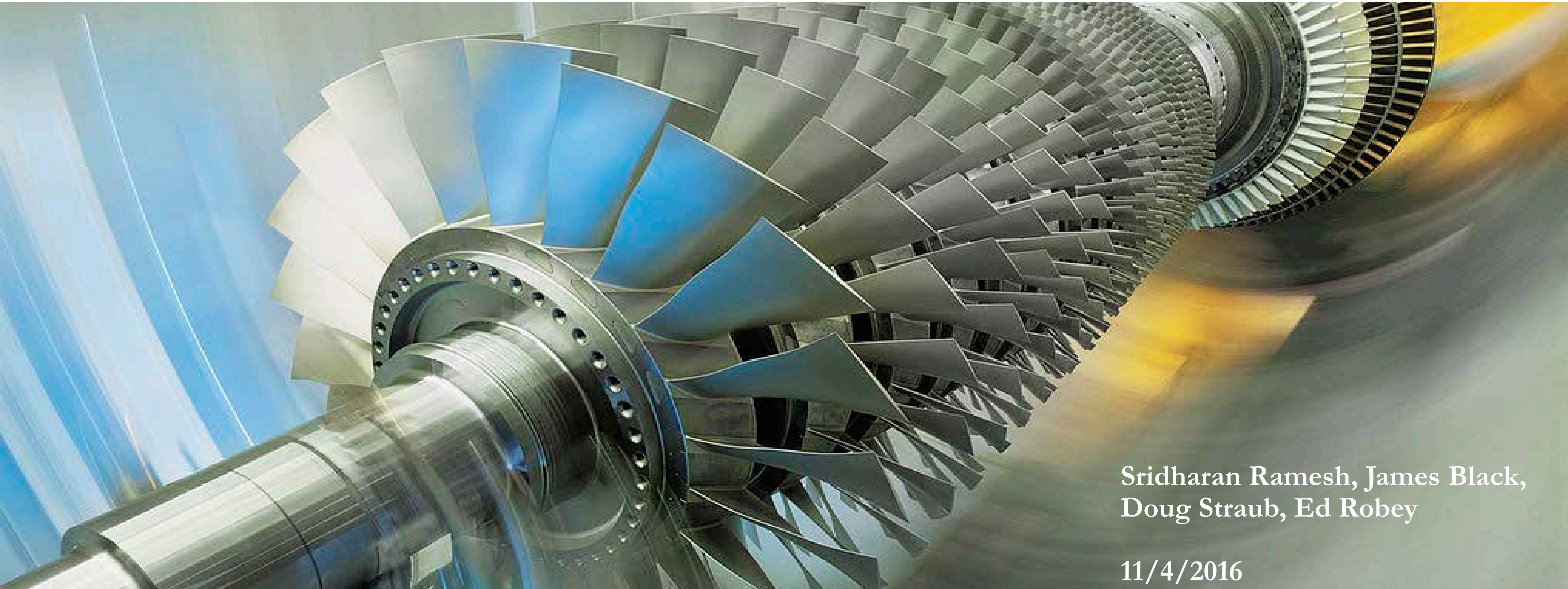
# UTSR Workshop

## Film Cooling experiments at Near-Engine Conditions

NATIONAL ENERGY TECHNOLOGY LABORATORY



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11/4/2016

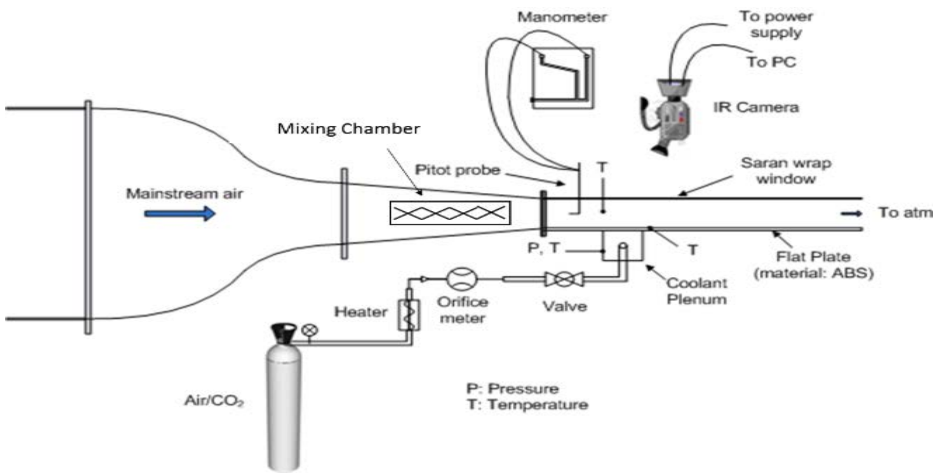
# Outline

- Objective
- Experimental facility
- Challenges
- Proposed methodology
- Role of CFD
- Future plans

# Objective

- Evaluation of film cooling performance at near engine conditions
- Comparison of experimental measurements obtained at high temperature high pressure facility with those obtained at lab scale conditions

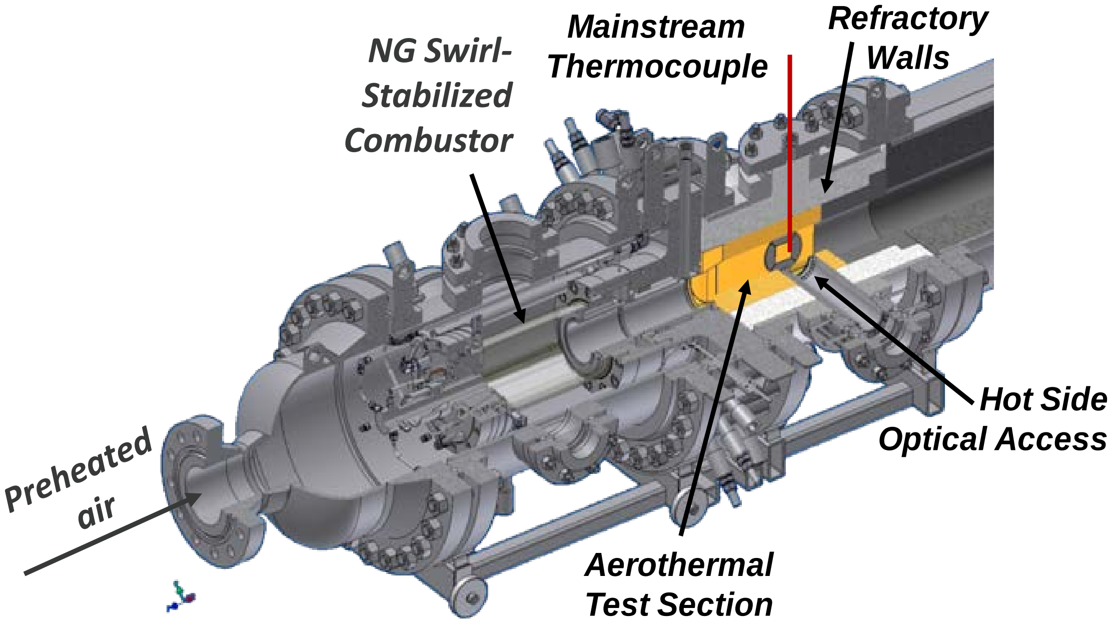
Lab scale flat plate test setup → Aero thermal facility

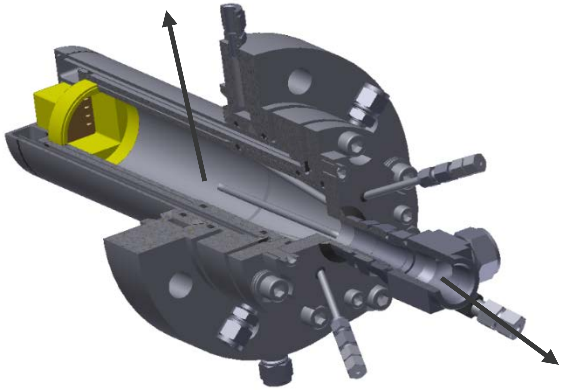



Low speed, Low temperature, Atm Pr,
Low turbulent intensity, No swirl

Moderate speed, High temperature, Pr >> Atm pr.,
Very high turbulent intensity, Moderate swirl

# NETL's High Temperature and High Pressure Test Facility




**Hot Gas Path Capabilities**

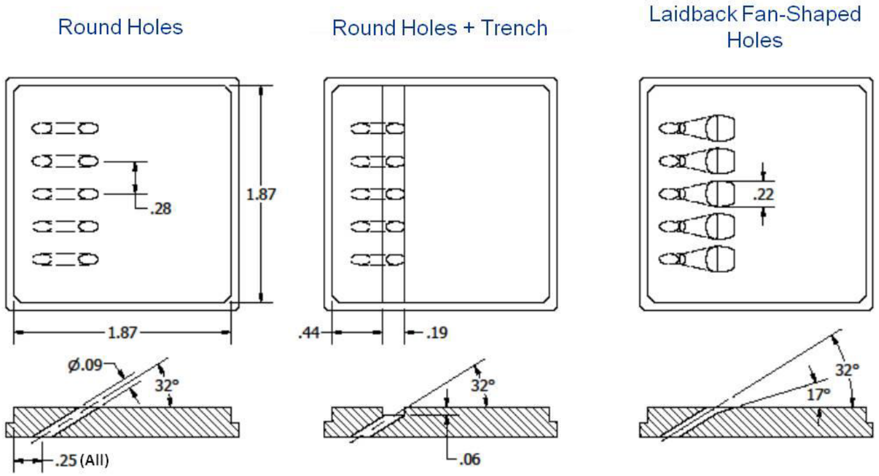
- ~70 m/s @ Tu ~ 15-20%
- 1000-1200°C
- 1 – 10 bar

