High Temperature Film Cooling Experiments at NETL

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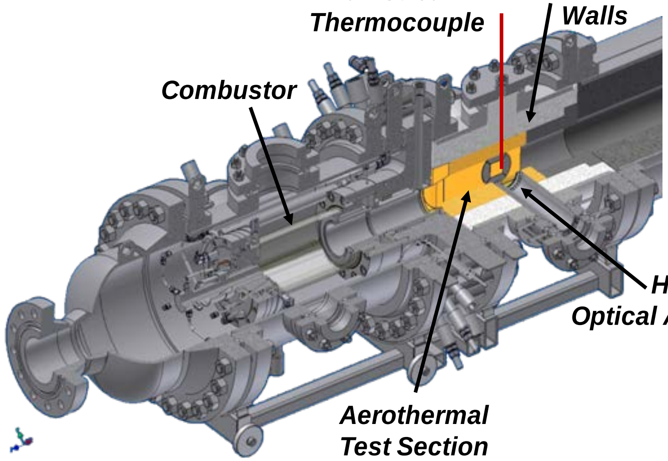
Solutions for Today | Options for Tomorrow

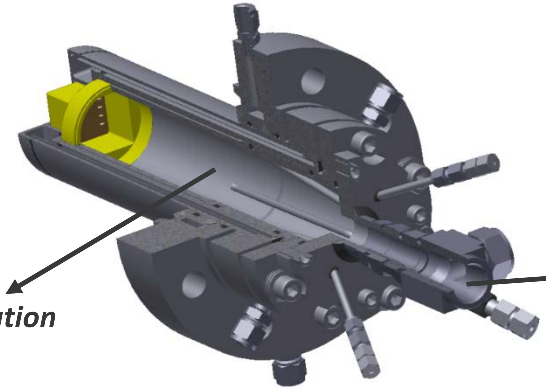
High temperature high pressure facility

70 m/s, ~ 2200 °F, up to 10 atm



Swirl stabilized premixed

Free stream – hot combustion exhaust (natural gas)
Properties – velocity and temperature
Nozzles – Swirl stabilized premixed flame vs. dilute diffusion flame array

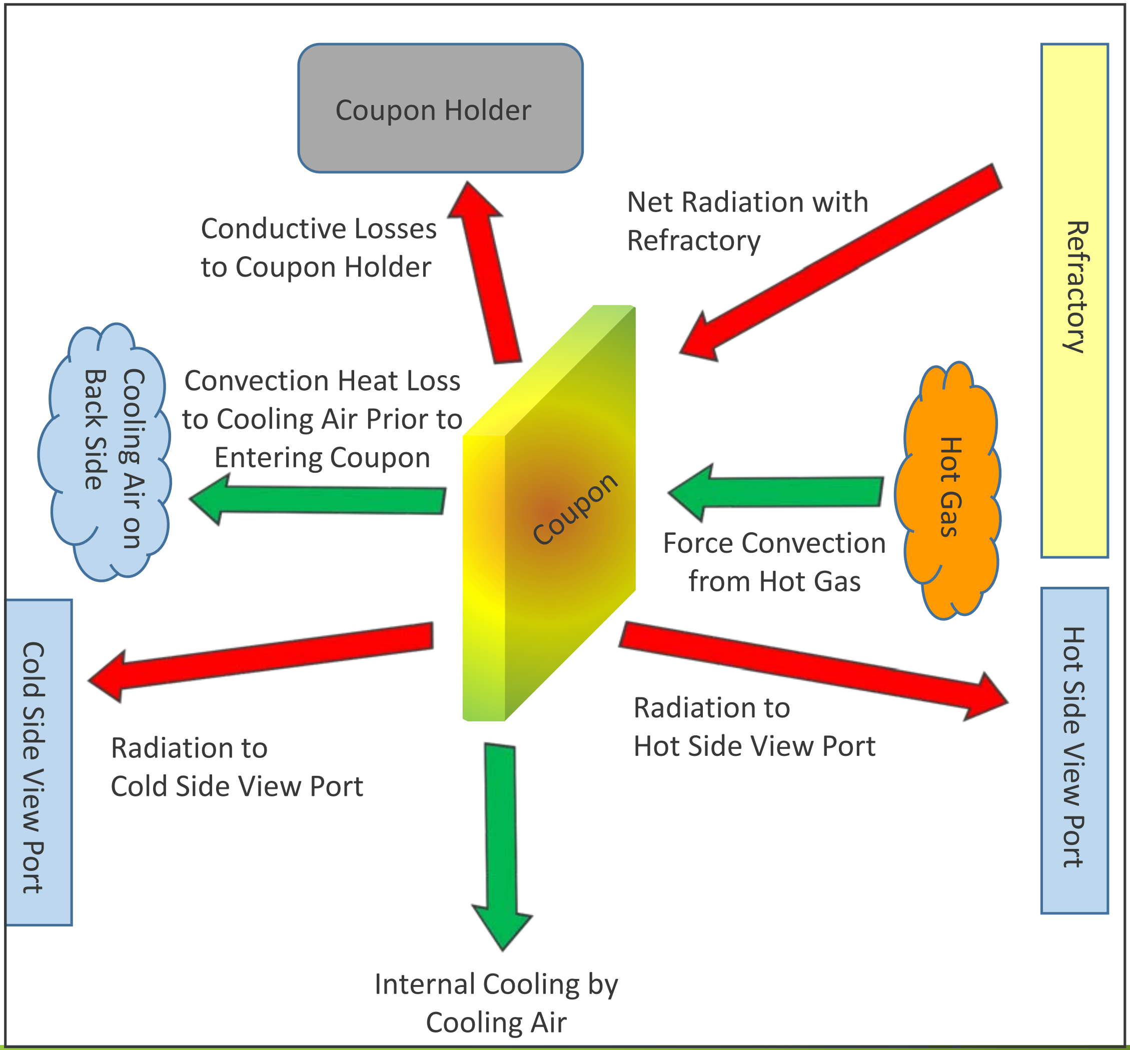


Coolant temperature measurement location

Cold Side Optical Access

Challenges with high temperature high pressure experiments

- Identify all sources of heat transfer that will impact coupon temperature
- Experimental measurements:
  - Mainstream velocity and temperature measurements
  - Surface temperature measurements:
    - Optical measurement technique
- Experimental methodology suited for this test rig
  - Quantify heat sources
    - Radiation input
    - Conduction losses
  - Estimate coupon surface: q'', h, θ
  - If possible, also estimate: q''_f, h_f, η



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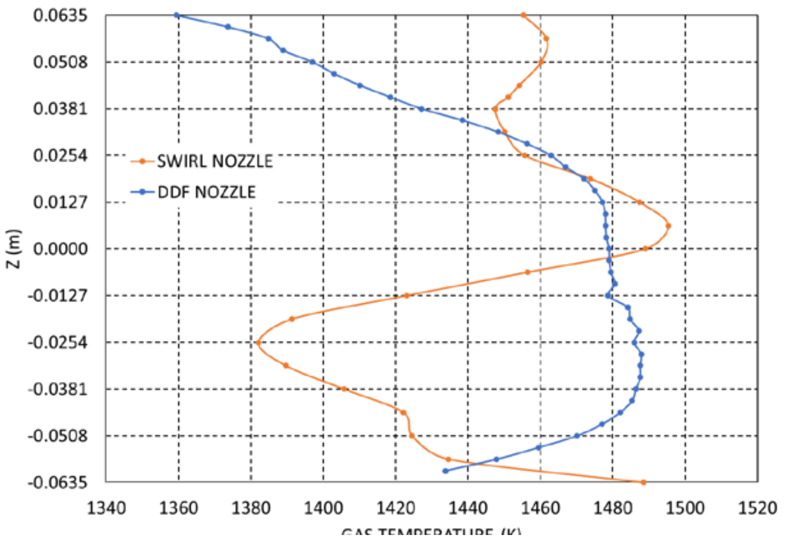
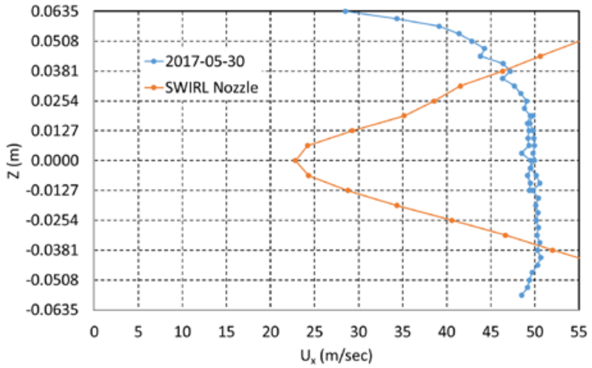
Vertical traverse
Temperature Profile



