High Temperature Film Cooling Experiments at NETL

Sridharan Ramesh (NETL, WVURC), Ed Robey (NETL, AECOM), Doug Straub (NETL), James Black (NETL)
High temperature high pressure facility

70 m/s, ~ 2200 °F, up to 10 atm

Free stream – hot combustion exhaust (natural gas)
Properties – velocity and temperature
Nozzles – Swirl stabilized premixed flame vs. dilute diffusion flame array
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: $q''$, $h$, $\theta$
  - If possible, also estimate: $q_f''$, $h_f$, $\eta$
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      - In-situ calibration
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Optical measurement technique
Test facility & Bench top calibration experiments

\[
I_{\text{cal}}(T) = \varepsilon_{bb} I_{bb}(T) + (1 - \varepsilon_{bb}) I_{bb}(T_{\text{amb ref}}) + K_0
\]

\[
I_{bb}(T) = \frac{I_{\text{cal}}(T) - K_0 - (1 - \varepsilon_{bb}) I_{bb}(T_{\text{amb ref}})}{\varepsilon_{bb}} = \frac{K_1}{e^{\frac{K_2}{T}} - 1}
\]

\[
\bar{I}_i = \bar{K}_0 + \varepsilon_{bb} \frac{\bar{K}_1}{e^{\frac{\bar{K}_2}{T_i}} - 1} + (1 - \varepsilon_{bb}) \frac{\bar{K}_1}{e^{\frac{\bar{K}_2}{T_{\text{amb}}}} - 1}
\]

\[
\text{SSE} = \sum_i (I_{\text{cal}}(T_i) - \bar{I}_i)^2
\]

Finding camera constants

Find \(\bar{K}_0, \bar{K}_1,\) and \(\bar{K}_2\) to minimize SSE:

\[
\bar{K}_0 = 2,201.1, \quad \bar{K}_1 = 1,230,587. \quad \bar{K}_2 = 3,402.5
\]

Where,

\[
I_{bb}(T) = \frac{K_i}{e^{\frac{K_2}{T}} - 1}
\]

and \(K_0\) accounts for dark current/noise

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

In-situ calibration

Test Section Surroundings (including window)

\[ \epsilon_{coup} I_{bb}(T_{coup}) \]

\[ (1 - \epsilon_{coup}) I_{bb}(T_{refl}) \]

\[ \tau_{wind1} \epsilon_{coup} I_{bb}(T_{coup}) \]

\[ \tau_{wind1} (1 - \epsilon_{coup}) I_{bb}(T_{refl}) \]

\[ \epsilon_{wind1} I_{bb}(T_{wind1}) \]

\[ \rho_{wind1} \tau_{wind2} I_{bb}(T_{amb}) \rightarrow \]

\[ \rightarrow \tau_{wind2} I_{bb}(T_{amb}) \]

\[ \rightarrow \epsilon_{wind2} I_{bb}(T_{wind2}) \]

\[ \frac{\tau_{wind2} \epsilon_{wind1}}{1 - \rho_{wind1} \rho_{wind2}} I_{bb}(T_{wind1}) \]

\[ \frac{\tau_{wind2} (1 - \epsilon_{coup})}{1 - \rho_{wind1} \rho_{wind2}} I_{bb}(T_{refl}) \]

\[ \epsilon_{wind2} I_{bb}(T_{wind2}) \]

\[ \frac{\tau_{wind2}^{2} \rho_{wind1}}{1 - \rho_{wind1} \rho_{wind2}} + \rho_{wind2} \] \[ I_{bb}(T_{amb}) \]

\[ \epsilon_{wind2} I_{bb}(T_{wind2}) \]

\[ \rightarrow \tau_{wind2} I_{bb}(T_{amb}) \]

\[ \rightarrow \epsilon_{wind2} I_{bb}(T_{wind2}) \]

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**Optical measurement technique**

**In-situ calibration**

\[
l_{\text{cam}}(x, y) = \frac{\varepsilon \tau_1 \tau_2}{1 - \rho_1 \rho_2} l_{bb}(T_c(x, y)) + \left\{ \begin{array}{l}
\frac{(1 - \varepsilon \tau_1 \tau_2)}{1 - \rho_1 \rho_2} l_{bb}(T_r(x, y)) \\
+ \left( \frac{\varepsilon_1 \tau_2}{1 - \rho_1 \rho_2} \right) l_{bb}(T_1(x, y)) \\
+ \left( \frac{\rho_1 \varepsilon_2 \tau_2}{1 - \rho_1 \rho_2} + \varepsilon_2 \right) l_{bb}(T_2(x, y)) \\
+ \left( \rho_2 + \frac{\rho_1 \tau_2}{1 - \rho_1 \rho_2} \right) l_{bb}(T_{amb}(x, y)) \\
+ K_0
\end{array} \right.
\]

Varies with changes in coupon temperature

\[
l_{\text{cam}} = \beta_1 l_{bb}(T_{coup}) + \beta_0
\]

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

In situ procedure: Camera measurements and temperatures of embedded thermocouples are used with regression to estimate slope and intercept terms
• 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 $I_{cam}$, $\beta_1$ and $\beta_0$.
• 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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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
  • \( J_i = E_i + \rho_i G_i \)
  • \( \rho_i = 1 - \alpha_i = 1 - \varepsilon_i \)
• 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:
\[
\frac{(E_{b,i} - I_i)}{1 - \epsilon_i} = I_i - \sum_{j} F_{i \rightarrow j} J_j
\]

Semi-transparent:
\[
\frac{\epsilon E_{b,w} + \tau G_{l,w} - (\epsilon_w + \tau) J_w}{1 - (\epsilon_w + \tau)} = I_i - \sum_{j} F_{i \rightarrow j} J_j
\]

- 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 = 5 in, 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

\[ dF_{di \rightarrow dj} = \frac{\cos \theta_i \cos \theta_j dA_j}{\pi r^2} \]  \hspace{1cm} (1)

\[ F_{i \rightarrow \text{refrac}} = 1 - \sum_{j=1}^{N} F_{i \rightarrow j} \]  \hspace{1cm} (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

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

Heat flux

\[ q_{\text{rad_n.coupon}} = \frac{(E_{b,coup} - J_{coup})}{1 - \varepsilon} \]
\[ \dot{q}_{\text{avg}} \sim 70 \text{ W} \]
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Test rig - heat sources

Conduction losses

- 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

Cylindrical coupon

Blank coupon

Region of interest
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

\[ \dot{q}_{avg} \sim 70 \text{ W} \]
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3D conduction (fea) boundary conditions
Hot side: Temperature from IR camera
Cold side: Temperature from IR camera
Side walls top 1/32": $Q_{\text{conduction}}$ estimated from experiments
Side walls remaining: adiabatic wall

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

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

$Q_{\text{convection}} + Q_{\text{radiation}}$

$1/32$” (~0.8mm) Metal Insulated support

$t \sim 1.6$ mm

lx ~ 1.215 in

ly ~ 1.48 in
Estimation of $q''$, $h$, $\theta$

- 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

$$q''_D = k \times (T_h - T_c)/t$$
$$q_{1D} = k \times A_{ROI} (T_h - T_c)/t$$
$$q_{conv} \sim 240 \text{ W}$$
$$h \sim 600 \text{ W/m}^2\text{K}$$
Conclusion

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.
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Backup slide
Blank coupon z dir heat flux