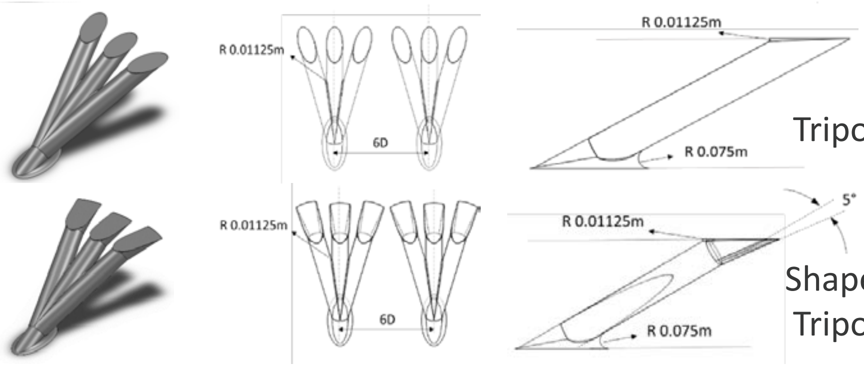
**Coolant Gas Path Capabilities**

– Ambient → ~ 300 °C
– 0.5 → 5 gm/sec
– No bypass flow

# Measurements on Test Articles

## Cooling Schemes

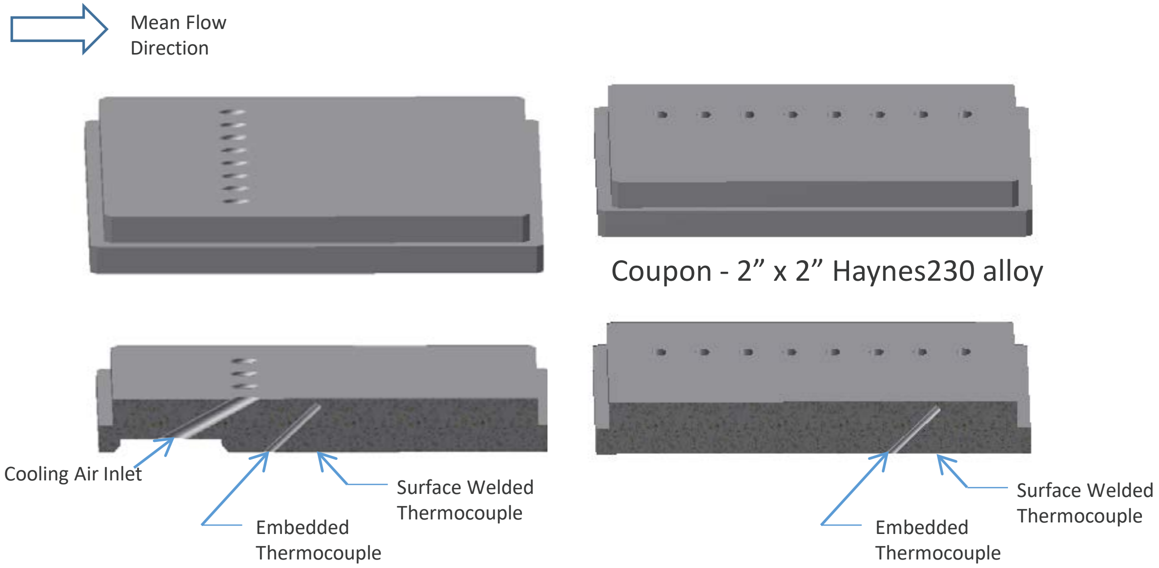


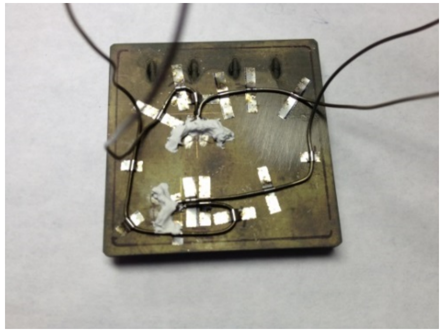

Tripod

Shaped Tripod

## Measurements




Coupon - 2” x 2” Haynes230 alloy



- **Calibrated thermocouples @ 4 locations**
  - 0.031” diameter Type K
  - 2 embedded within 0.020” from hot side
  - 2 cold side

# Experimental Results - NETL

Issues

Coupon (center) effectiveness, $\varphi = \dfrac{T_m - T_{wh}}{T_m - T_{c,internal}}$

Heat transfer , $q = kA\dfrac{T_{wh} - T_{wc}}{dx}$

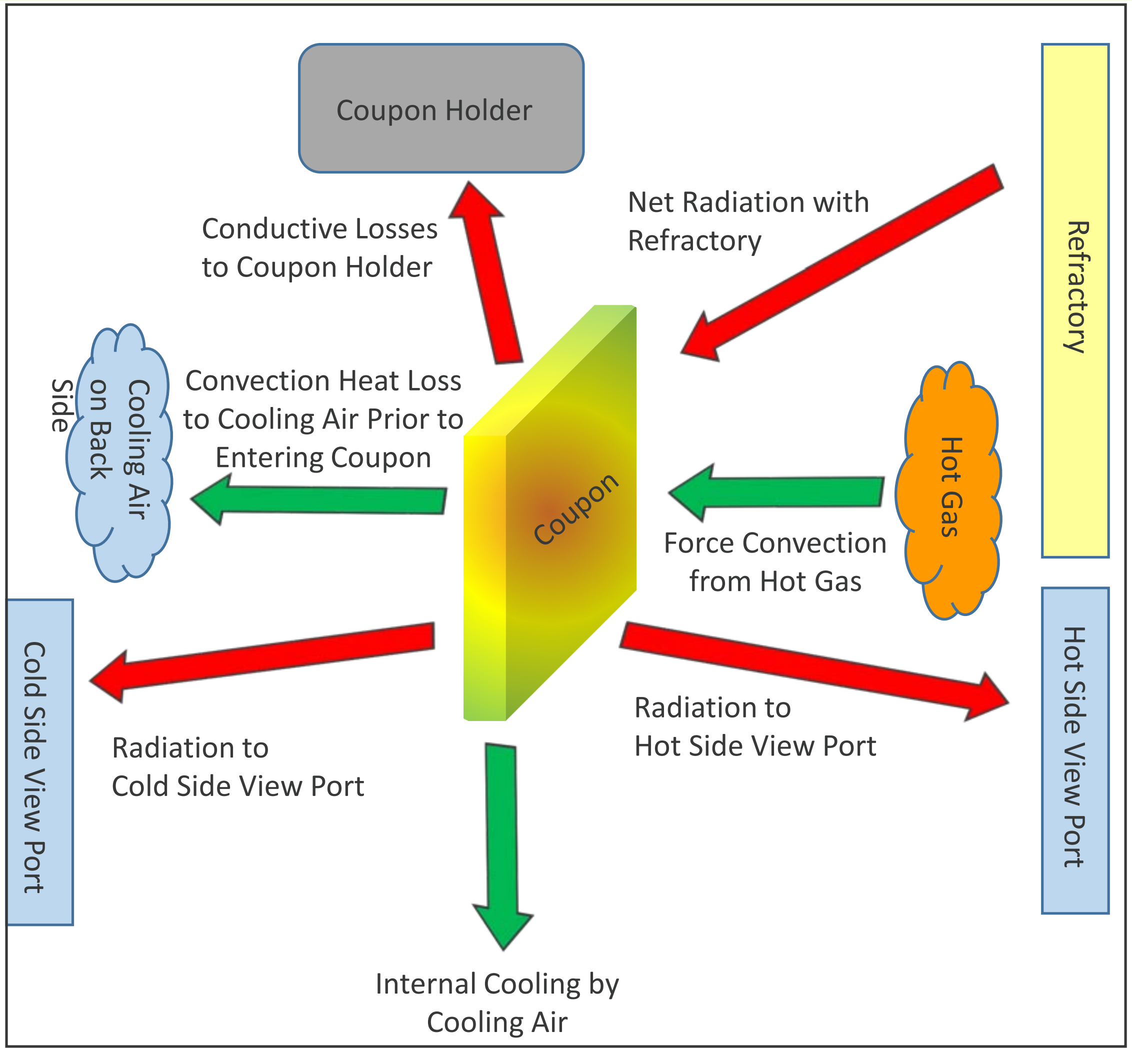
Overall heat transfer coefficient, $q'' = H\,(T_m - T_{wh})$

$H \ni \{h_{convection}, h_{radiation}\}$

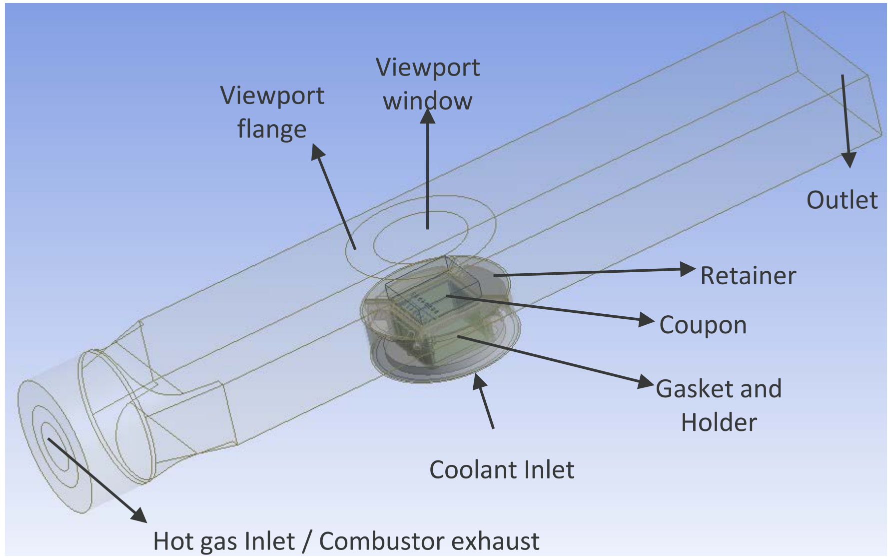
$\eta$ ?

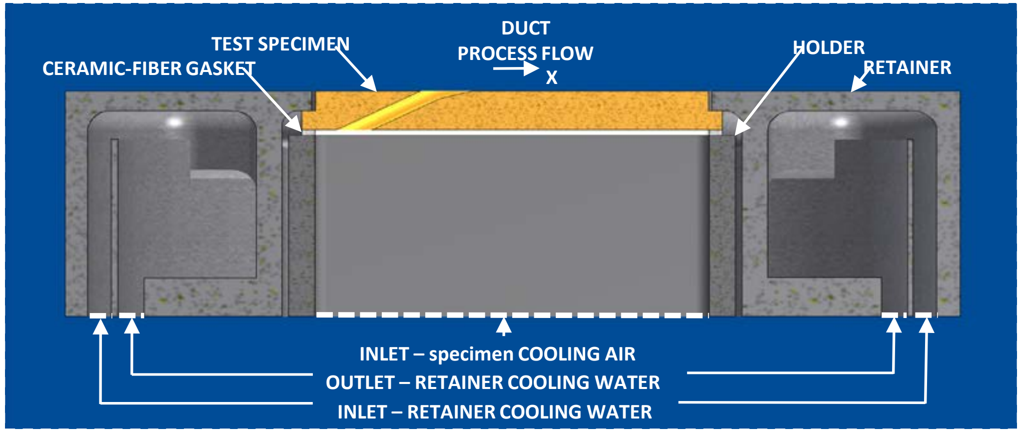
Challenges

- Limited experimental measurements owing to high temperature (1450 K) and high pressure test facility condition (View factors, conduction losses, refractory temperature -> radiation)
- Lack of instrumentation and difficulties in obtaining velocity and temperature measurements of the flow field and surfaces