Vertical traverse
Axial Velocity Profile



Challenges with high temperature high pressure experiments

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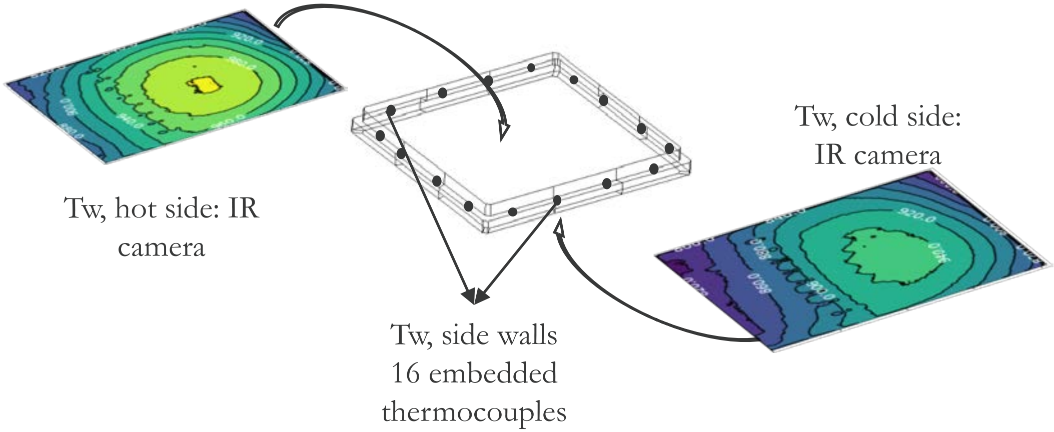
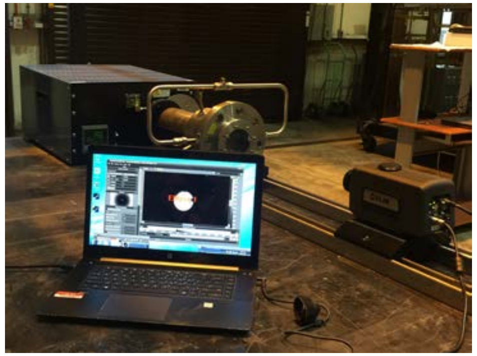
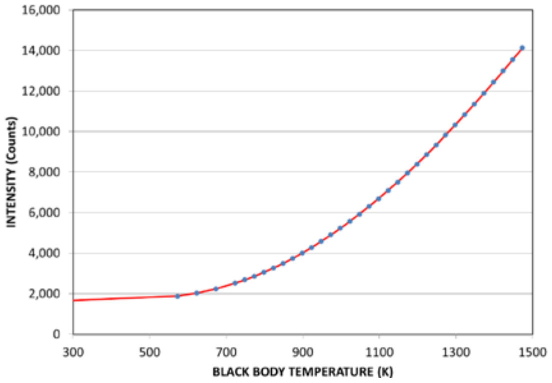
Surface temperature measurement



IR camera bench top calibration





Optical measurement technique

Test facility & Bench top calibration experiments

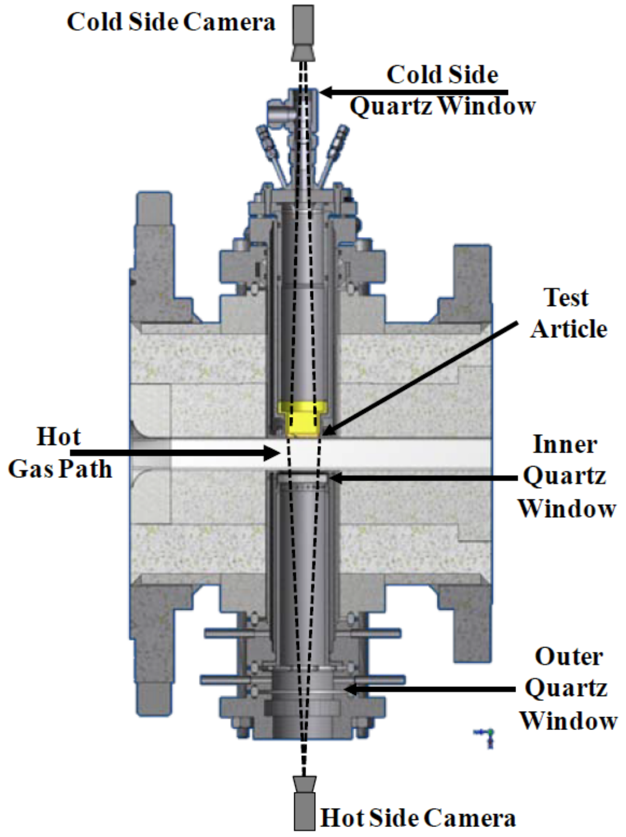
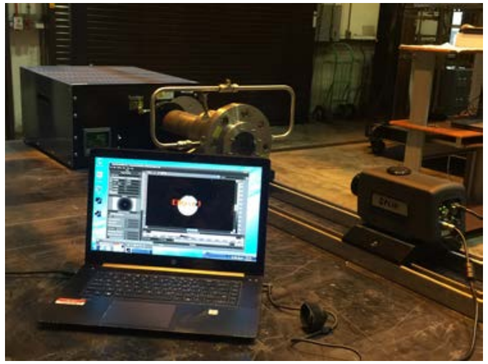
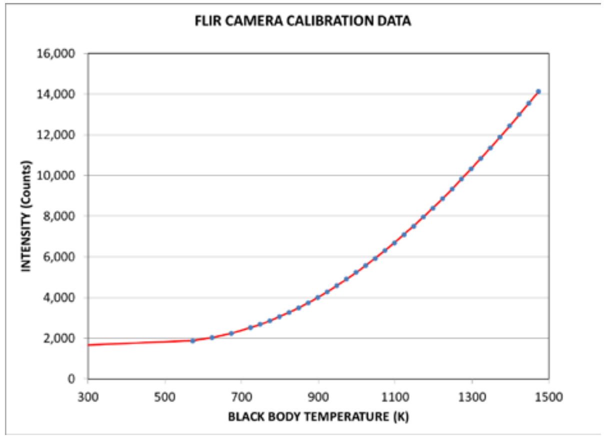


Figure 4. Aerothermal test section with optical access on both sides of test article.





Finding camera constants

$$I_{cal}(T) = \varepsilon_{bb} I_{bb}(T) + (1-\varepsilon_{bb}) I_{bb}(T_{ambrefl}) + K_0$$

$$I_{bb}(T) = \frac{I_{cal}(T) - K_0 - (1-\varepsilon_{bb}) I_{bb}(T_{ambrefl})}{\varepsilon_{bb}} = \frac{K_1}{e^{\frac{K_2}{T}} - 1}$$

$$\widehat{I_i} = \widehat{K_0} + \varepsilon_{bb} \frac{\widehat{K_1}}{e^{\frac{\widehat{K_2}}{T_i}} - 1} + (1-\varepsilon_{bb}) \frac{\widehat{K_1}}{e^{\frac{\widehat{K_2}}{T_{amb}}} - 1}$$

