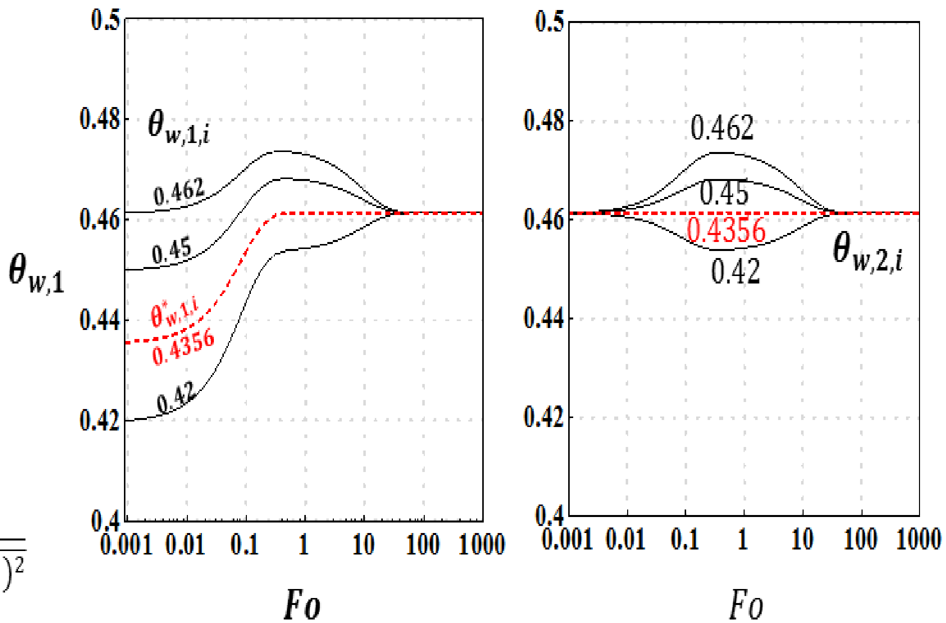
and hot gas: $T_{\infty,1}$ = 1,482°C

coolant: $T_{\infty,2}$ = 400°C

Then, $\theta_{max,allowable}$ = 0.462

$\rightarrow \theta^*_{w,1,i}$ = 0.4356,

($T^*_{w,1,i}$ = 871°C)



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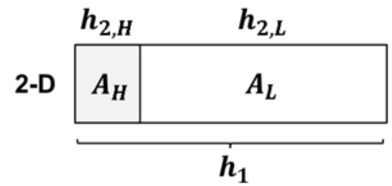
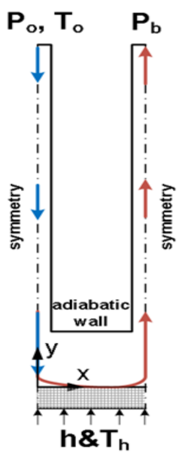
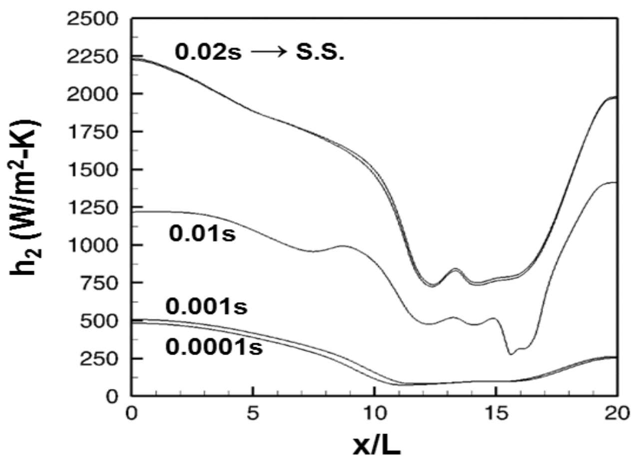
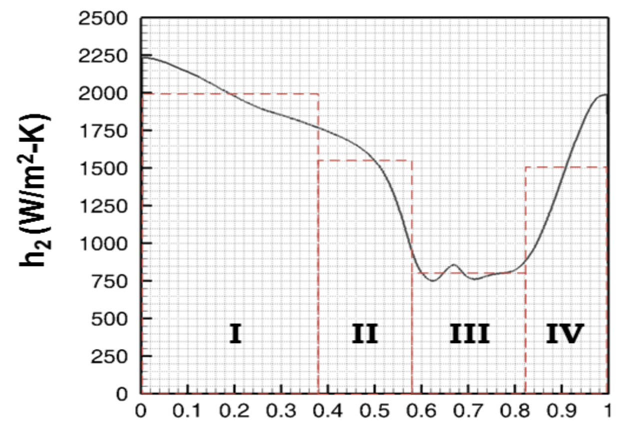
Generalization to Multidimensions