# Heat Transfer Mechanism – Aero Thermal Test Rig




**Heat Transfer modes**

| | Location | Contribution |
|---|---|---|
| | **Convection** | |
| 1. | Convection from hot gas to coupon | Major |
| 2. | Convection through film cooling holes | Major |
| 3. | Convection on coupon cold side exposed to coolant plenum | Major |
| 4. | Convection on coupon sides and region exposed to airgap | Negligible |
| | **Conduction** | |
| 5. | Conduction losses due to contact with retainer | Major |
| 6. | Conduction losses due to contact with gasket | Major |
| | **Radiation** | |
| 7. | Radiation from refractory to coupon hot side | Major |
| 8. | Radiation from coupon hot side to viewport window | Major |
| 9. | Radiation from coupon hot side to viewport flange | Major |
| 10. | Radiation from coupon cold side to plenum walls | Major |
| 11. | Radiation from coupon holes to viewport window | Negligible |
| 12. | Radiation from coupon holes to viewport flange | Negligible |
| 13. | Radiation from coupon sides and regions exposed to airgap to retainer | Negligible |

# Experimental Methodology – Energy Balance

## Convective heat load on coupon*

| | |
|---|---|
| Region exposed to hot gas | $(1\text{-}c)\, h_0 A (T_g - T_s)$ |
| Film cooled region | $c\, h_f A (T_f - T_s)$ |
| Lets assume | $h_0 = h_f$ |
| c | portion of coupon affected by film cooling |
| η | $(T_g - T_f)/(T_g - T_{c,exit})$ |
| Tf | $T_g - \eta.(T_g - T_{ce})$ |
| **Final convected heat load due to hot gas** | $(1\text{-}c)\, h A (T_g - T_s) + c\, h A (T_g - \eta (T_g - T_{ce}) - T_s)$ |
| **Convection in film cooling holes** | |
| heat gained by coolant | $m.C_p (T_{c,e} - T_{c,i})$ |
| **Convection on cold side Coupon** | CFD |

## Radiative heat load on coupon*

| | |
|---|---|
| **Radiative heat load entering coupon** | |
| incident radiation from refractory to coupon | $\sigma\, \varepsilon_r A_r F_{rs} (T_r^4 - T_s^4)$ |
| **Radiative heat load leaving coupon** | |
| coupon hot side to view port window | $\sigma\, \varepsilon_s A_s F_{sw} (T_s^4 - T_w^4)$ |
| coupon hot side to view port flange | $\sigma\, \varepsilon_s A_s F_{sf} (T_s^4 - T_f^4)$ |
| coupon cold side to coolant plenum walls | $\sigma\, \varepsilon_s A_s F_{sp} (T_s^4 - T_p^4)$ |

## Conduction losses from coupon to holder assembly

| | |
|---|---|
| **coupon - gasket contact losses** | CFD |
| **coupon - retainer contact losses** | CFD |

**Nomenclature**

A = Coupon surface area, $m^2$
c = portion of coupon affected by film cooling
$C_p$ = Specific heat of coolant
m = coolant mass flow rate
h = Heat transfer coefficient, W/m-K
T = Temperature, K
F = View factor
ε = Surface emissivity
η = film cooling effectiveness
σ = Stefan Boltzmann constant

**Subscripts**

*c = coolant*
*g = hot gas*
*f = film*
*p = plenum coolant*
*r = refractory*
*s = coupon surface (hot side)*
*sc = coupon surface cold side*
*v = viewport*

# Experimental Methodology

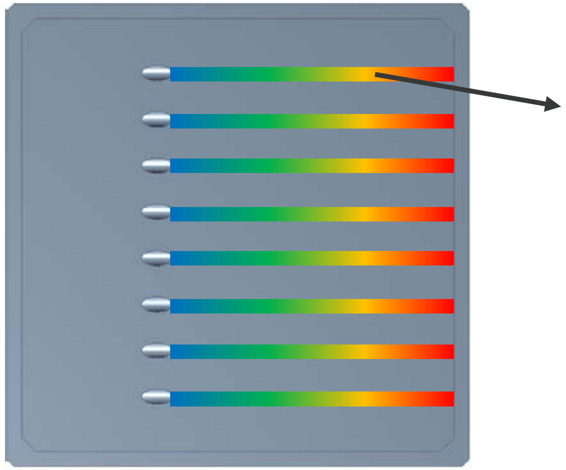
Coupon overall energy balance

Hot gas convection + Refractory radiation = Coupon radiation to plenum and viewport window + Coupon cold side cooling + Conduction losses coupon-holder assembly + Convection through film cooling holes

$$c.h_f A\left(T_g - \eta(T_g - T_{c,exit}) - T_w\right) + (1-c)h_0 A\left(T_g - T_w\right)$$
$$= \sigma\varepsilon_s A_s F_{s\rightarrow v}(T_s^4 - T_v^4) + \sigma\varepsilon_s A_s F_{s\rightarrow p}\left(T_s^4 - T_p^4\right) + \dot{m}C_p\left(T_{c,exit} - T_{c,inlet}\right) + Q_{condn\ losses} + Q_{h,\ backside\ cooling} - \sigma\varepsilon_s A F_{s\rightarrow r}(T_r^4 - T_s^4)$$

Empirical correlations / CFD ?

| From CFD | From Experiment | Assumptions |
|---|---|---|
| View factors: $F_{sv}$, $F_{sp}$, $F_{sr}$ | Temperature: $T_s$, $T_{c,exit}$, $T_{c,inlet}$ | $h_0 = h_f$ |
| Temperature: $T_r$, $T_{c,exit}$ | $\dot{m}$ | |
| HTC: $h_0$ | | |
| Conduction losses, q | | |
| Backside cooling, q | | |



estimate for coolant coverage: c=d.x.n/A

where,
d = hole diameter
x = downstream distance covered by film cooling hole
n = number of holes
A = coupon surface area

# Experimental Methodology

$$c.h_f A(T_g - \eta(T_g - T_{c,exit}) - T_w) + (1-c)h_0 A(T_g - T_w)$$
$$= \sigma\varepsilon_s A_s F_{s\to v}(T_s^4 - T_v^4) + \sigma\varepsilon_s A_s F_{s\to p}(T_s^4 - T_p^4) + \dot{m}C_p(T_{c,exit} - T_{c,inlet}) + \sum kA_i \frac{dT}{dx} + Q_{h,\ backside\ cooling} - \sigma\varepsilon_s A F_{s\to r}(T_r^4 - T_s^4)$$

Hole shapes: CY, AV, SHAV, SH
BR: 0.5, 1 and 2.0

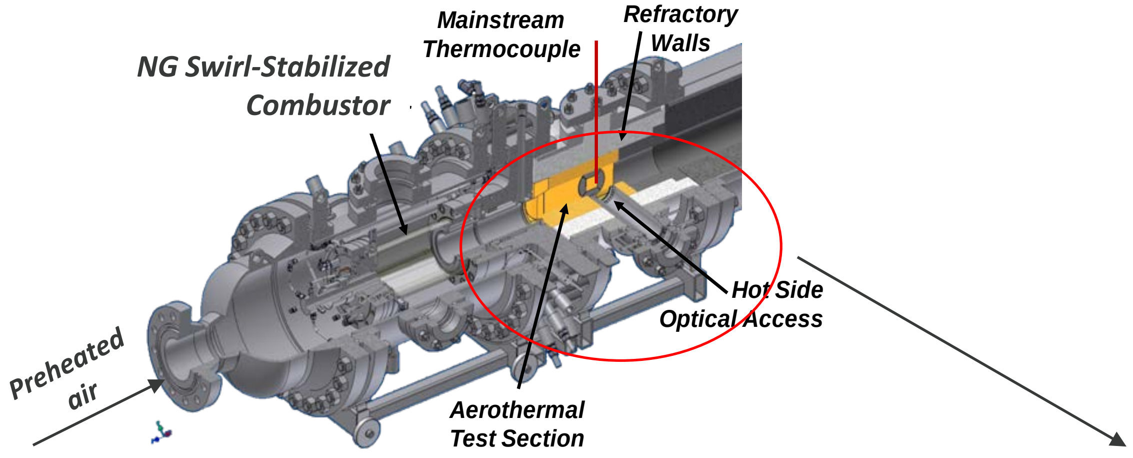
Run 1: $T_\infty$ = 1450 K, $T_{c,inlet}$ = 390 K

Run 2: $T_\infty$ = 1400 K, $T_{c,inlet}$ = 376.55 K

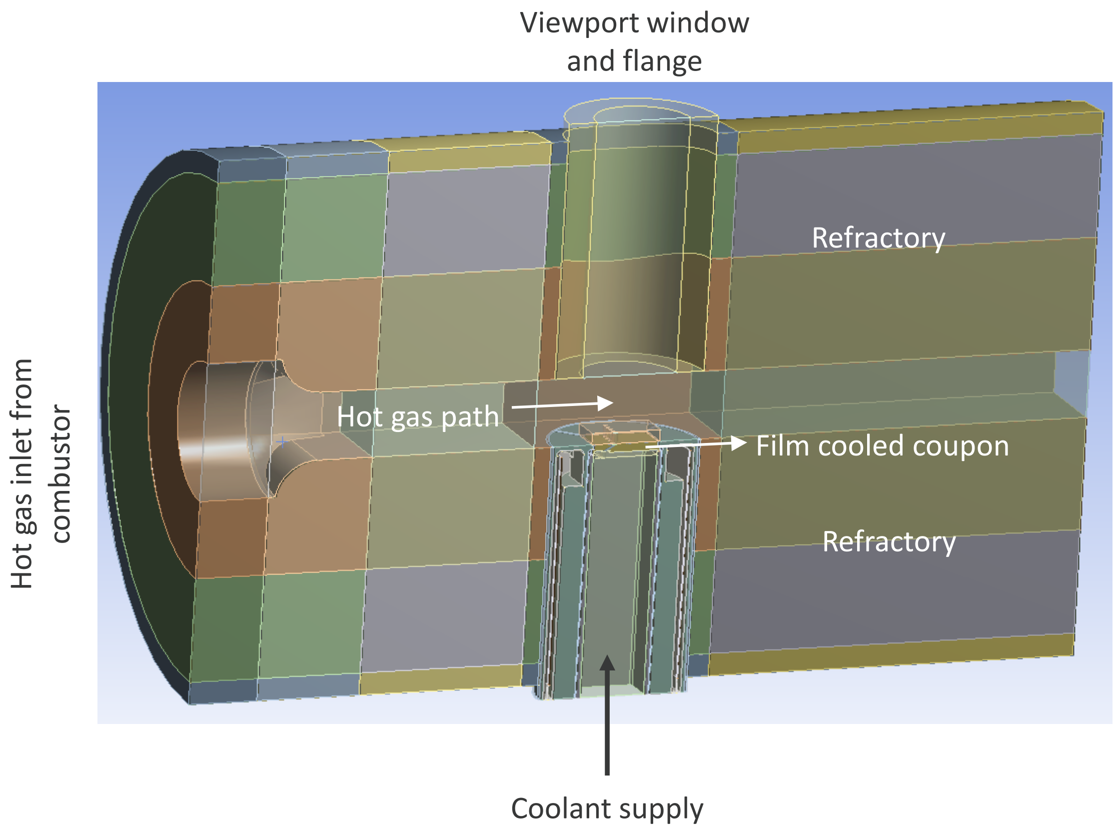
$h_f$, $\eta$ and $T_{c,exit}$ ⟶ $\varphi = \frac{1-x}{1+Bi+hf/hi} + \eta . x$, $\quad x = \frac{T_\infty - T_{c,exit}}{T_\infty - T_{c,inlet}}$