$$SSE = \sum_i \left(I_{cal}(T_i) - \widehat{I_i}\right)^2$$

Find $\widehat{K_0}$, $\widehat{K_1}$, and $\widehat{K_2}$ to minimize SSE

$\widehat{K_0}$=2,201.1
$\widehat{K_1}$=1,230,587.
$\widehat{K_2}$=3,402.5

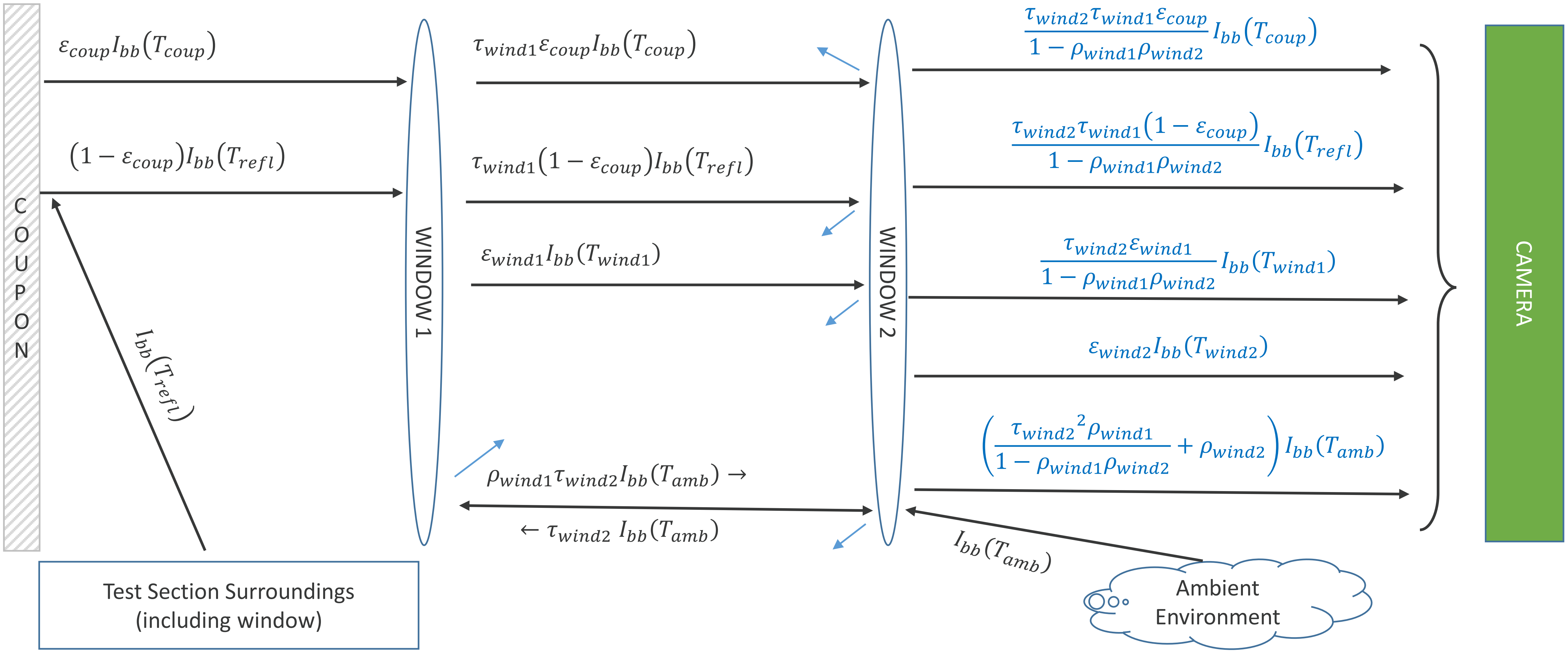
Where,

$$I_{bb}(T) = \frac{K_1}{e^{\frac{K_2}{T}} - 1}$$

and K_0 accounts for dark current/noise

Optical measurement technique

In – situ calibration



Optical measurement technique

In – situ calibration

$$I_{cam}(x,y) = \frac{\varepsilon\tau_1\tau_2}{1-\rho_1\rho_2} I_{bb}\big(T_c(x,y)\big) + \left\{ \begin{array}{l} \left(\frac{(1-\varepsilon)\tau_1\tau_2}{1-\rho_1\rho_2}\right) I_{bb}\big(T_r(x,y)\big) \\ + \left(\frac{\varepsilon_1\tau_2}{1-\rho_1\rho_2}\right) I_{bb}\big(T_1(x,y)\big) \\ + \left(\frac{\rho_1\varepsilon_2\tau_2}{1-\rho_1\rho_2} + \varepsilon_2\right) I_{bb}\big(T_2(x,y)\big) \\ + \left(\rho_2 + \frac{\rho_1\tau_2^2}{1-\rho_1\rho_2}\right) I_{bb}\big(T_{amb}(x,y)\big) \\ + K_0 \end{array} \right\}$$

"Constant" provided test section, viewport, and environment are constant

$$\left\{\frac{\tau_{wind1}\tau_{wind2}e_{coup}}{1-\rho_{wind1}\rho_{wind2}}\right\} I_{bb}\big(T_{coup}\big)$$

Varies with changes in coupon temperature

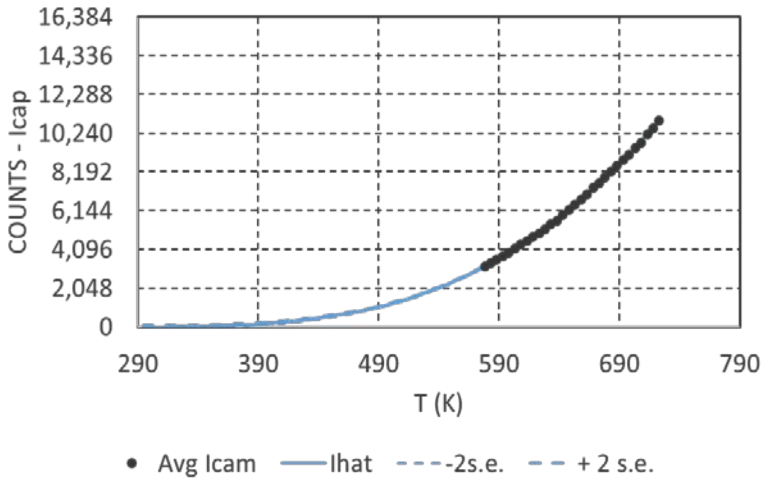
$$I_{cam} = \beta_1 I_{bb}\big(T_{coup}\big) + \beta_0$$

In situ procedure: Camera measurements and temperatures of embedded thermocouples are used with regression to estimate slope and intercept terms

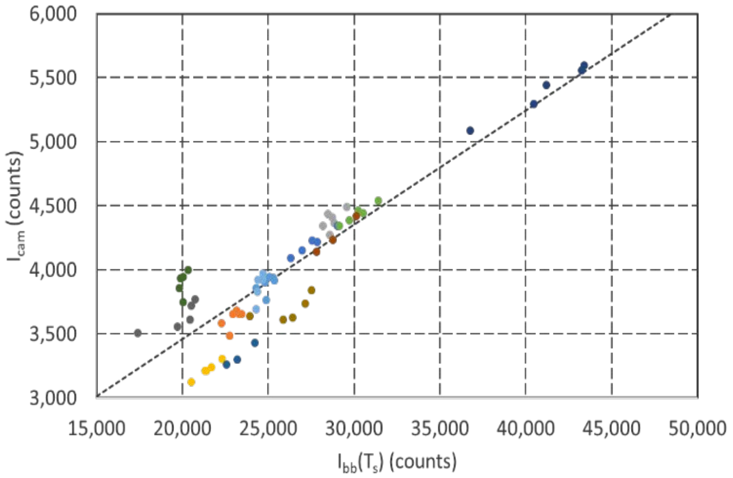
Optical measurement technique

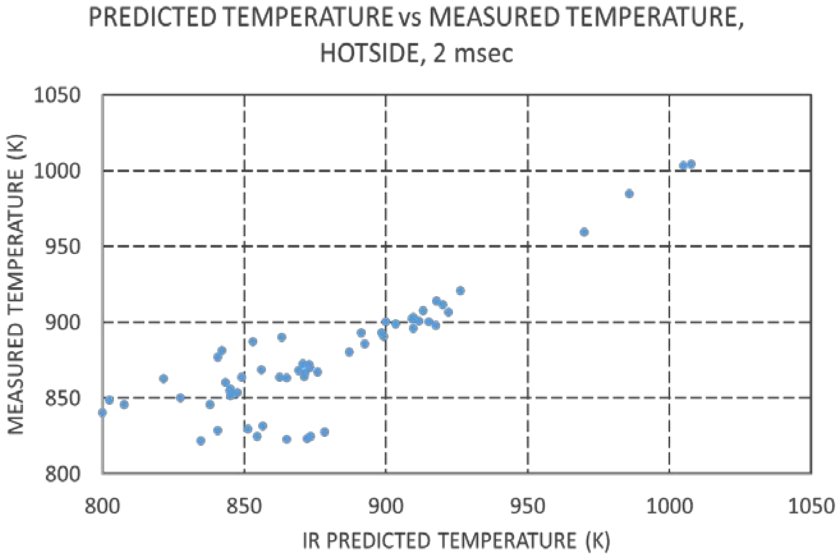
Calibration results

Blackbody calibration experiment



In-situ calibration





- Blackbody calibration: curve fit shown can predict temperatures to within less than 1 K
- In-situ calibration: standard linear regression using 3 surface TCs and different BRs or backside cooling flow rates
- In-situ calibration: $I_{bb, coupon}$ and T_{coupon} is now found using estimates for I_{cam}, β_1 and β_0.
- Coupon temperature is mostly in the range 1000-1100 K expect near the edges where its starts to see the effects of the water cooled coupon holder; RMS difference between measured and predicted was 8.8 K for temperatures > 880K