$$\bar{h}_2 = \frac{h_{2,H}A_H + h_{2,L}A_L}{A_H + A_L} = h_{2\,(1D)}$$







$$A_i^* = \frac{A_i}{\sum_1^n A_i}$$

Segment #		I	II	III	IV
		0.38	0.2	0.24	0.18
h_1(W/m²-K)		1,090	1,090	1,090	1,090
h_2(W/m²-K)		2,000	1,550	800	1,500
τ_{II}	$R_T^i \cdot C_i$ (s)	0.0165	0.0166	0.0167	0.0166
τ_{III}	$R_T^i \cdot C_i$ (s)	1.579	1.841	2.564	1.876
	(s)	1.94			

Duration of Over Temperature

Solid Only - α=constant - Ti=900°C	CFD	Model =1.94s	Error
99.5%	10.8s	10.3s	4.6%
99.9%	14s	13.6s	3%

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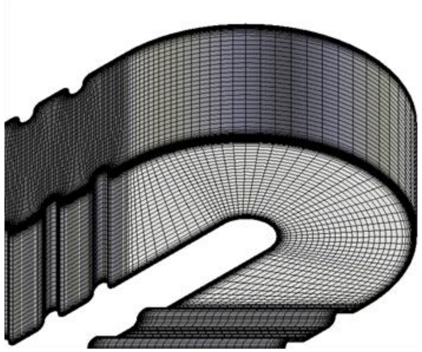
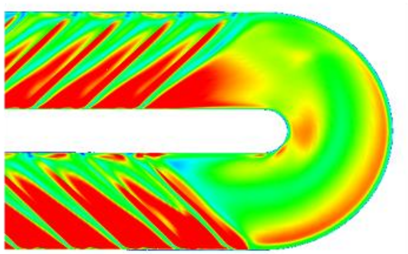
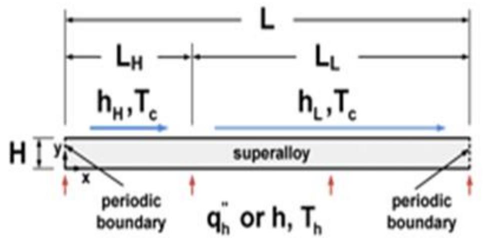
Summary & Current Work

Effects of Averaging: C.S. Lee, T. I-P. Shih



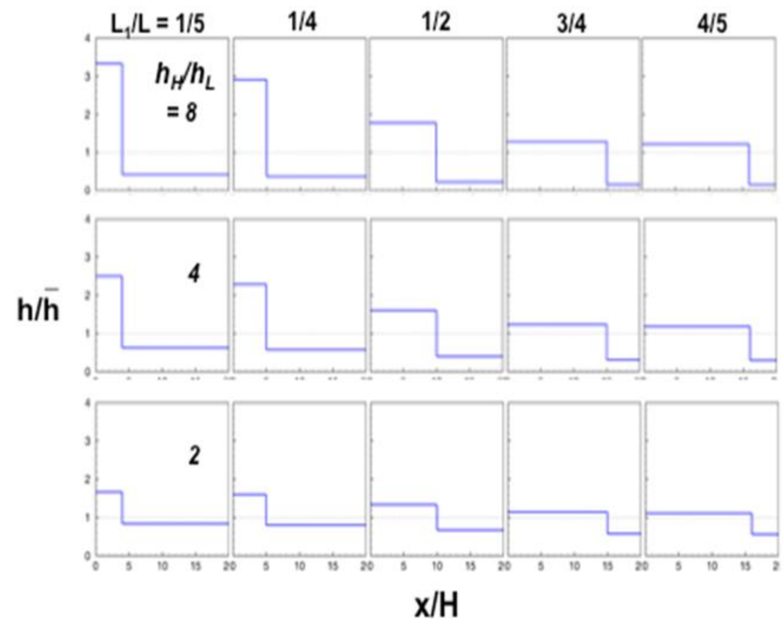


$$\bar{h} = \frac{h_H L_H + h_L L_L}{(L_H + L_L)} = 1442.5 \text{ W/m}^2\text{-K}, \; T_c = 400 \text{ °C}$$