Net heat flux reduction, $$\frac{\Delta q''}{q''_0} = 1 - \frac{h_f}{h_0}\left(1 - \frac{\eta}{\varphi}\right)$$

# Numerical Analysis




Cross sectional view – Aero thermal test rig

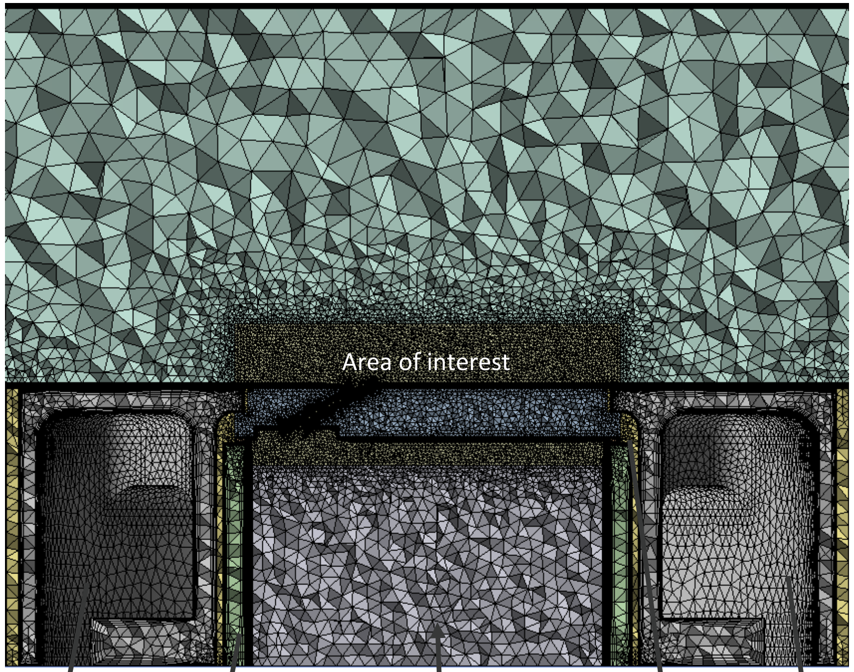



Objective: Obtain view factors, conduction losses, back side cooling heat transfer rate, refractory temperature

Challenges:

- Large size of the computational domain; Hole dia = 1/15" while Hot gas path width = 5"
- Conjugate heat transfer model with radiation

# Mesh and Setup




| Hot-gas (in) | AOI (in) | Mesh size (million) |
|---|---|---|
| 0.175 | 0.04 | 5 |
| 0.175 | 0.025 | 6.13 |
| 0.175 | 0.02 | 7.6 |
| 0.125 | 0.025 | 8.62 |

- Mesh Independent study: 5, 6.13, 7.6 and 8.62 million tetrahedral elements
- Inflational layers on solids: holder, gasket and retainer to refine mesh sizes near the boundary/interface
- Intended y+ ~ 1

**Boundary Conditions**

- Inlet: a) Velocity – Axial, Radial and Tangential; b) Static Temperature and c) Turb. KE and ε are obtained from Combustor CFD case **"aerothermal-with-combustor-only-rsm.cas"** – NETL database
- Outlet**:** pressure set to zero
- Operating Pressure**:** 3 bar
- Surface emissivity**:** literature and other sources
- Turbulence model: SST KW; RKE EWT
- Species Transport : Methyl – air mixture
- Radiation model: S2S; DO

**Numerical Schemes:**

P-V coupling: SIMPLE; Second order Upwind scheme for spatial discretization;
Gradient – Green gauss node based
Pressure - Standard

# Effect of turbulence model

| Model | Coupon maximum temperature (K) | Difference (K) |
|---|---|---|
| SST k-ω | 837 | - |
| Realizable k-ε | 843 | -6 |
| RNG k-ε | 852 | -15 |

Experimental variations in coupon temperature: ~ 20 K

| Model | Conduction losses (W) | Difference (K) |
|---|---|---|
| SST k-ω | 223 | - |
| Realizable k-ε | 233 | 10 |

Though the differences are quite small, SST k-ω model is preferred over Realizable k-ε owing to the accurate film cooling predictions at higher blowing ratios[1]

**Summary/Literature/Documentation:**

SST k-ω:

- Integrated to wall; resolves BL; predicts separation accurately;
- most widely used in film cooling studies and heat transfer studies
- Improved model compared to k-ω; blending function to switch k-ω near to k-ε towards mainstream;
- Modified eddy viscosity accounts for transport of turbulent stress; S: invariant measure of strain rate; $F_2$: blending function

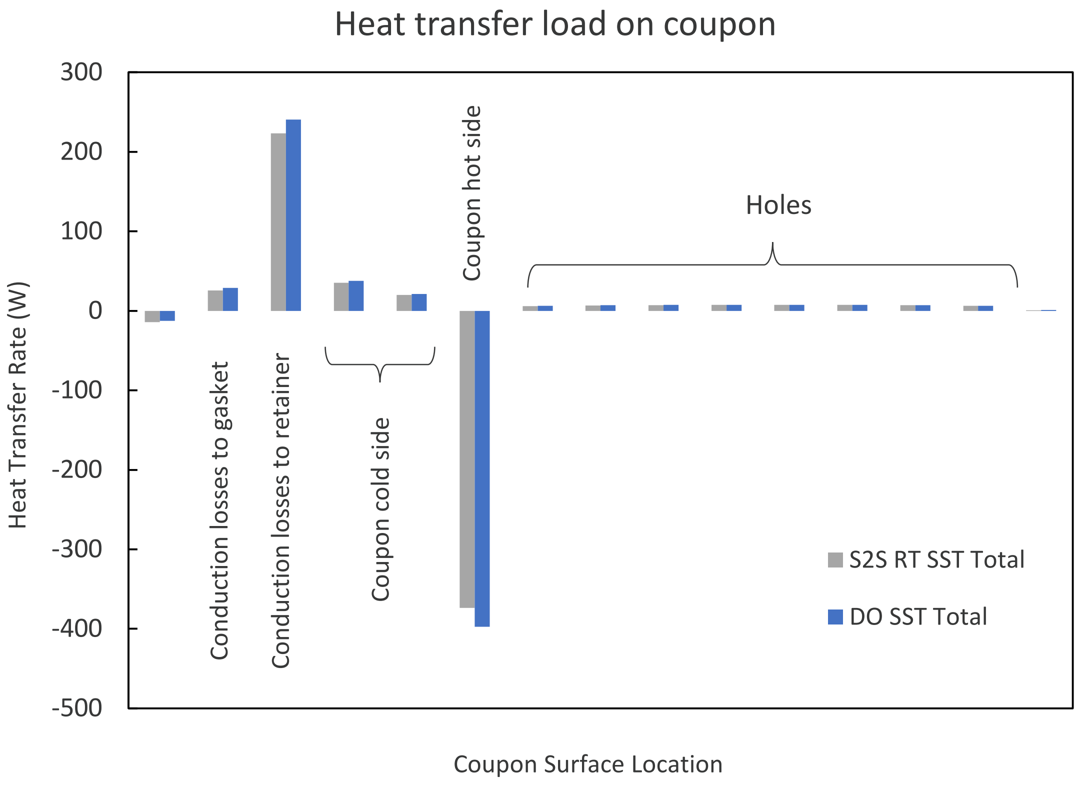
$$\nu_T = \frac{a_1 k}{\max(a_1 \omega, S F_2)}$$

Realizable k-ε and RNG k-ε :

- Works wells in cases of separated flow, streamline curvature, vortices unlike standard k-ε model
- Variable $C_\mu$ accounts for realizability in case of Realizable k-ε
- Enhanced Wall Treatment (EWT) behaves like two layer zonal method when with $y^+$ ~1; more accurate
- Scalable Wall Functions (ScWF) behave similar to standard wall functions but

Usage of curvature correction to account for the incoming swirl from the combustor exhaust gas: modify production term with an empirical function

# Effect of radiation model




**Summary on Radiation models**

Assumptions/simplifications:

- Combustor exhaust gases are modeled using Species Transport.
- Hot gas is assumed not to behave as a participating media.
- Radiation exchange is only between surfaces. Grey diffuse radiation.

Surface to Surface model:

- find view factors from each participating surface;
- $F_{12} = \frac{\iint cos\beta_1 . cos\beta_2 / \pi r^2)}{A_1}$
- all surfaces are treated opaque; converges relatively faster
- Does not support mesh adaption or hanging nodes

Discrete Ordinates method

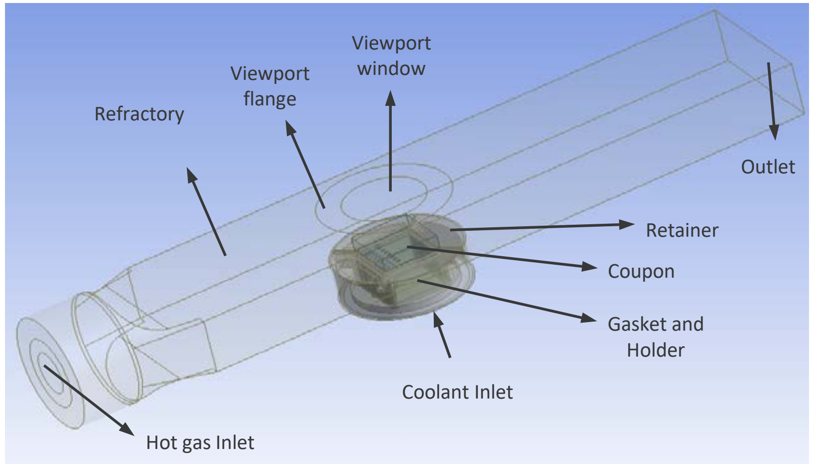
- Solve radiation transport equation for a finite number of discrete solid angles
- Allows walls be to treated as Semi-transparent surfaces

| Location | difference: S2S and DO (W) | % difference |
|---|---|---|
| Coupon hot side surface | 24 | -6.4 |