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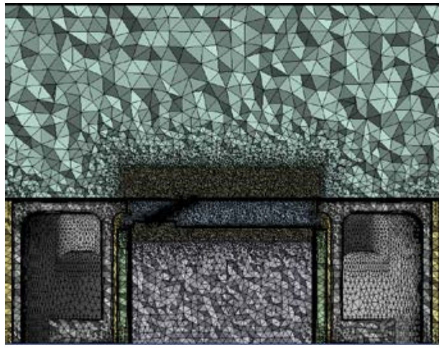
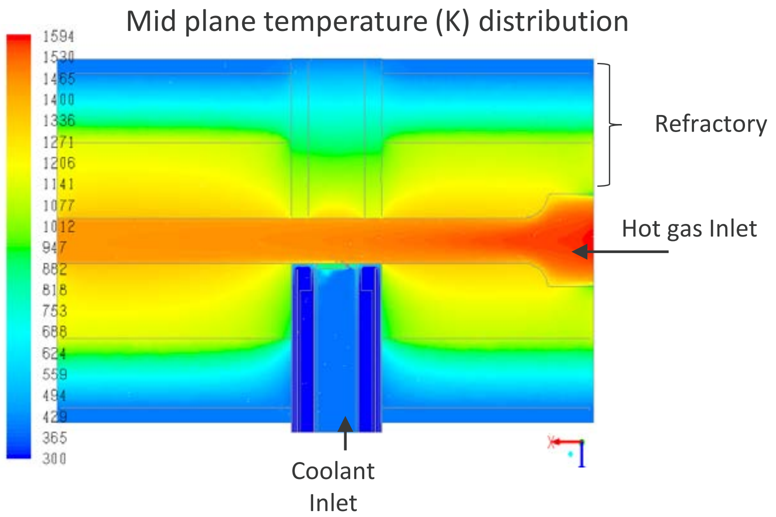
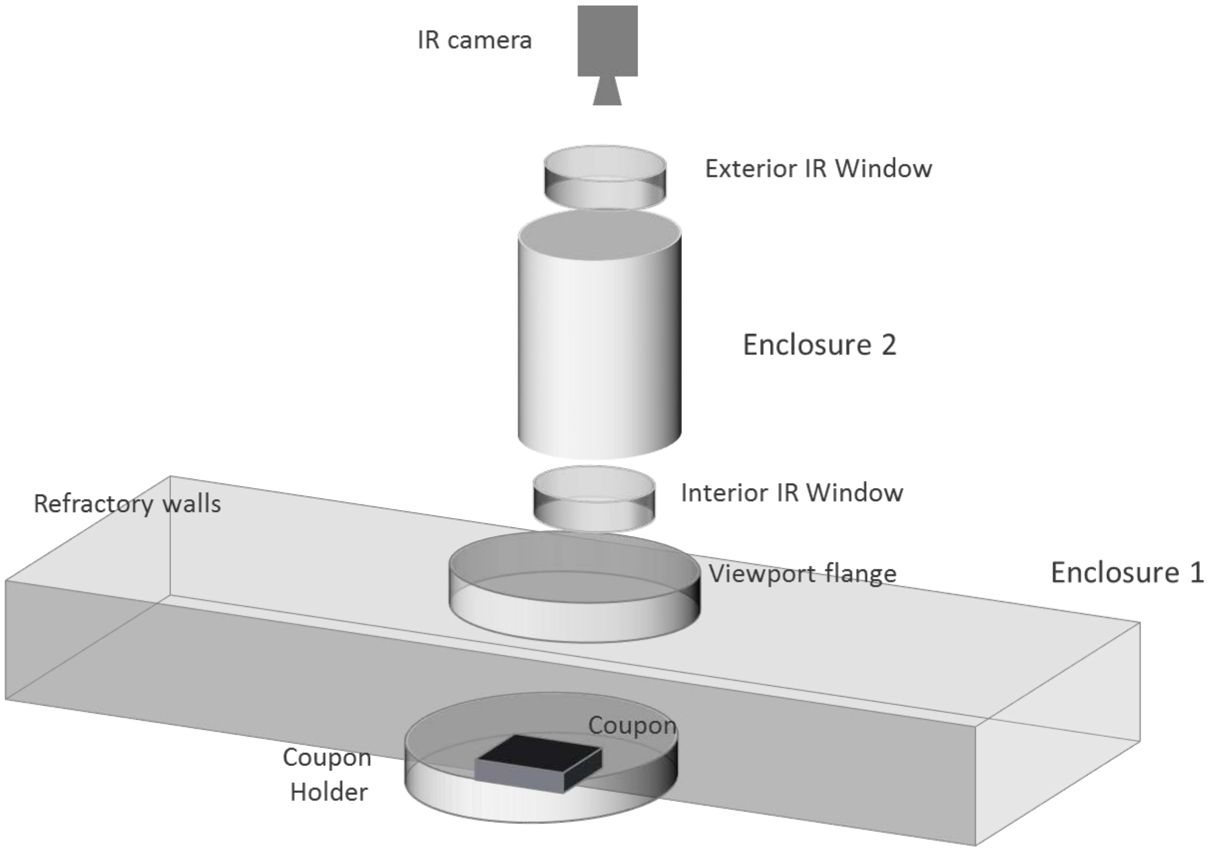
Aero thermal test rig – Conjugate CFD with radiation modelling





Test rig – heat sources

Radiation analysis – Simple analysis

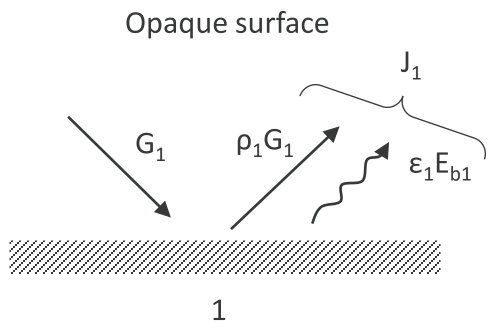


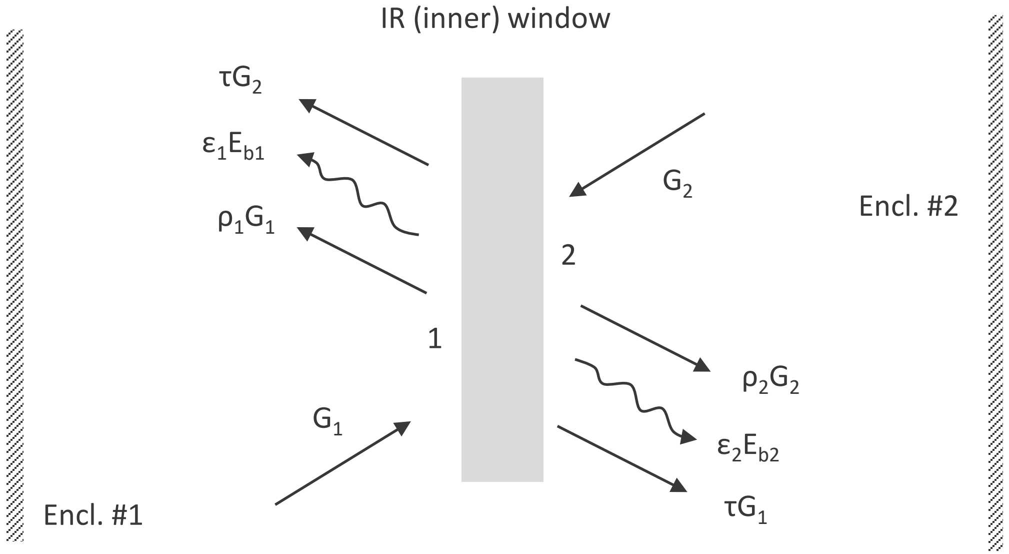
- Simple radiation model for sensitivity analysis
- Detailed model that accounts for temperature variations on coupon surface
- Both models have some similarities
  - Surfaces are assumed to be diffuse
  - Radiation leaving surface is treated as gray
- Simple model: 5 surfaces from Enclosure 1 and 3 from Enclosure 2 participate in radiation
  - View factors are estimated using existing correlations and charts
- Detailed model: view factors are calculated from one elemental area to another
- Preliminary analysis relies on uniform surface properties. Wherever possible surfaces are coated with high emissivity paint. Refractory walls, water cooled holder and surfaces in enclosure 2 are expected to have uniform surface temperatures.