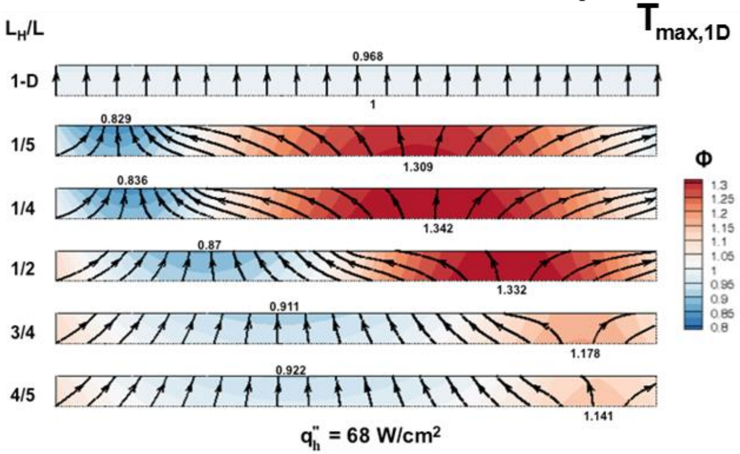


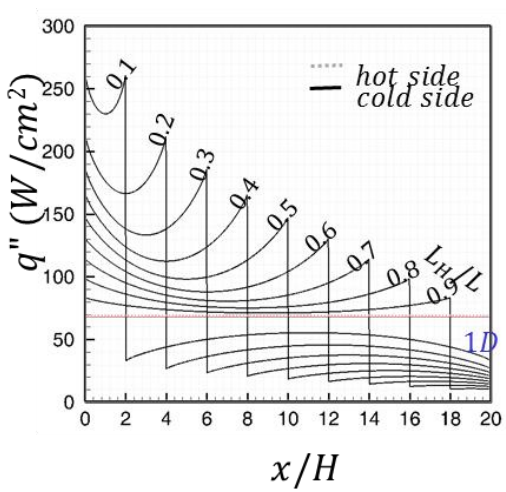
H = 1 mm
L = 20 H
T_c = 400 °C
T_h = 1482 °C

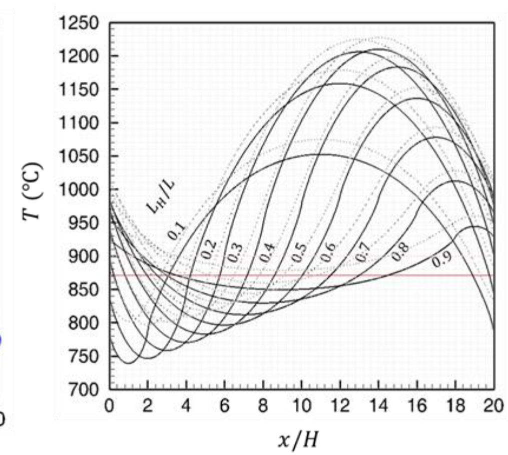
Lee & Shih (2015)



$$\Phi = \frac{T}{T_{max,1D}}$$







See IGTI2015-43552 for details.

Summary

Performed a CFD study to examine the Bath rim-seal configuration. Found that blades on the rotor indeed do not affect the pressure distribution downstream of the stator. However, inertial frame and inertial plus non-inertial frame with frozen rotor do not yield the same results. The culprit is the frozen-rotor BC.

Developed a model to estimate the maximum over temperature, its duration, cooling needed at steady state, and precooling temperature needed before sudden increase in heating load to ensure no over temperature during the transient.

When the variation in the HTC is accounted for, the maximum temperature in the plate could be as high as 1.363 times the maximum temperature predicted by assuming an averaged HTC. Also, the difference in the maximum and minimum temperature in the plate can increase by a factor of 16, which strongly affects thermal stress.