# Model assumptions

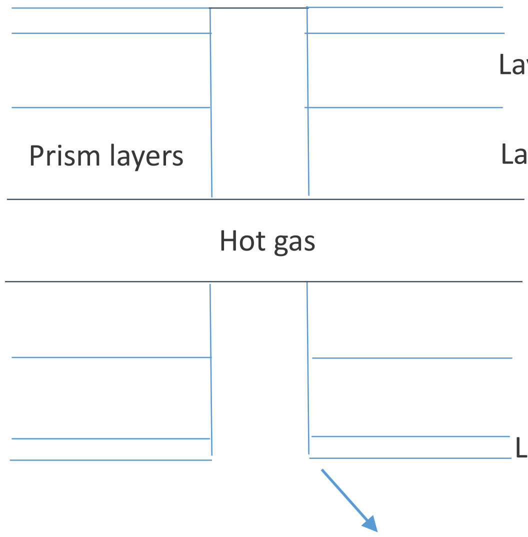
- **Simplified Rig:**
  - **Refractory:** Simplified using shell wall conduction
  - **Retainer Cooling:** Water used to maintain retainer temperature has been simplified using a constant Temp BC = 300 K. Change in water temperature in actual aero thermal rig ~ 1 K.
  - ~5 million tetrahedral elements

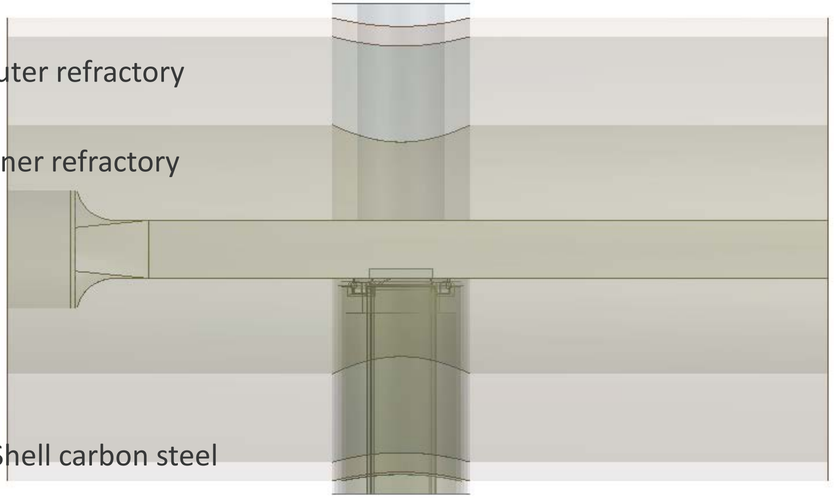
- **Actual Aero Thermal Rig:**
  - **Refractory:** included in the model
  - **Retainer cooling:** water domain included in the model
  - ~9 million tetrahedral element converted to ~5 million polyhedral elements




Simplified rig

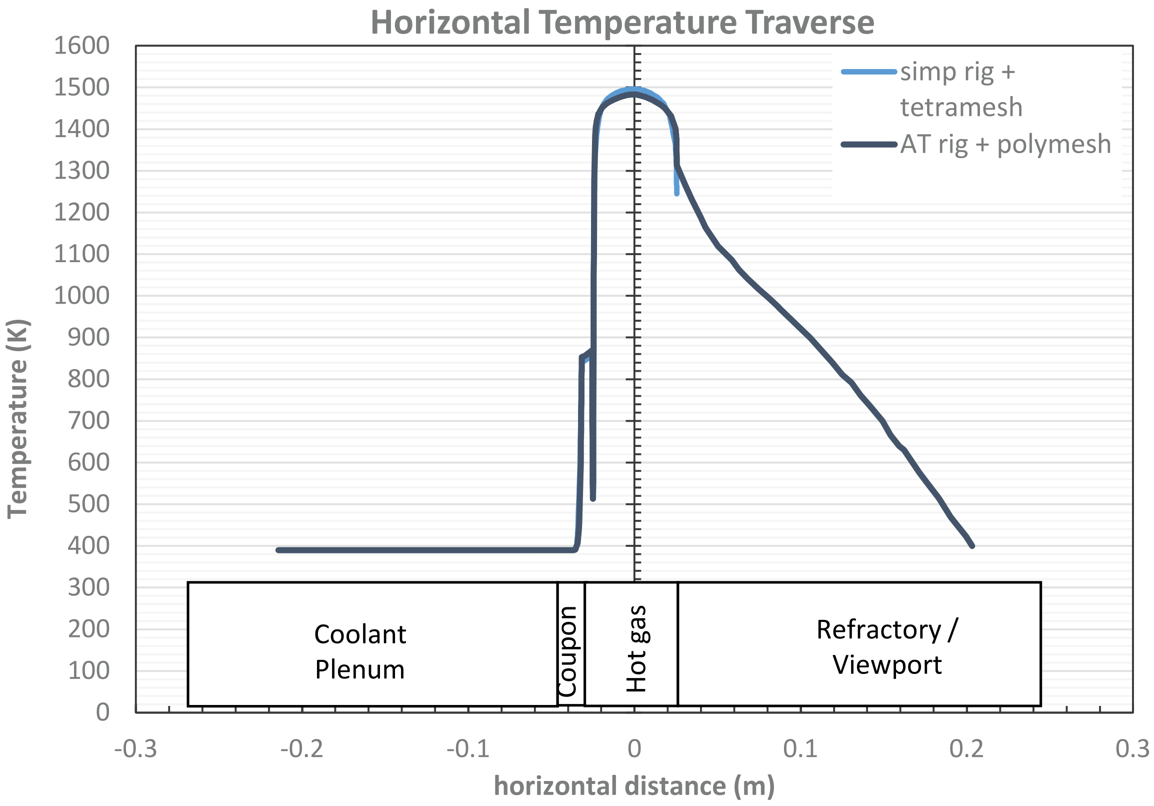
Shell wall conduction

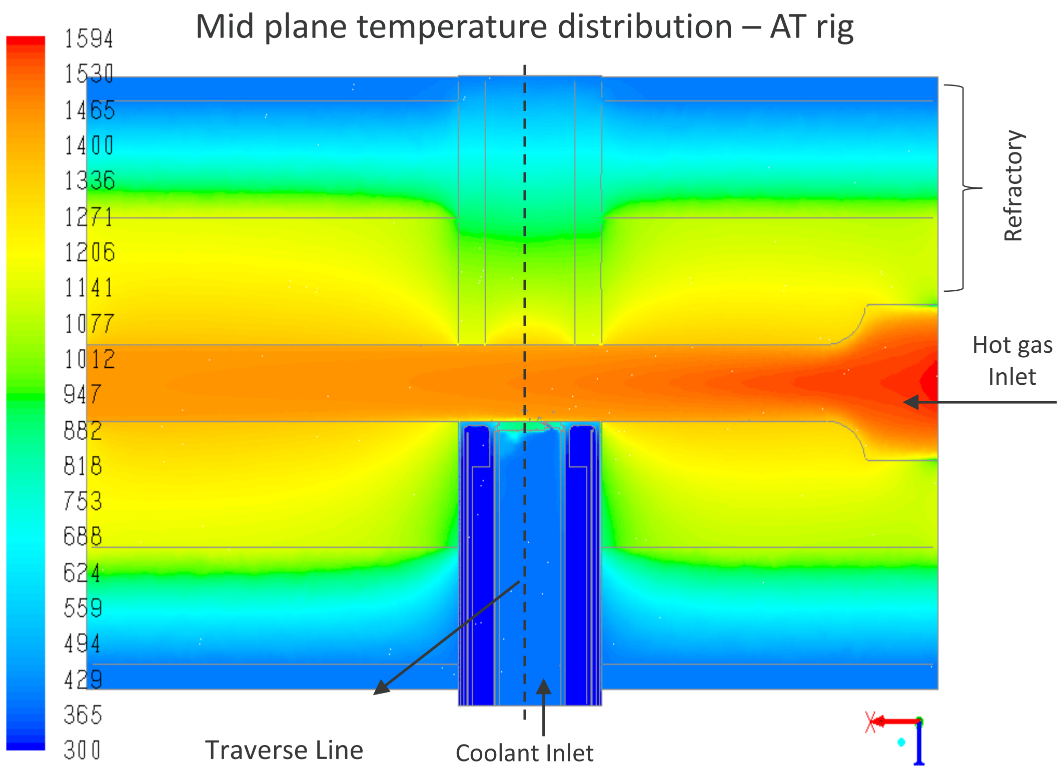



Aero-thermal rig

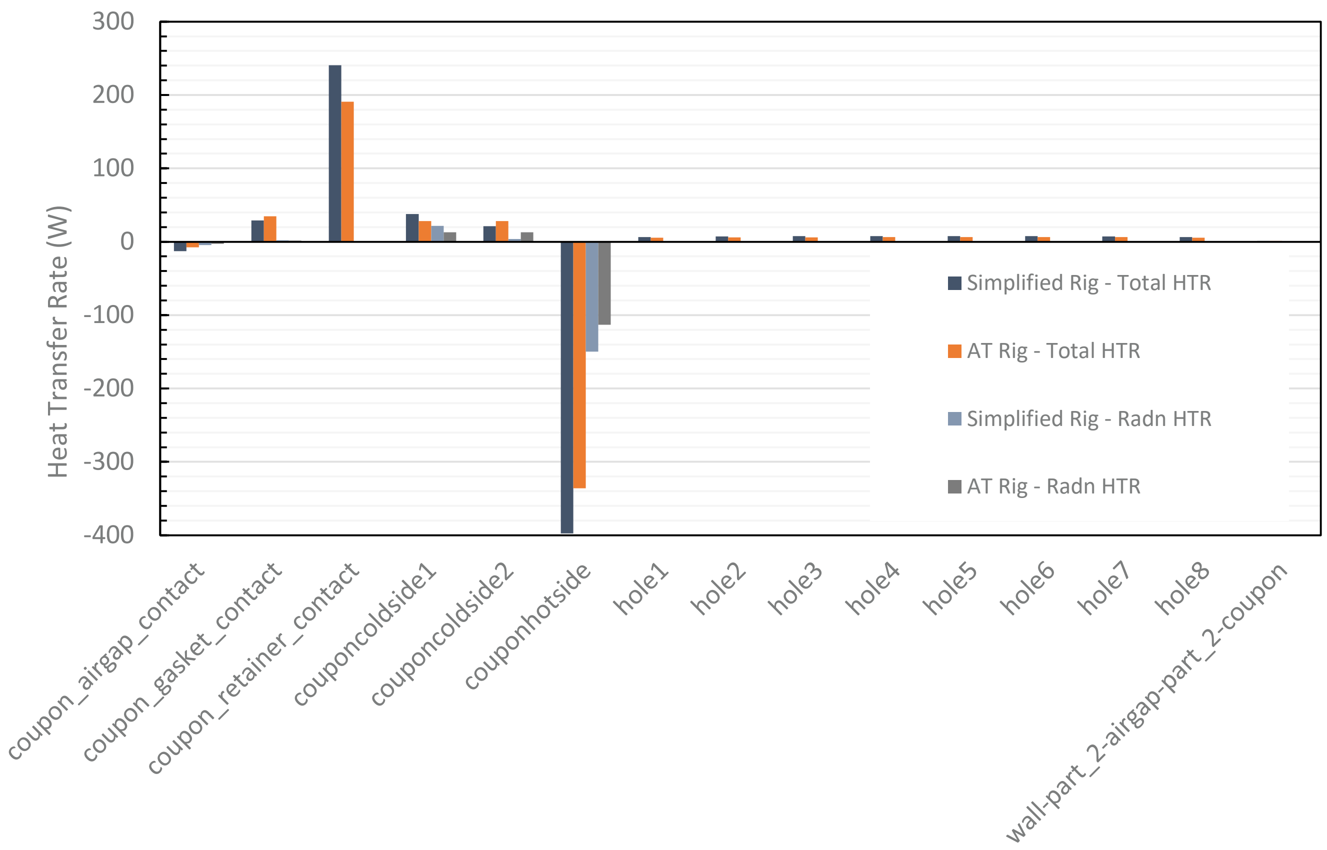
# Simplified vs. Actual AT Rig




- Difference in hot gas peak temperature is: 13 K, 0.86 %,
- Film temperature distribution shows agreeable match but difference in lowest temperature is ~ 40 K, 7.8%