Test rig – heat sources

Radiation analysis – Opaque and Semi-transparent surface

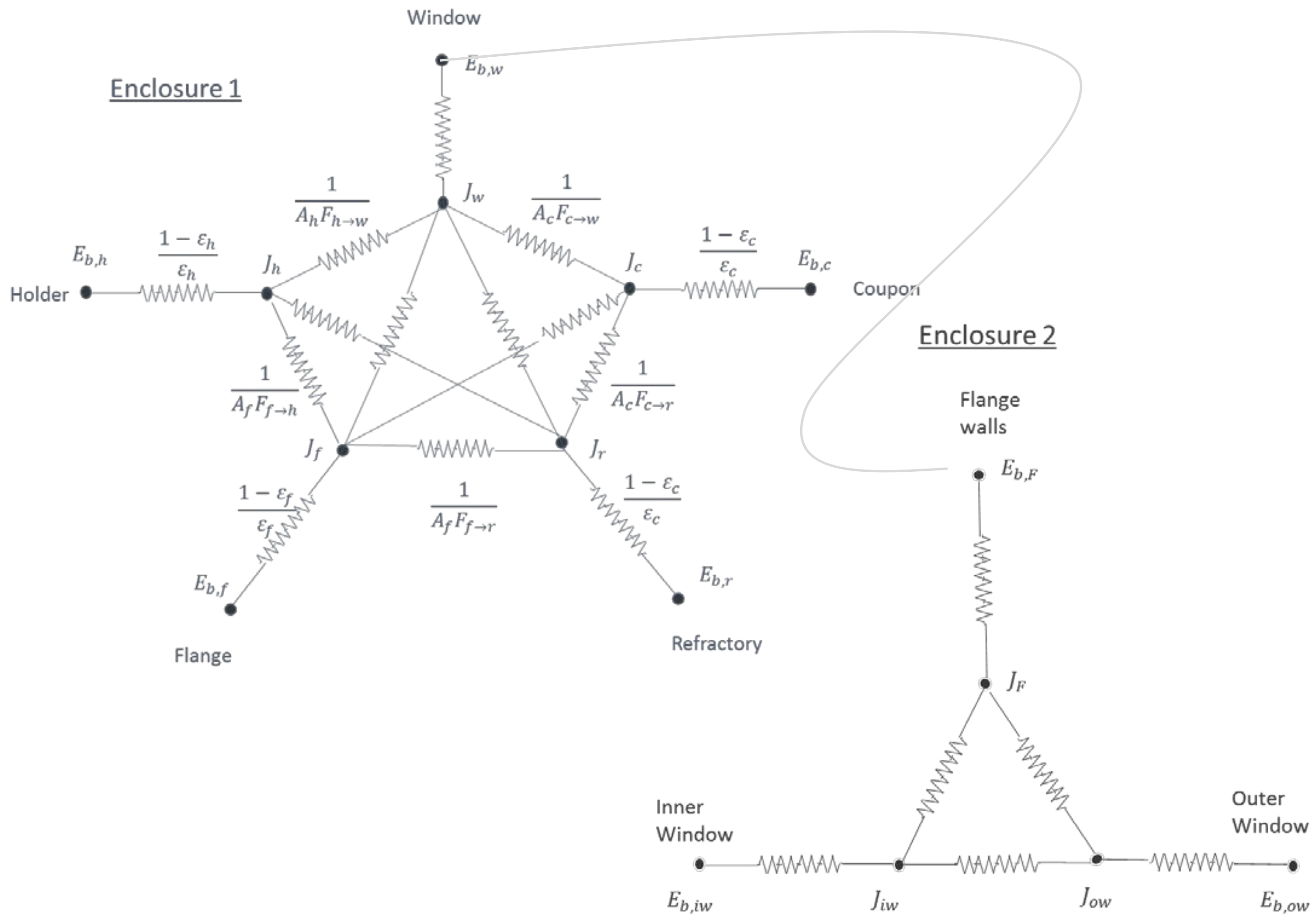
- For opaque surfaces
  - $J_i = E_i + \rho_i G_i$
  - $\rho_i = 1 - \alpha_i = 1 - \epsilon_i$
- For IR Window in Enclosure 1:
  - $J_w = E_w + \rho_w G_w + \tau G_{iw}$
- For IR window in Enclosure 2:
  - $J_{iw} = E_{iw} + \rho_{iw} G_{iw} + \tau G_w$
    - Where G_w is net irradiation leaving IR window in Enclosure 1
  - $J_{ow} = E_{ow} + \rho_{ow} G_{ow} + \tau E_{b,surr}$
    - Accounts for external/ambient radiation entering the enclosure





Test rig – heat sources

Radiation analysis – Opaque and Semi-transparent surface



System of equations

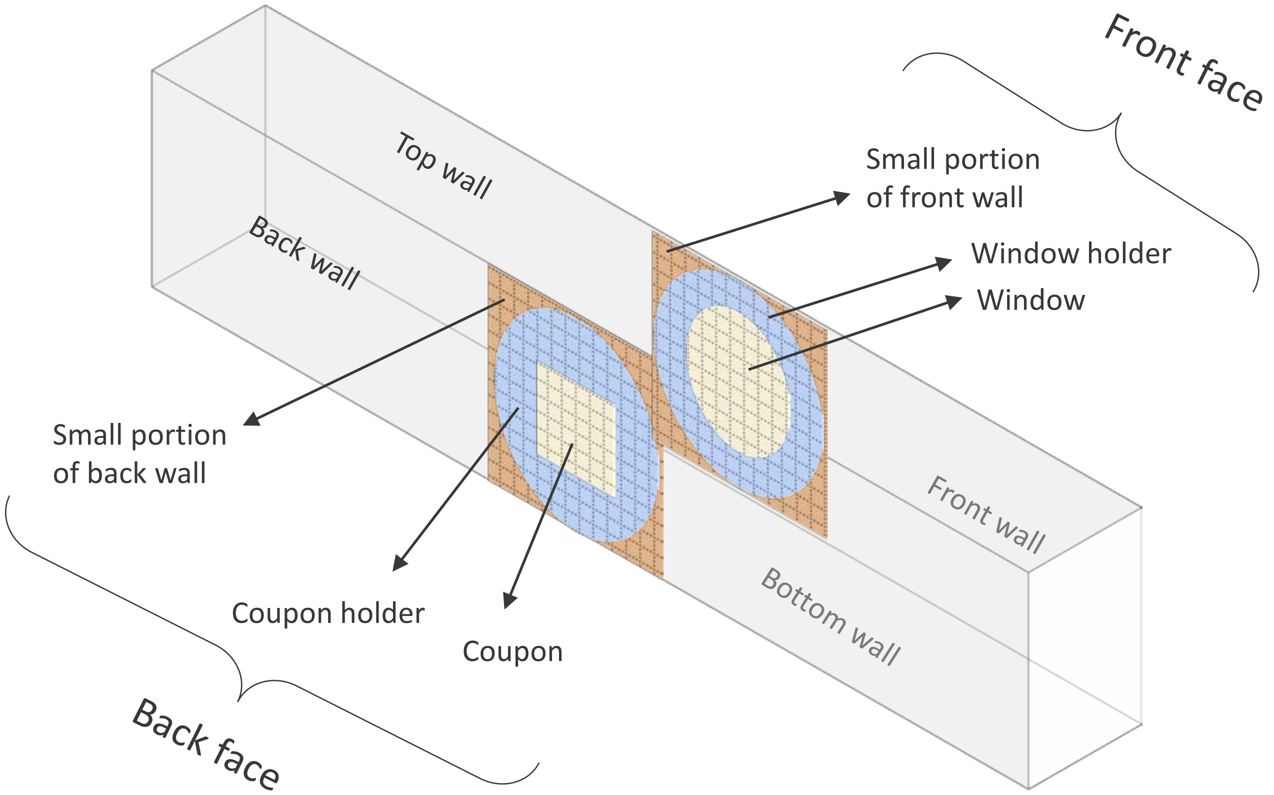
Opaque:
$$\frac{(E_{b,i} - J_i)}{\frac{1-\varepsilon_i}{\varepsilon_i}} = J_i - \sum_{j}^{N-1} F_{i\to j} J_j$$

Semi-transparent:
$$\frac{\varepsilon E_{b,w} + \tau G_{iw} - (\varepsilon_w + \tau) J_w}{1 - (\varepsilon_w + \tau)} = J_i - \sum_{j}^{N-1} F_{i\to j} J_j$$

- Starts with initial guess for transmitted intensity
- Solve system of equations for Enclosure 1 and 2 simultaneously
- Iteratively solve for transmitted intensity

