Numerical simulations of supersonic film cooling for liquid rocket nozzle applications: A validation study

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Introduction
• **J-2X nozzle extension**
  - $dP/dx \neq 0$
  - $M_1 = 3.74$,
  - $T_1 = 3767 \text{ K}$,
  - $P_{01} = 82 \text{ atm}$
  - $M_2 = 1.84$,
  - $T_2 = 539 \text{ K}$,
  - $P_{02} = 2.4 \text{ atm}$

• **UMD tunnel**
  - J-2X relevant conditions
    - Core $Ma = 2.4$
    - Film $Ma$
      - 0, 0.5, 0.7 & 1.2
Motivation

• **Some previous studies** - Weighardt (ZWB, 1900, 1946), Lucas et al. (NASA, TN D-1988, 1963), Goldstein (Advances in Heat Transfer, 1971), Aupoix et al. (AIAA, 36, 1998) & Konopka et al. (AIAA 2010-6792)

• More experimental data is needed to adequately validate CFD codes for supersonic film cooling
  – E.g., most studies do not provide flow profiles, with no study providing minimally-intrusive flow profiles

• **RANS and LES techniques should be further tested to assess performance for film cooling flows**
Objective

• Develop a detailed understanding of film cooling fluid dynamics so that predictive CFD approaches can be developed
  – Generate a database of measurements in ‘J-2X’ relevant model problems*** that can be used for CFD validation
  – Thorough assessment of RANS (using Loci-CHEM) and LES (using OpenFOAM)

***Model problems
  – Film cooling over a flat plate at constant pressure
  – Film cooling over a flat plate with a pressure gradient
Experimental heat flux
• **Inverse modeling** - measure temperature inside the solid and reconstruct unknown wall heat flux
Heat flux determination procedure

• Divide the measured temperature data into several sections
• Tune heat flux at the surface for reproducing the measured temperature inside the solid
  — Done using the bisection method with a 1D finite difference based conduction solver
Reynolds Averaged Navier Stokes (RANS) simulations:
Loci-CHEM
RANS: boundary conditions & mesh

$T_0 = 295 \text{ [K]}$

$P_0 = 1 \text{ atm}$

$T_{wall} = 333 \text{ [K]}$

$T_{wall} = 333 \text{ [K]}$

$T_0 = 323 \text{ [K]}$
RANS vs experiments: schlieren

Experiments

RANS

Ma_{film} = 0

Ma_{film} = 0.5
RANS vs experiments: schlieren

Experiments

\[ Ma_{\text{film}} = 0.7 \]

RANS

\[ Ma_{\text{film}} = 1.2 \]
RANS vs experiments: lower wall heat flux
RANS vs experiments: upper wall heat flux

**Ma\_film = 0**

- Heat flux \( [\text{kW/m}^2] \)
- \( x/S \)

**Ma\_film = 0.5**

- Heat flux \( [\text{kW/m}^2] \)
- \( x/S \)

**Ma\_film = 0.7**

- Heat flux \( [\text{kW/m}^2] \)
- \( x/S \)

**Ma\_film = 1.2**

- Heat flux \( [\text{kW/m}^2] \)
- \( x/S \)

Experiment
RANS (Loci-CHEM)
Discrepancies - why?

- **Possible reasons and solutions**
  - Limitations of **RANS models** e.g., difficulty in handling variable density flows
    - LES
  - **Fixed temperature BC** for heated walls
    - Conjugate Heat Transfer (CHT)
  - Relatively new **inverse modeling code**
    - Check effects of different parameters
  - **Experiments**
    - Understand the instrumentation better
Large Eddy Simulations (LES): OpenFOAM
Why OpenFOAM?

• Getting very popular in
  – Academia &
  – Industry

• Why?
  – Free
  – Open source
  – Easy to extend/develop
  – Several models for e.g., turbulence, combustion
  – Unstructured meshes
  – Scalability up to 1000s of CPUs

http://openfoam.com/
LES: inflow schematic & sponge layer

2D RANS

2D profiles of U, k, ω and R

Synthetic Eddy Method (SEM)

LES

Sponge layer
Coarse LES: wall heat flux contours

Temperature [K]
(front view)

Lower wall heat flux [kW/m²]
(top view)

Ma_{film} = 0

Ma_{film} = 0.5

Ma_{film} = 0.7

Ma_{film} = 1.2
LES: domain size & resolution

<table>
<thead>
<tr>
<th>cell count (million)</th>
<th>$L_{span}$ (in S)</th>
<th>$\Delta x^+$</th>
<th>$\Delta y^+$</th>
<th>$\Delta z^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>2.2</td>
<td>30</td>
<td>2.5-20</td>
<td>25</td>
</tr>
</tbody>
</table>

\[
\Delta x^+ + \Delta y^+ + \Delta z^+ + 13 = 2.2 + 30 + 2.5 - 20 + 25
\]
LES vs experiments: lower wall heat flux

Ma_{film} = 0

Ma_{film} = 0.5

Ma_{film} = 0.7

Ma_{film} = 1.2

Heat flux [kW/m²]

Heat flux [kW/m²]

x/S

x/S

Experiment

RANS (Loci-CHEM)

Preliminary LES (OpenFOAM)
Concluding remarks

• RANS (Loci-CHEM)
  - Flow structures in reasonable agreement with experimental data
  - Comparison with experimental heat flux profiles not impressive
    • Disagreement worse on the upper wall

• LES (OpenFOAM)
  - Providing high resolution insight into the film cooling dynamics
  - Preliminary LES shows improvement over RANS
  - Higher resolution simulations expected to provide more accurate results
Future work

- Heat flux determination (or inverse modeling) procedure
  - Check sensitivity to different parameters e.g., number of divisions

- Reynolds Averaged Navier Stokes (RANS) simulations
  - Understand the source of discrepancies in heat flux profiles
  - Conjugate heat transfer

- Large Eddy Simulations (LES)
  - Conduct higher resolution simulations
  - Larger span size
  - Resolve the upper wall
Acknowledgements

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Thank you; questions?
Back up slides
LES: domain

- Can not do LES of the full domain (high computational cost)
- Reduced domain needed
- But inflow fluctuations become important with reduced domain due to relatively high turbulent kinetic energy
LES: inflow (Synthetic Eddy Method)

- Jarrin et al. (IJHFF, 27, 2006)
- Velocity signal – sum of synthetic eddies with random position & intensity
- Eddies convected in a virtual streamwise periodic domain around the inlet boundary
- Synthetic eddy characteristics determined e.g., from a RANS solution
LES: inflow validation

- Synthetic Eddy Method (SEM)
  - Inlet signal evolves into a natural turbulent signal in roughly $15 \times \delta$
- Random noise at the inlet
  - Inflow signal is damped by the solver and flow re-laminarizes
- Consistent with Jarrin et al. (IJHFF, 27, 2006)
To avoid reflections from the outlet a **sponge layer** (grey) was used.

Flow fluctuations are damped in the sponge layer by source terms before it leaves the domain.

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) &= \sigma (\rho_{\text{ref}} - \rho), \\
\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j + p \delta_{ij} - \tau_{ij}) &= \sigma [(\rho u_i)_{\text{ref}} - \rho u_i], \\
\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_j} [(E + p) u_j + q_j - u_k \tau_{kj}] &= \sigma (E_{\text{ref}} - E),
\end{align*}
\]

Tested on the shock-vorticity/entropy wave interaction problem from Johnsen et al. (JCP, 229, 2010).