# Simplified vs. Actual AT Rig

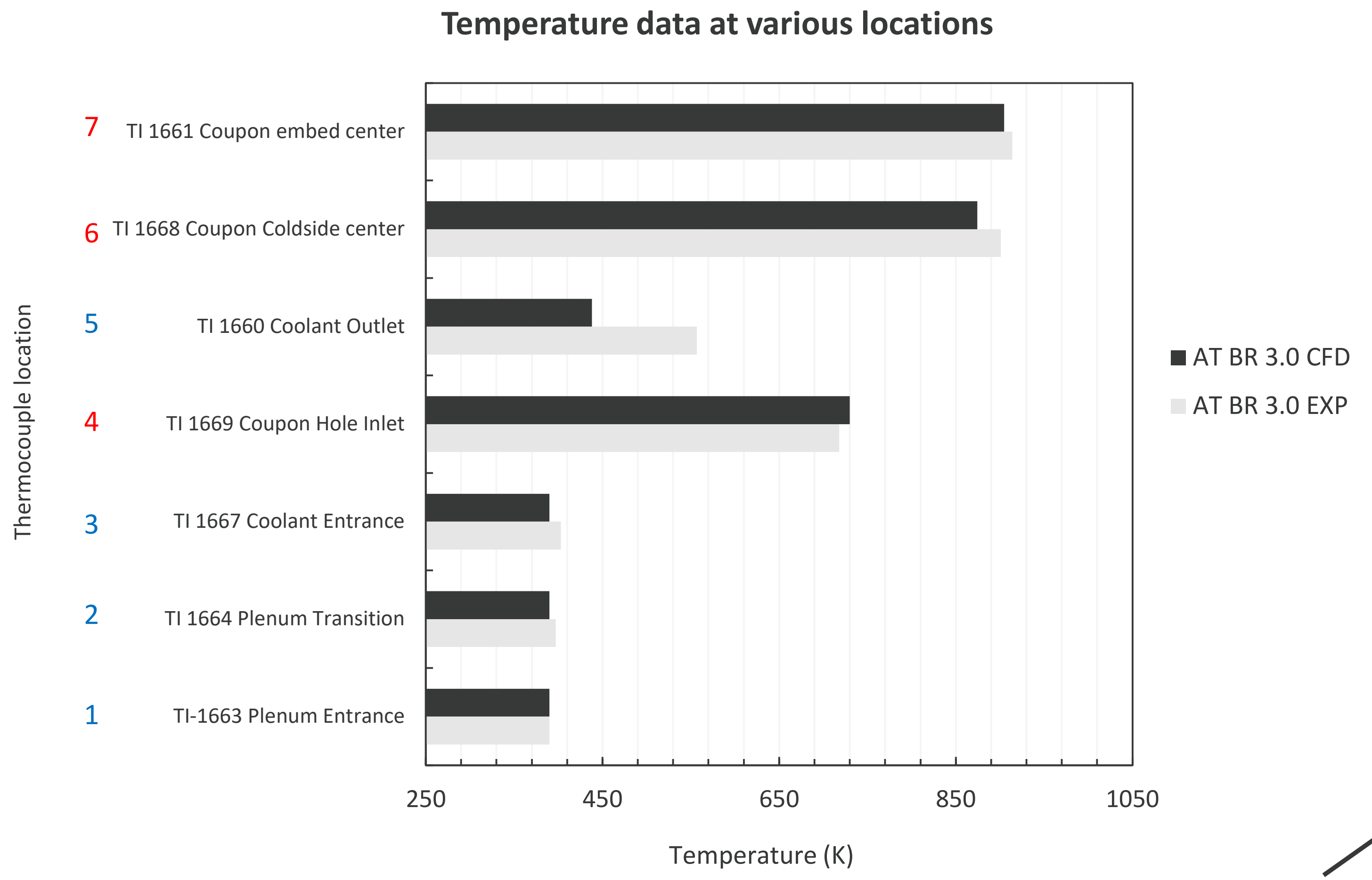


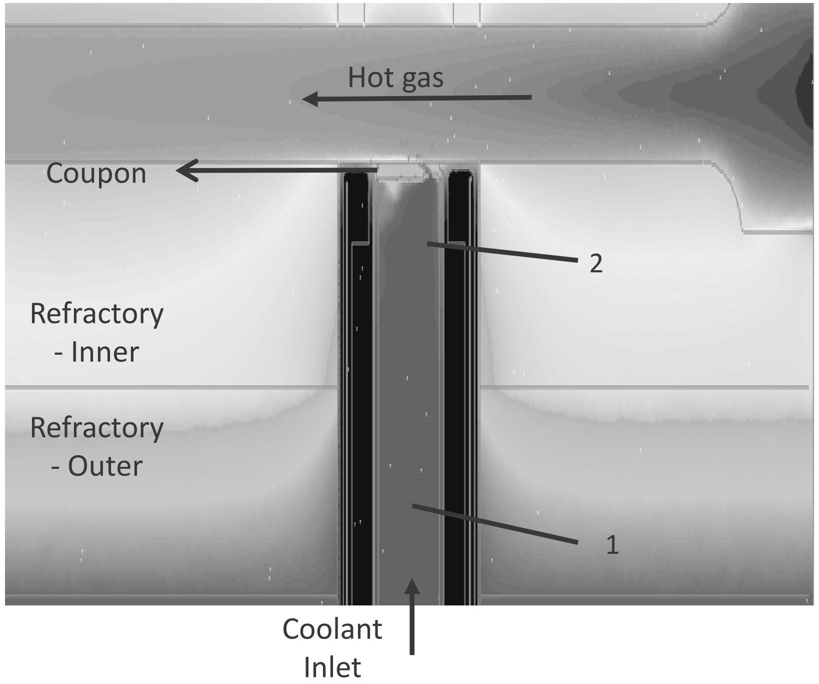

| Location | Area Avg. Temperature diff (K) | % difference (increase) |
|---|---|---|
| Retainer hot side | 100 | 22 |
| Coupon hot side | 21 | 2.55 |
| Holes | 30 | 3.8 |
| Refractory | -14 | -1 |
| Viewport window | 36 | 2.9 |

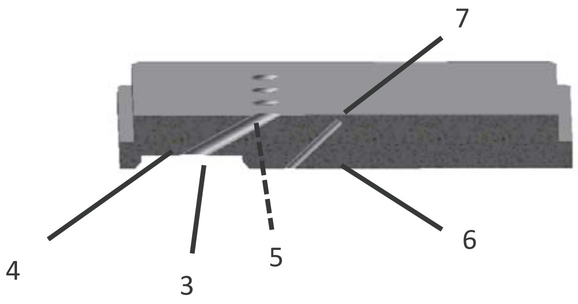
| Location | Total heat transfer rate Difference (W) | % difference (increase) |
|---|---|---|
| Coupon – Retainer Contact | 50 | 26.3 |
| Coupon – Gasket Contact | -6 | -20.6 |
| Coupon hot side | 62 | 15.6 |

| Assumption | Validity |
|---|---|
| Refractory walls replaced with shell conduction | ✓ |
| Retainer cooling water domain replaced with fixed temperature boundary condition | ✗ |

# Comparison of CFD vs Experiment




1. Coolant @ Plenum Inlet
2. Coolant 2” away from coupon
3. Coolant near hole inlet
4. Coupon between adj. hole inlets
5. Coolant near hole exit
6. Coupon center – cold side
7. Coupon center – hot side

