Transient Three-Dimensional Analysis of Nozzle Side Load in Regeneratively Cooled Engines
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Introduction

- Nozzle side loads are potentially detrimental to the integrity and life of almost all launch vehicles.
- The lack of a detailed prediction capability results in reduced life and increased weight for reusable nozzle systems.
- A clear understanding of the mechanisms that contribute to side loads during engine startup, shutdown, and steady-state operations must be established. A CFD based predictive tool must be developed to aid the understanding of side load physics and development of future reusable engines.
Introduction Continued

- CFD transient nozzle side load studies
  - Wang on an axisymmetric SSME nozzle hot-firing, 1992
    - Equilibrium reacting flow, simulated startup & shutdown sequence
  - Chen, et al. on an axisymmetric cold flow J2S nozzle, 1994
    - Cold flow, impulse start
  - Yonezawa, et al. on 2-D LE-7A nozzle side load, 2002
    - Cold flow, linear ramp rate in pressure
    - 32.5% Ar + 67.5% N2 @ $\gamma = 1.5$
  - Yonezawa, et al. on 3-D side loads for LE-7, LE-7A, and CTP50-R5-L nozzles, 2002
    - Frozen flow (25% $H_2 + 75% H_2O$), linear ramp rate in pressure & temperature for LE-7 and LE-7A
    - Cold $N_2$ and linear ramp rate for CTP50-R5-L
  - Wang on 2-D and axisymmetric SSME nozzles, 2004
    - Fully chemical reacting flow with simulated engine start-up sequence
    - Coanda effect, afterburning wave, FSS to RSS and vice versa, and lip lambda shock oscillation.
    - Factors affect side load physics: ramp rate and reaction
Objectives

- Identify the 3-D Block-I SSME start-up side load physics and compute the associated aerodynamic side load using an anchored computational methodology.

- Study the effect of (regenerative) wall cooling on side load physics.
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i) = 0
\]
\[
\frac{\partial \rho \alpha_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i \alpha_i) = \frac{\partial}{\partial x_j} \left[ \left( \rho D + \frac{\mu_t}{\sigma_\alpha} \right) \right] + \omega_i
\]
\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}
\]
\[
\frac{\partial \rho H}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i H) = \frac{\partial p}{\partial t} + Q_r + \frac{\partial}{\partial x_j} \left[ \left( \frac{K}{C_p} + \frac{\mu_t}{\sigma_H} \right) \nabla H \right] + \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) - \left( \frac{K}{C_p} + \frac{\mu_t}{\sigma_H} \right) \right] \nabla \left( \frac{V^2}{2} \right) + \theta
\]
\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i k) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \rho (\Pi - \varepsilon)
\]
\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho \frac{\varepsilon}{k} \left( C_1 \Pi - C_2 \varepsilon + C_3 \frac{\Pi^2}{\varepsilon} \right)
\]
Simulated Start-Up Inlet Conditions
## Computational Grid

<table>
<thead>
<tr>
<th>Grid</th>
<th># points</th>
<th># cells</th>
<th># structured cells</th>
<th># unstructured cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>3d6</td>
<td>1,286,934</td>
<td>1,275,120</td>
<td>1,101,600</td>
<td>173,520</td>
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</tbody>
</table>
## Run Matrix

<table>
<thead>
<tr>
<th>geometry</th>
<th>chemistry</th>
<th>wall B.C.</th>
<th>ramp time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>finite-rate</td>
<td>adiabatic</td>
<td>5 s</td>
</tr>
<tr>
<td>3-D</td>
<td>finite-rate</td>
<td>cooled</td>
<td>5 s</td>
</tr>
</tbody>
</table>

![Graph of wall temperature vs. distance](attachment:image.png)

- adiabatic wall, frozen chemistry
- adiabatic wall, equilibrium chemistry
- adiabatic wall, finite-rate chemistry
- cooled wall, finite-rate chemistry

![Graph of wall temperature vs. distance](attachment:image.png)
Effect of cooled wall on flow separation