Test rig – heat sources

Radiation analysis – 3D model; View factor estimation – Enclosure 1



View factor calculation – Current approach

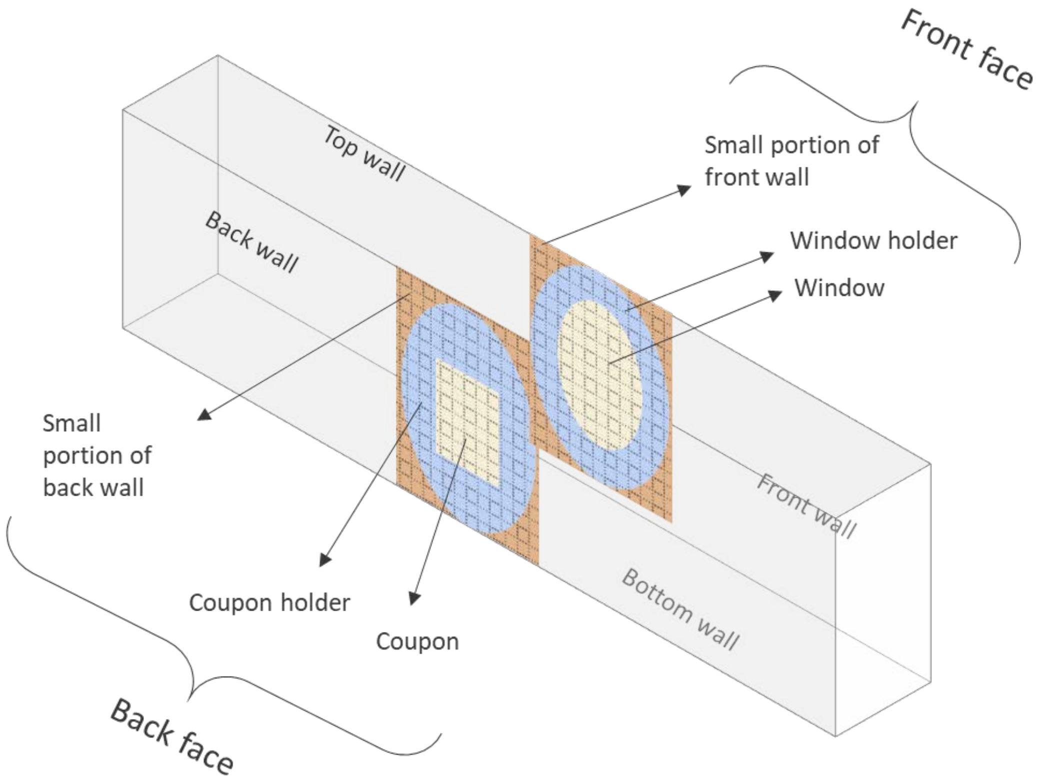
- Primary surfaces: 2 (front and back face)
  - Small portions of back wall & front wall containing coupon, window and their holder
  - Remaining refractory surface treated as 1 single face with uniform T and surface properties
    - This assumption was made in the original approach as well
  - Coupon and its holder: info. stored in F(back wall)
  - Window and its holder: info. stored in F(front wall)
- Discretization:
  - Lx = 4 in, dx = 0.05 in, nx = 80
  - Lz = 5in, dz = 0.05 in, nz = 100
  - Resultant VF matrix for 1 surface: 80*100 = 8000
- VF is estimated from back face to front and vice versa using Eqn. 1
- VF from region of interest (elemental area) to “refractory” is calculated using Eqn. 2

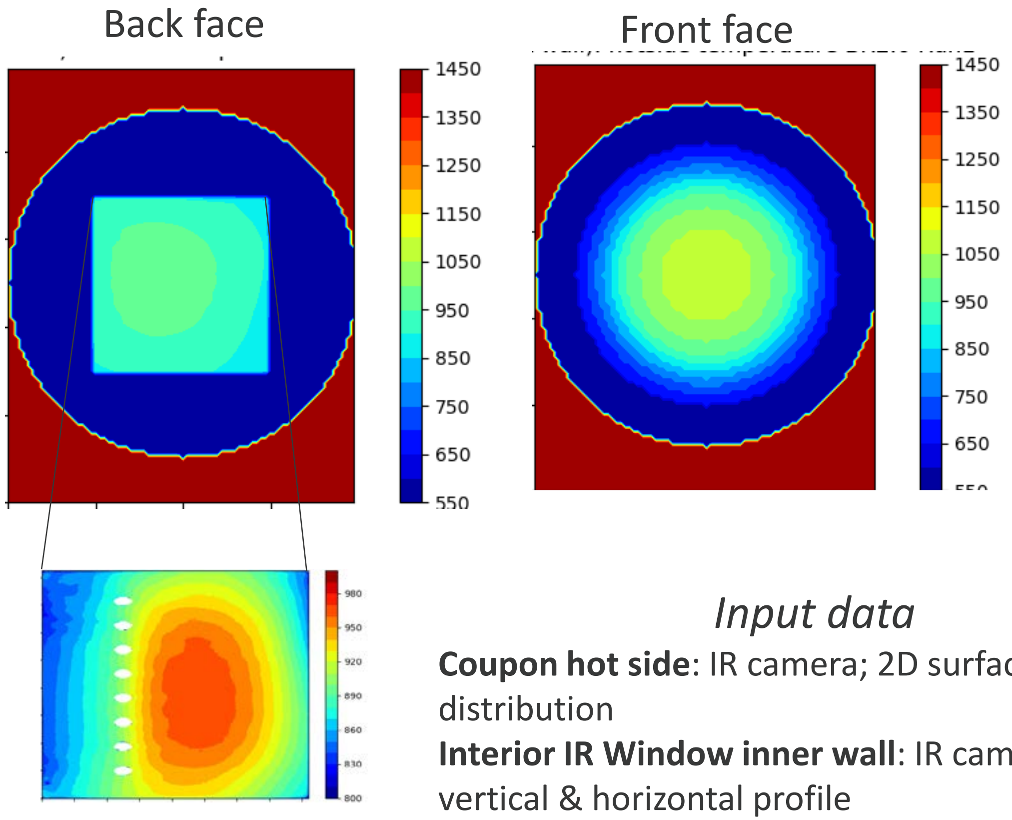
$$dF_{di\rightarrow dj} = \frac{\cos\theta_i \ \cos\theta_j \, dA_j}{\pi r^2} \qquad (1)$$

$$F_{i\rightarrow refrac} = 1 - \sum_{j=1}^{N} F_{i\rightarrow j} \qquad (2)$$

Test rig – heat sources

Radiation analysis – 3D model; Inputs – Enclosure 1



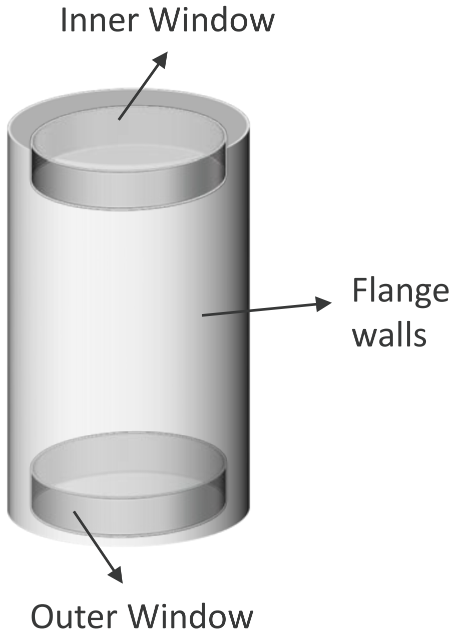


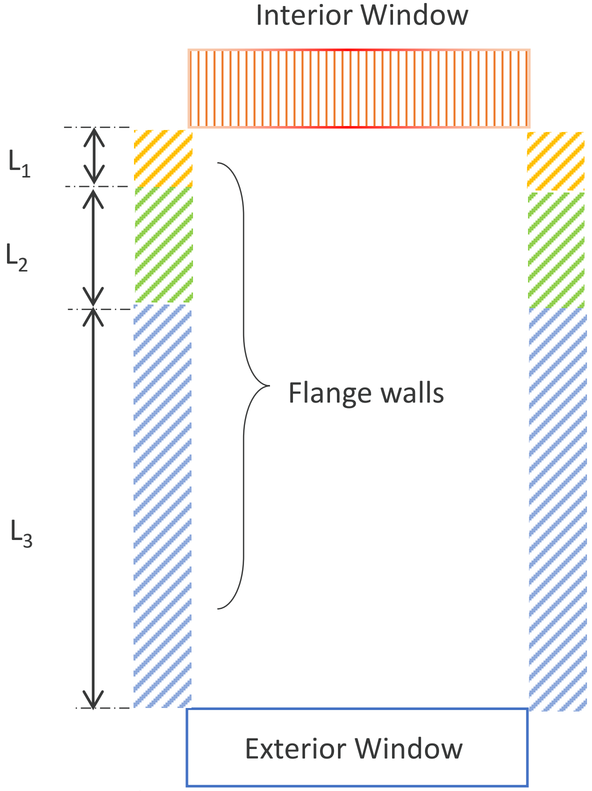
Input data

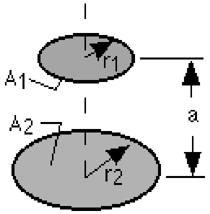
Coupon hot side: IR camera; 2D surface distribution
Interior IR Window inner wall: IR camera, vertical & horizontal profile
Portions of **Coupon Holder**: IR camera
Flange – Same as coupon holder
Refractory – 1D conduction through wall

Test rig – heat sources

Radiation analysis – 3D model; View factor estimation – Enclosure 2







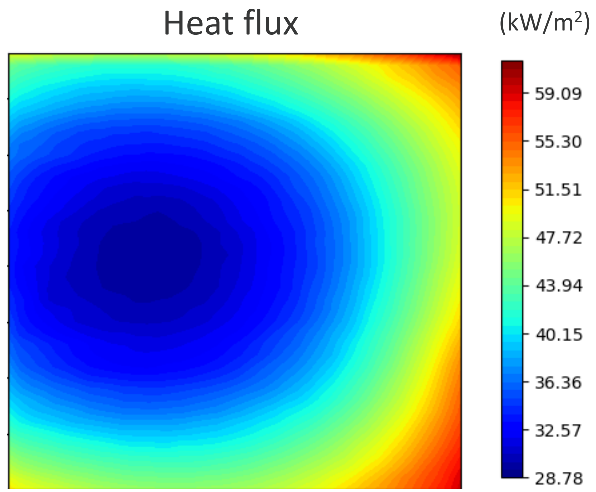
$$F_{1-2} = \frac{1}{2}\left\{X - \left[X^2 - 4\left(\frac{R_2}{R_1}\right)^2\right]^{1/2}\right\}$$