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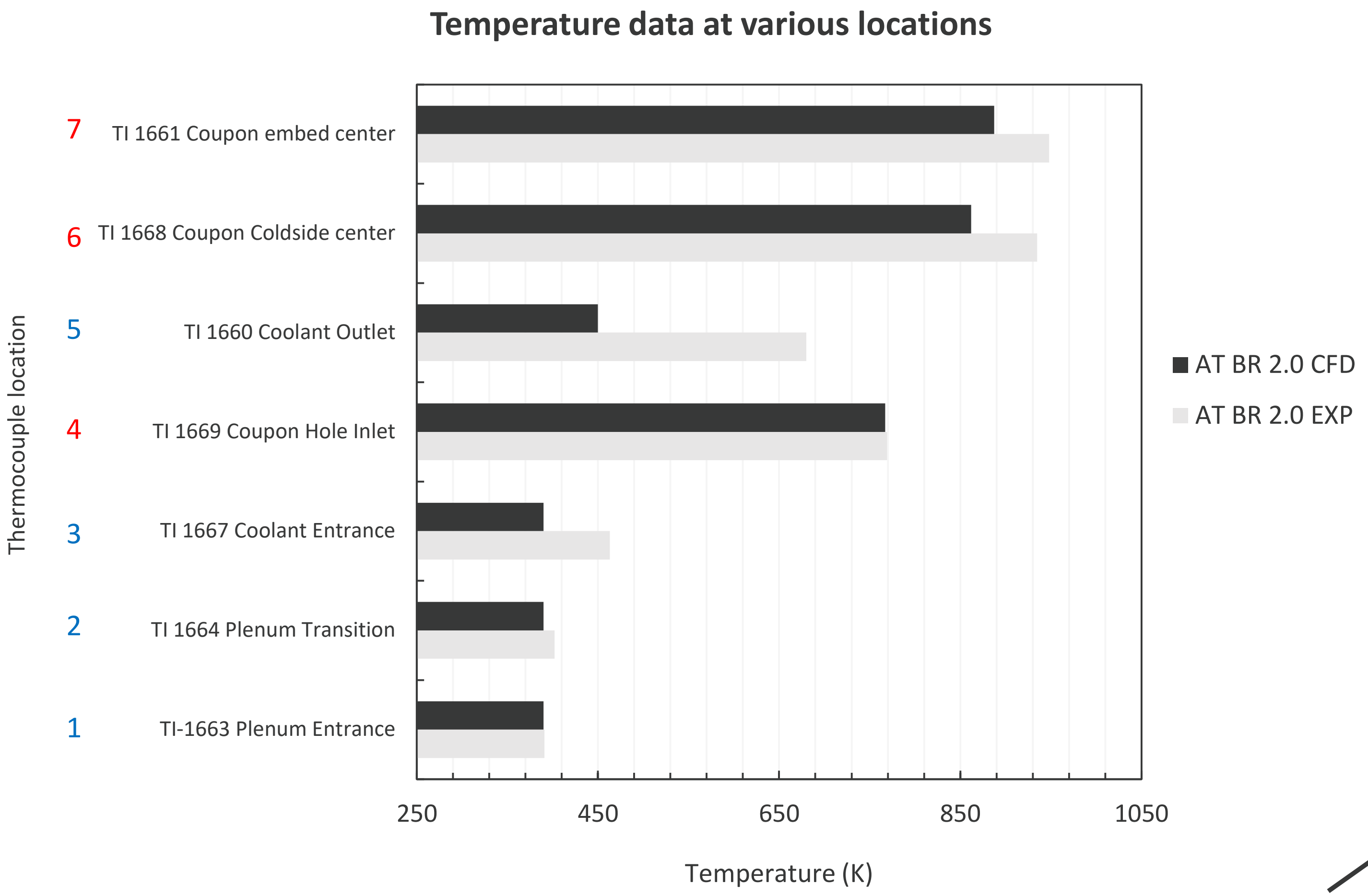


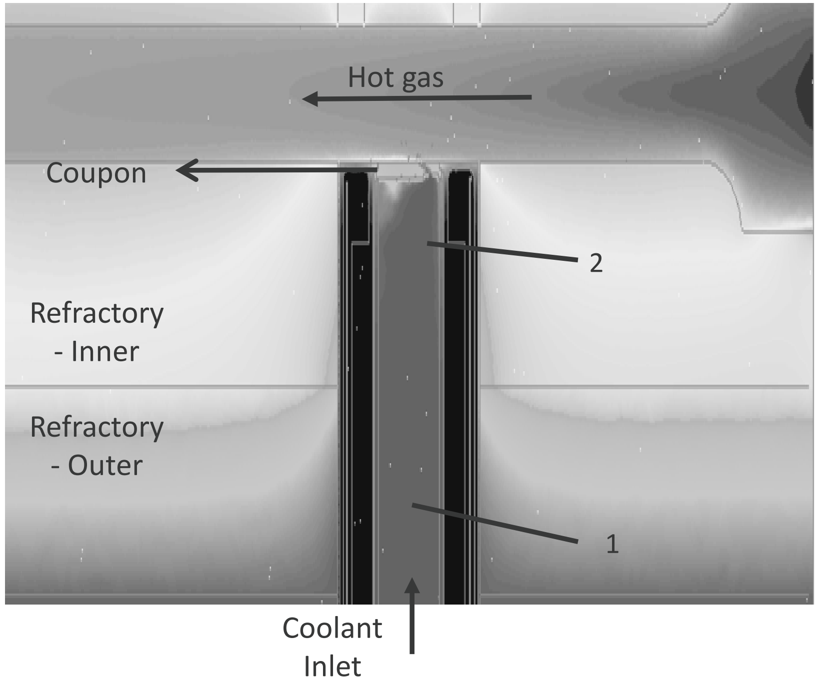


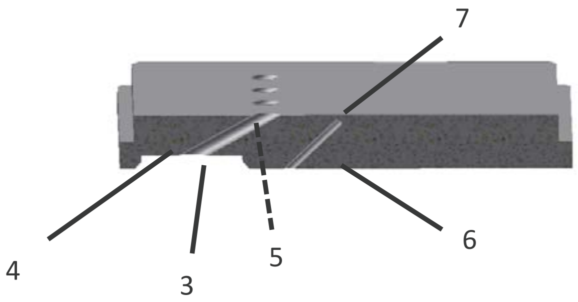


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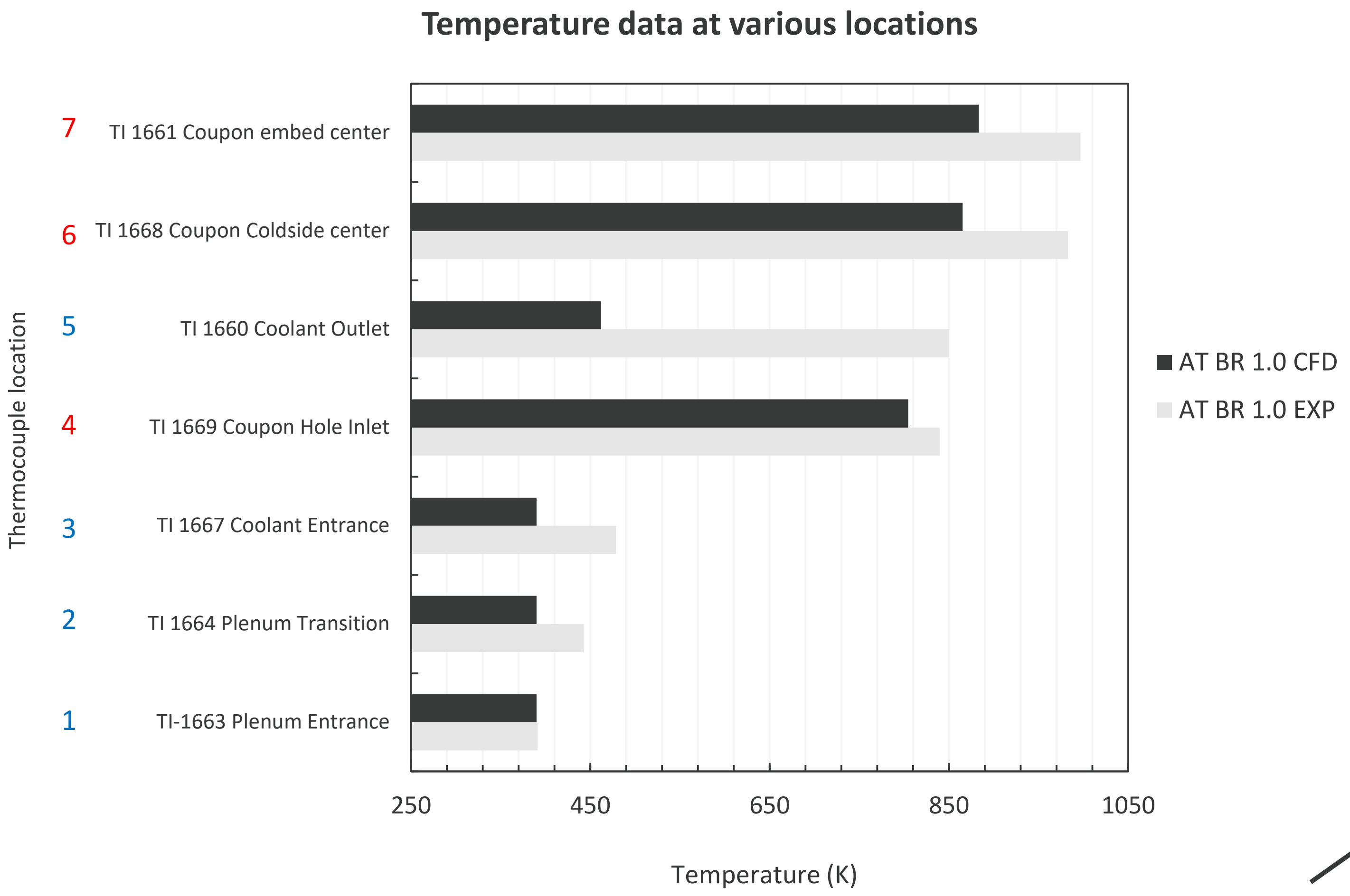