- In 1973, Nave & Coffey noted that colder walls tend to retard separation by observing flow separation during J-2S engine firing.
- In 1988, Chang, Krozon, and Merkle did steady CFD analyses on axisymmetric conical and contoured nozzles and found that cold wall B.C. results in a much thinner boundary layer than was computed for the hot-wall conditions. This thinner, cold wall boundary layer is also less susceptible to separation than were the hot-wall results.
- In 1994, Shimura, Asaka, and Lee did steady CFD analyses on a 2-D planar conical nozzle and reached similar conclusion as that of Chang, Krozen, and Merkle.
Computed y-plane temperature contours of the cooled nozzle showing combustion wave.
Computed y-plane pressure contours of the cooled nozzle showing combustion wave
Computed z-plane Mach number contours of the cooled nozzle showing FSS-to-RSS transition.
Computed side forces for the adiabatic nozzle from 0 ~ 2 s
Computed side forces for the cooled nozzle from 0 ~ 2 s
Computed scalar contours for the adiabatic nozzle at 2.625 s
Computed exhausting and receding wall OH contours for the adiabatic nozzle

2.8300 s  2.8400 s

2.8475 s  2.8450 s
Computed side force loci for the adiabatic nozzle
Computed scalar contours for the cooled nozzle at 2.580 s
Computed exhausting and receding wall OH contours for the cooled nozzle
Computed tangential force loci for the cooled nozzle

- $2.9425 - 2.95125$ s
- $2.95125 - 2.9775$ s
- $3.0031 - 3.0125$ s
- $3.0455 - 3.0605$ s
Computed side forces for the adiabatic nozzle from 2 ~ 4 s
Computed side forces for the cooled nozzle from 2 ~ 4 s
Computed near lip wall pressure, shear stress, and heat flux histories for the cooled nozzle
Computed frequency domain for the cooled nozzle during RSS oscillation across the lip
<table>
<thead>
<tr>
<th>Variable</th>
<th>pressure</th>
<th>temperature</th>
<th>pressure</th>
<th>heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic nozzle</td>
<td>45</td>
<td>49</td>
<td>122</td>
<td>125</td>
</tr>
<tr>
<td>Cooled nozzle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A comparison of dominant frequencies during shock oscillations across the lip.
## A comparison of local peak side loads

<table>
<thead>
<tr>
<th>$F_{yz}$, kN</th>
<th>Test</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Adiabatic nozzle</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>395</td>
</tr>
<tr>
<td>1st mode</td>
<td>90*</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>2nd mode</td>
<td>200*</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

* Normalized.
Conclusions

- 3-D numerical studies of the Block-I SSME nozzle start-up side load physics and predictions of the associated aerodynamic side load for adiabatic and cooled nozzles were performed.

- Three types of shock evolutions generate significant side loads: the occurrence of combustion wave, transitions among FSS, RSS and simultaneous FSS and RSS, and shock oscillations across the lip.

- Wall boundary conditions affect the computed side load physics.
Conclusions - continued

- The creation of **combustion wave** and the **FSS-to-RSS transition** are common to both adiabatic and cooled nozzles just after the first pressure rise event. After which the adiabatic nozzle prefers the FSS, while the cooled nozzle favors the RSS.

- After the second pressure event, the peak side load of the **adiabatic nozzle** occurs due to the numerous **transitions between FSS, RSS, and partial RSS**, after which lip FSS oscillations follows until the nozzle flows full; for the **cooled nozzle**, RSS persists throughout, and significant side load happens during the **RSS oscillation across the lip**.

- By comparing the computed results with those of test observations, it is deduced that **cooled wall is a more realistic boundary condition** than that of an adiabatic wall for a regeneratively cooled engine.
Conclusions - continued

- Since the side load induced by combustion wave may be avoided with sparklers, and that induced by the FSS-to-RSS transition is considerably lower, the RSS oscillation across the lip along with its associated tangential shock motion appear to be the dominant side load physics for the regeneratively cooled, high aspect-ratio rocket engines.