Input data

Interior IR window outer wall: IR camera, vertical & horizontal profile

Flange walls – varies between IR window and water temperature

Exterior IR window both walls – Ambient conditions



$$q''_{radn,coupon} = \frac{(E_{b,coup} - J_{coup})}{\frac{1-\varepsilon}{\varepsilon}}$$

$$\dot{q}_{avg} \sim 70\ W$$

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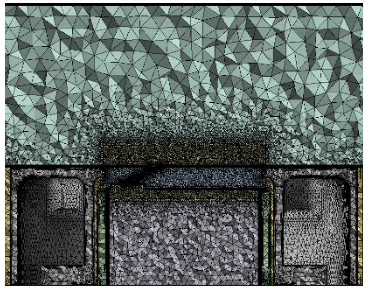
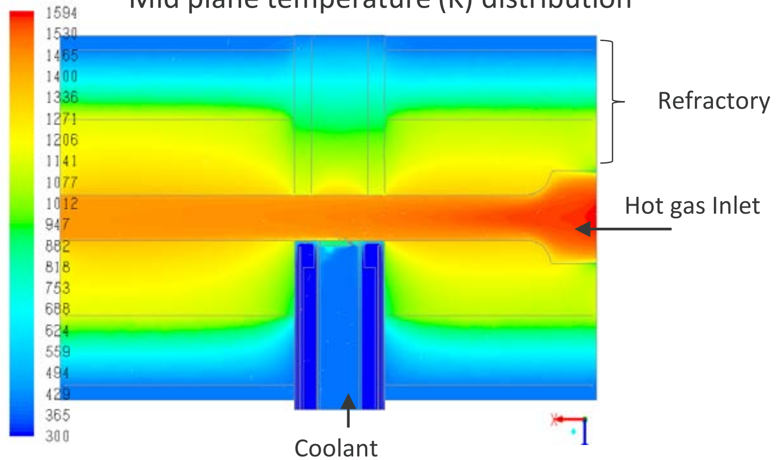


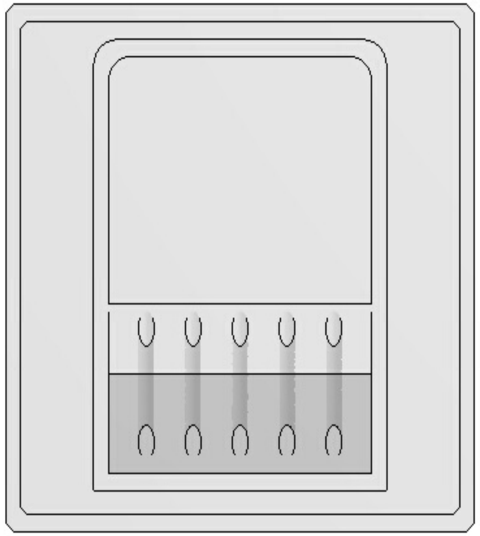
Mid plane temperature (K) distribution



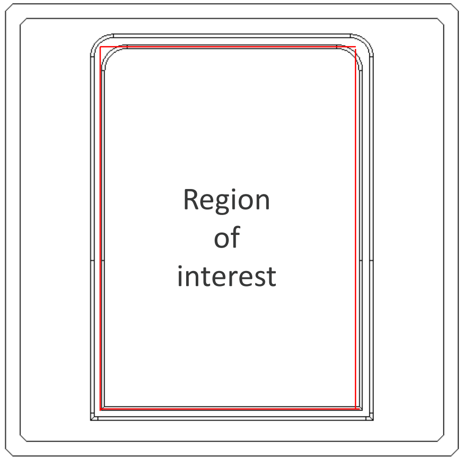
Test rig – heat sources

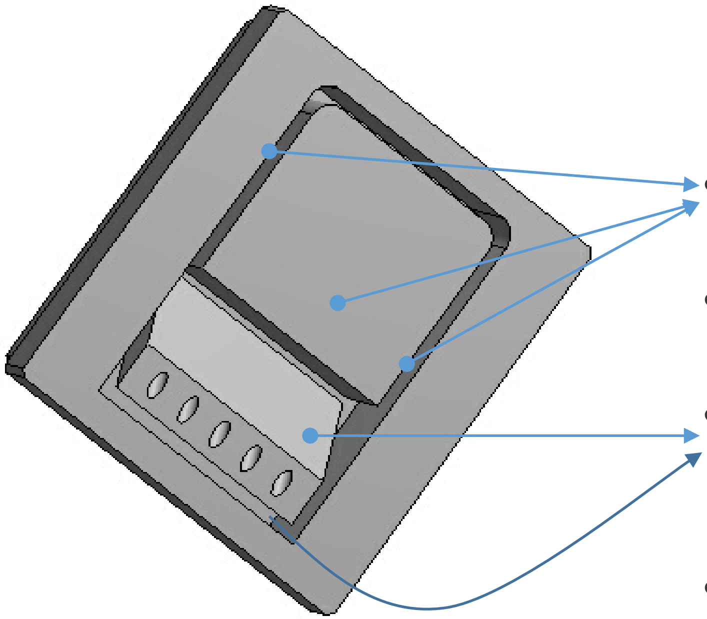
Conduction losses

Cylindrical coupon



Blank coupon



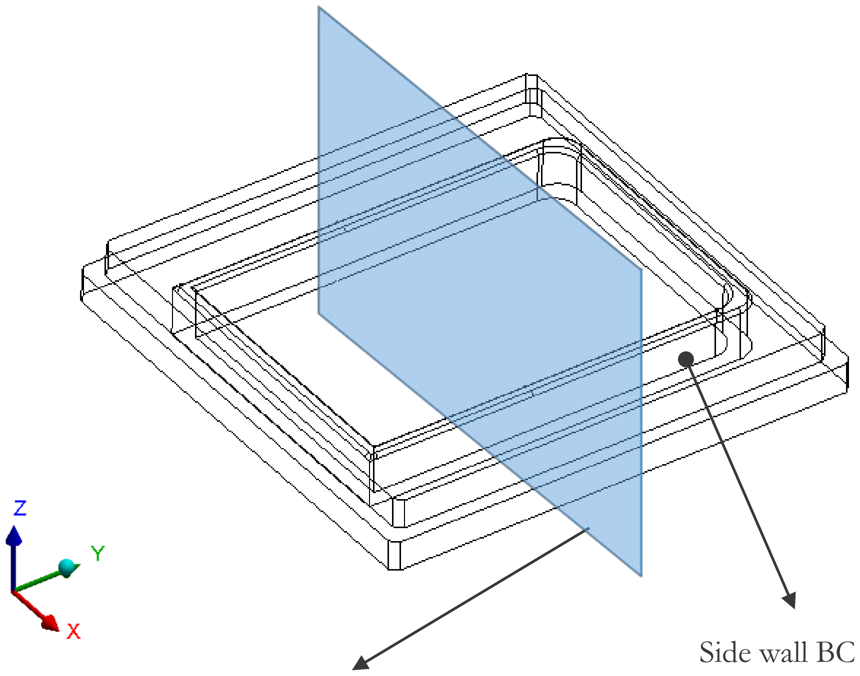


- Thermal break insulates coupon from losing heat to holder
- Separate back plate welded to coupon creates air pocket
- Significantly minimizes heat transfer to coolant hole from all sides. Aids in estimation of coolant exit temperature
- Heat transfer downstream of coolant holes is expected to be more 1D
  - correction needed to account for conduction through the 1/32” metal support