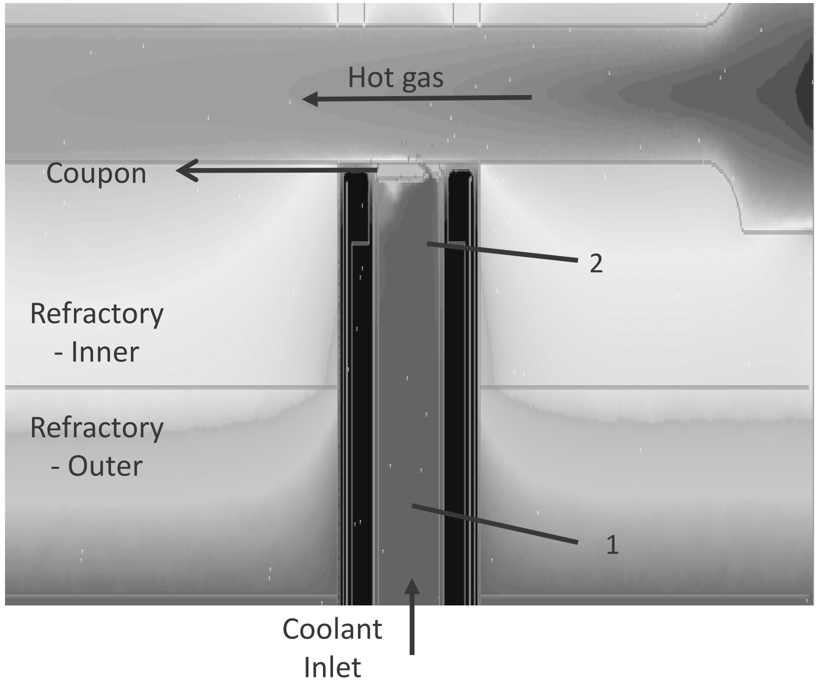


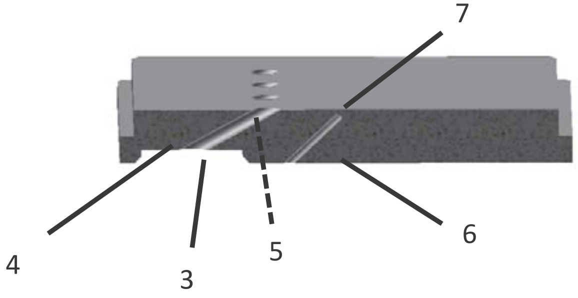


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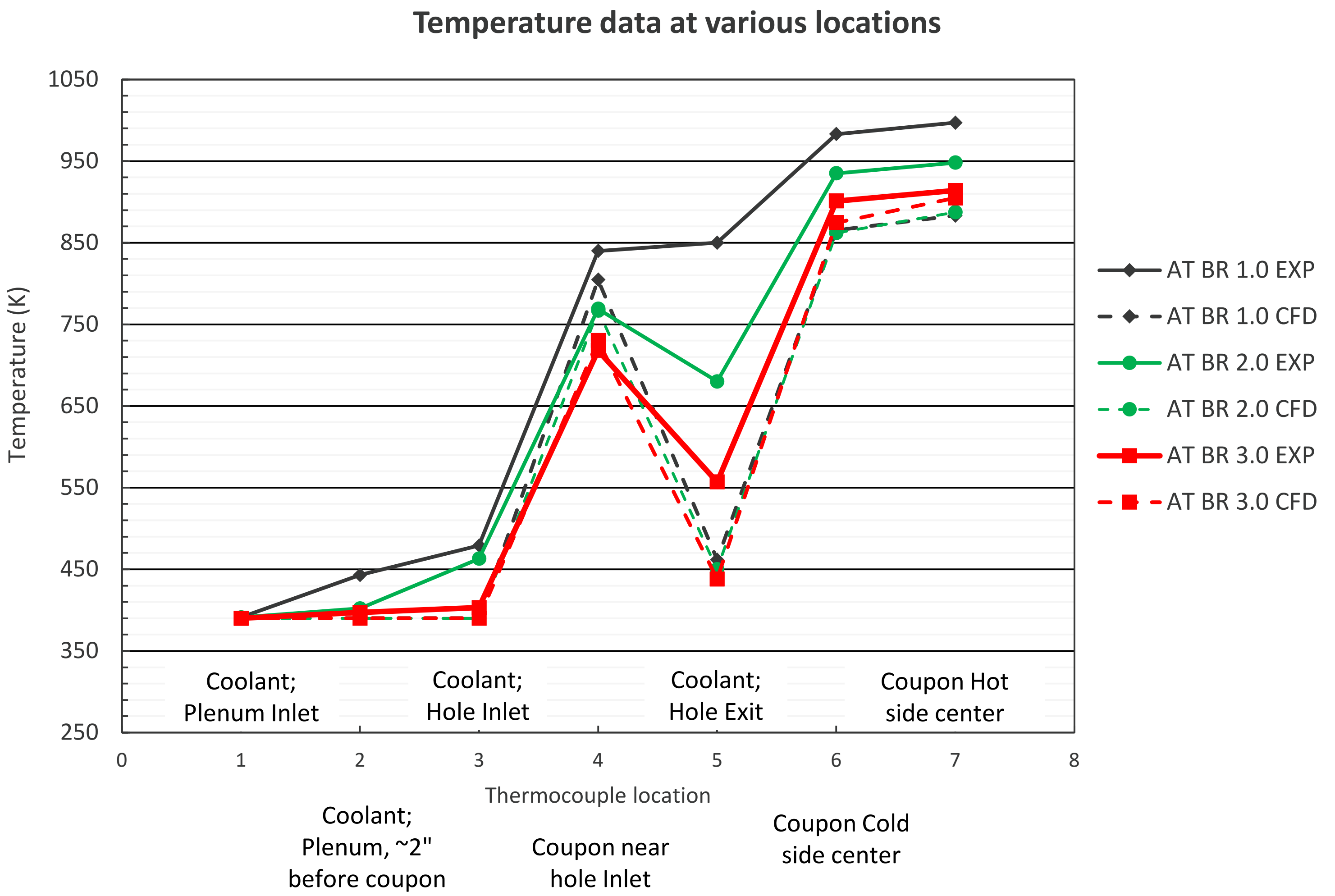
# Comparison of CFD vs Experiment

NATIONAL ENERGY TECHNOLOGY LABORATORY




- CFD matches with experiment only at very high blowing ratios: BR 3.0
- Effect of blowing ratio on overall effectiveness was not observed in the CFD data: Possible reasons
  - Experimentally measured turbulence intensity was roughly ~ 15% (high uncertainty).
  - Film cooling performance at low blowing ratios decreases with increases in mainstream TI
  - Thermocouple radiation correction might explain some differences in Temp. in the coolant plenum

**On going plans:**

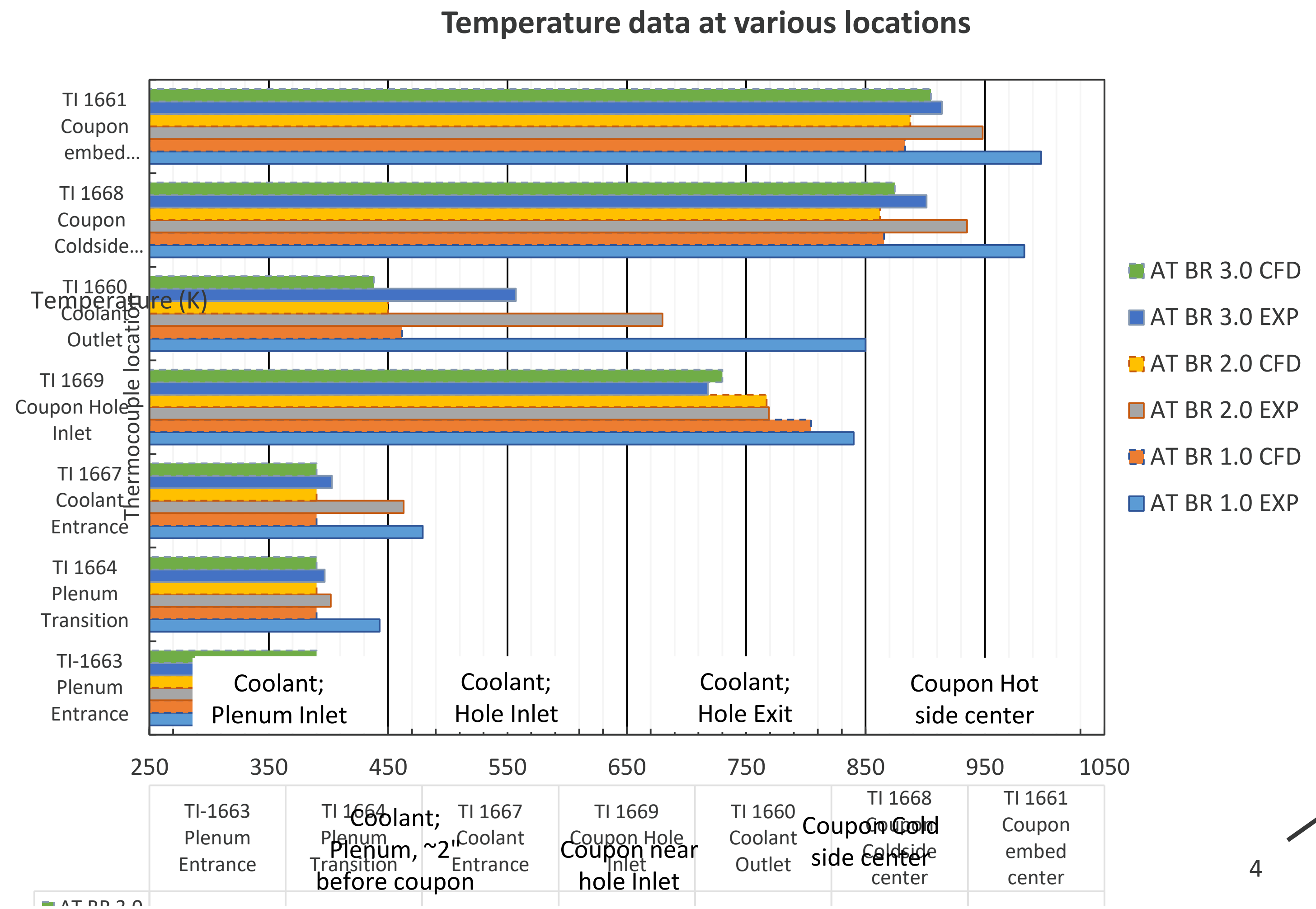
- Cold flow validation cases with RANS model to understand the deficiencies
- Validation for blank coupon with hole film cooling holes

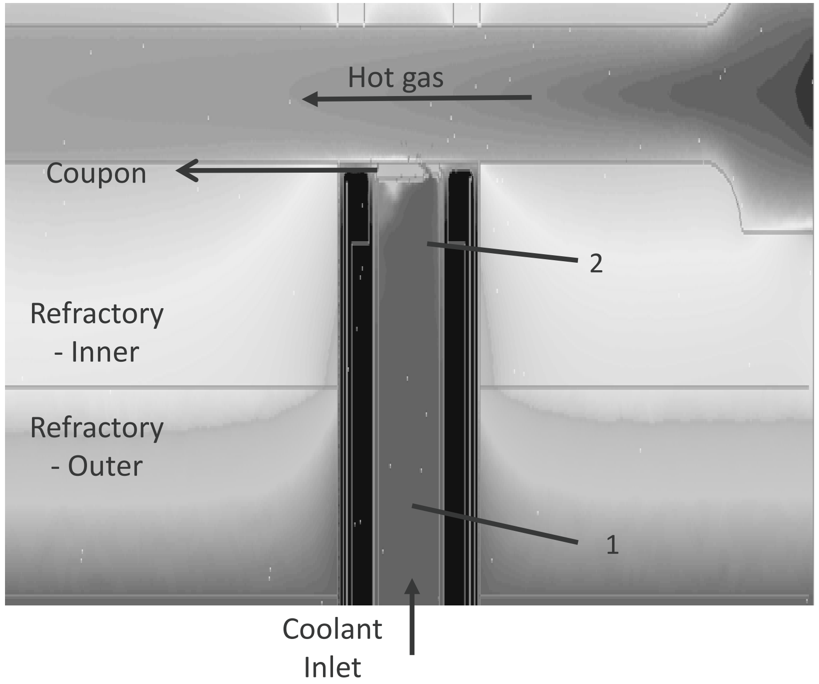
# Thank you

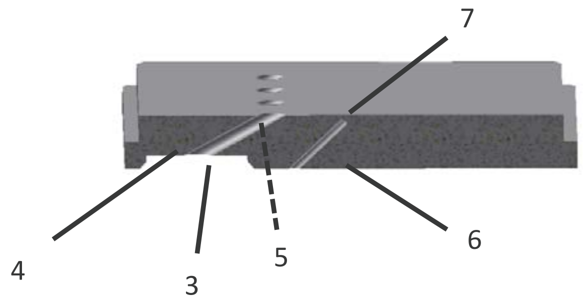
QUESTIONS?

# Backup slides

# Comparison of CFD vs Experiment

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