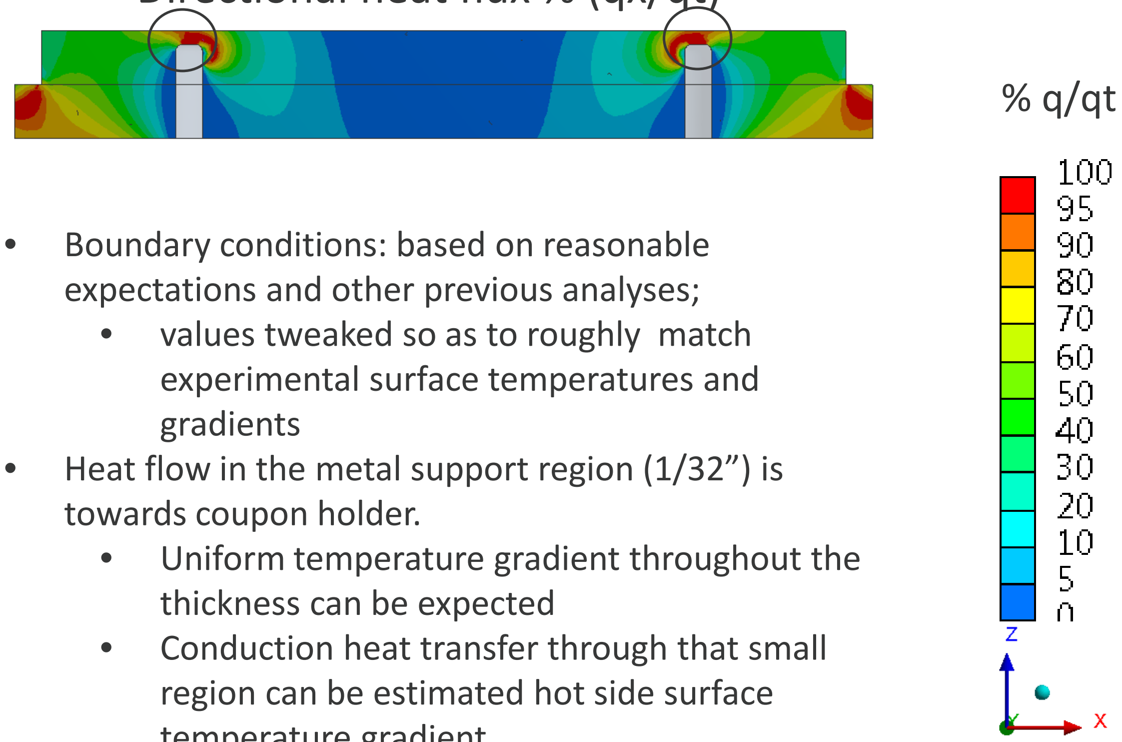
Test rig – heat sources

Conduction losses – Preliminary FEA results

Blank coupon



Directional heat flux % (qx/qt)



- Boundary conditions: based on reasonable expectations and other previous analyses;
  - values tweaked so as to roughly match experimental surface temperatures and gradients
- Heat flow in the metal support region (1/32”) is towards coupon holder.
  - Uniform temperature gradient throughout the thickness can be expected
  - Conduction heat transfer through that small region can be estimated hot side surface temperature gradient
    - Future efforts will focus on improving the accuracy of such measurements

$$\dot{q}_{avg} \sim 70\ W$$

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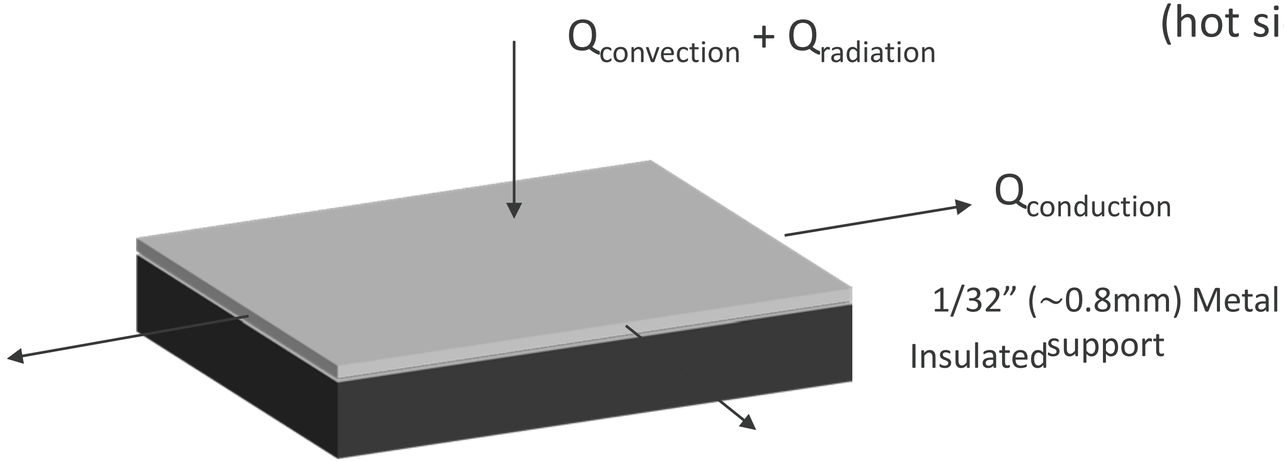
Estimate coupon surface: q'', h, θ

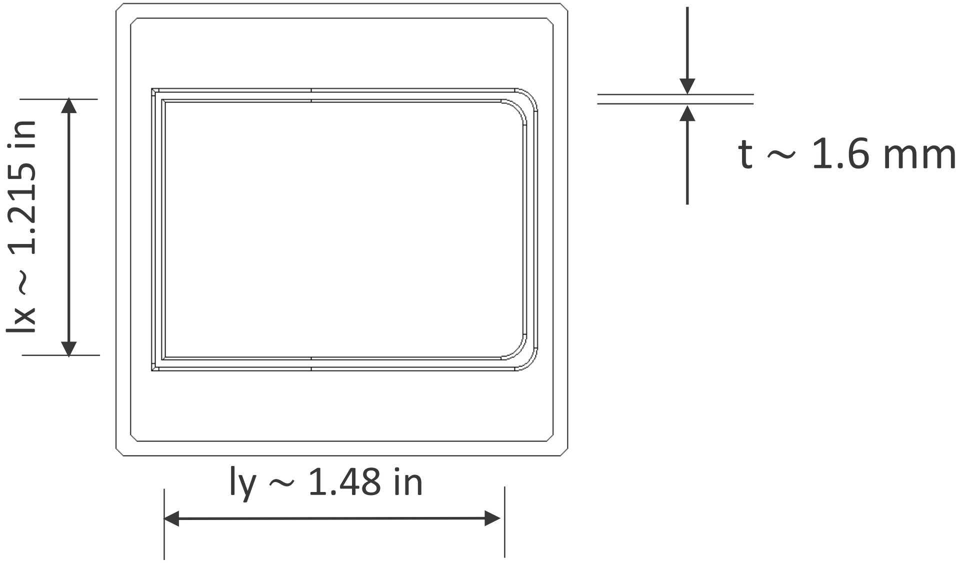
3D conduction (fea) boundary conditions

Hot side: Temperature from IR camera
Cold side: Temperature from IR camera
Side walls top 1/32": $Q_{conduction}$ estimated from experiments
Side walls remaining: adiabatic wall

q_{in} = Heat flux entering hot side (hot side surface gradient)

$$q_{conv} = q_{in} - q_{rad}$$





Estimation of q'', h, θ

- Blank coupon experiments
- 3 different back side cooling Blank coupon
- 3 additional experiments to be conducted with insulated cold side
- Coupon cold side IR window transmissivity was really low
  - Unable to capture surface temperature distribution using IR camera
  - Preliminary q” and h estimated using Thermocouple welded near center on cold side

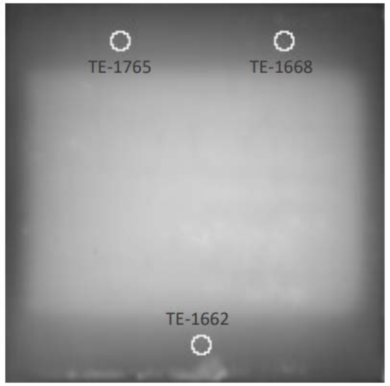
$$q''_{1D} = k * (T_h - T_c)/t$$

$$q_{1D} = k * A_{ROI}(T_h - T_c)/t$$

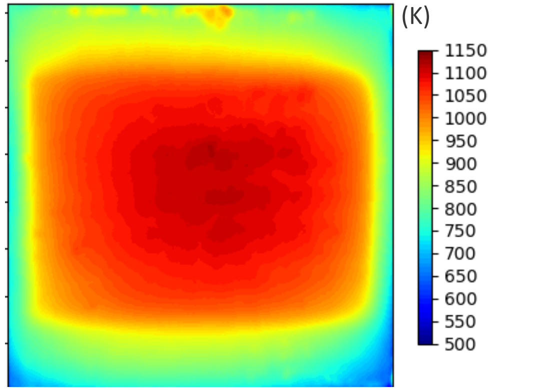
$$q_{conv} \sim 240\ W$$

$$h \sim 600\ W/m^2K$$

IR camera image calibrated with 3 embedded TCs



Coupon Hot Side



Conclusion

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1) Measuring q'', h, eta, and phi in a high temperature test facility has a number of challenges
2) We have made significant progress on the IR temperature measurements and have plans to make even more improvements
3) We have developed models and approaches to improve our HTC measurements
4) We hope to have the capability to measure these key film cooling parameters by early to mid-2019.

Thank you.

Acknowledgements

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Backup slide

Blank coupon z dir heat flux