Shock Wave Interactions
A CFD Study of CUBRC LENS-II Turbulent Experiments

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ERC, Inc.

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Acknowledgments

- Michael Holden and Timothy Wadhams for the kind invitation

- Michael Wright and Michael Barnhardt of NASA Ames Research Center for encouragement of the work through NASA’s ESM (formerly HEDL) program

- NASA Ames Research Center for funding this work via Contract NNA10DE12C to ERC, Inc.
Objective(s)

Primary

To predict surface distributions of pressure and heat flux using “standard” simulation model(s) for:

(a) Sharp cone-flare (7° /40° ) model
(b) Hollow cylinder-flare (36° ) model

tested at turbulent flow conditions in LENS-II at CUBRC

Secondary

To explore transition (to turbulence) aspects of flow for these configurations

Focus of this presentation is solely on the sharp cone-flare model
Modeling & Computing Strategy

Modeling

- v4.03.1 of Dplr
  - Ideal gas ($\gamma = 1.4$) for all cases
  - Sutherland’s law for viscosity of air
  - Constant Prandtl number = 0.71
  - Isothermal wall, $T_w = 300$ K

Strategy

- Perform laminar computations for cone alone (no flare)
  - Extract $Re_\theta$ from computed flow field using Blayer
    - Edge detection method: 99.5% of freestream enthalpy
  - Use $Re_\theta$ (from laminar solution) to specify onset of transition

- Perform turbulent computations for full configuration
  - SST model with no compressibility correction
  - Dhawan-Narasimha model for transition (intermittency)
Cone-Flare Model

Cone-flare model has a sharp tip
Sufficient run length to ensure natural transition ahead of flare (interaction region)

7° cone is identical to that of HIFiRE-1 configuration
HIFiRE-1 had a cylindrical section before the flare and the tip was blunt (2.5 mm radius)
Learning Case – HIFiRE-1/Run 30
(“Open” Validation Case in AIAA 2013-2836)

<table>
<thead>
<tr>
<th>Run #</th>
<th>43</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\rho/\text{g.m}^{-3})</td>
<td>38</td>
<td>67</td>
</tr>
<tr>
<td>(V/\text{km.s}^{-1})</td>
<td>2.20</td>
<td>2.17</td>
</tr>
<tr>
<td>(T/\text{K})</td>
<td>250</td>
<td>227</td>
</tr>
<tr>
<td>(Re \times 10^{-6})</td>
<td>3.7</td>
<td>9.8</td>
</tr>
<tr>
<td>(L/\text{m})</td>
<td>2.342</td>
<td>?</td>
</tr>
<tr>
<td>(H_0/\text{MJ.kg}^{-1})</td>
<td>2.65</td>
<td>2.58</td>
</tr>
<tr>
<td>(h_w/H_0)</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Run 43 of blind study matrix is comparable to Run 30 (HIFiRE-1)

Comparison of laminar results with experimental data shows transition location at 429 mm

Extract \(Re_\theta\) at \(x = 429\) mm from laminar flow solution
Transition Location (Run 30)

\[ \text{Re}_\theta \text{ at } x = 429 \text{ mm is } \approx 700 \text{ – preferred location for Baldwin-Lomax model} \]

\[ \text{Re}_\theta = 600 \text{ occurs at } x = 310 \text{ mm – preferred location for SST model} \]
Turbulent Flow Computations – Run 30 (HIHiRe-1)

**Pressure**

- Laminar
- Turbulent (B-L)
- Transition (B-L)
- Transition (SST)
- Experiment (Run 30)

**Heat Flux**

- Laminar
- Turbulent (B-L)
- Transition (B-L)
- Transition (SST)
- Experiment (Run 30)

*SST model (without compressibility) provides best agreement with experimental data*

*Input transition locations for B-L and SST models are different!!!*
# Blind Study Test Matrix for Cone-Flare Geometry

<table>
<thead>
<tr>
<th>Run #</th>
<th>26</th>
<th>28</th>
<th>33</th>
<th>34</th>
<th>45</th>
<th>14</th>
<th>43</th>
<th>37</th>
<th>40</th>
<th>41</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mach 5</td>
<td>Mach 6</td>
<td>Mach 7</td>
<td>Mach 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho/\text{g.m}^{-3}$</td>
<td>284</td>
<td>141.7</td>
<td>73.7</td>
<td>71.12</td>
<td>111.3</td>
<td>57.21</td>
<td>37.88</td>
<td>43.7</td>
<td>24.22</td>
<td>23.55</td>
</tr>
<tr>
<td>$V/\text{km.s}^-$</td>
<td>0.89</td>
<td>1.48</td>
<td>0.93</td>
<td>1.58</td>
<td>1.85</td>
<td>1.18</td>
<td>2.20</td>
<td>1.28</td>
<td>1.75</td>
<td>2.10</td>
</tr>
<tr>
<td>$T/\text{K}$</td>
<td>76</td>
<td>220</td>
<td>56</td>
<td>170</td>
<td>244</td>
<td>67</td>
<td>250</td>
<td>60</td>
<td>118</td>
<td>167</td>
</tr>
<tr>
<td>$Re \times m \times 10^6$</td>
<td>49</td>
<td>14.5</td>
<td>18.5</td>
<td>9.7</td>
<td>13.1</td>
<td>15.0</td>
<td>5.2</td>
<td>14.0</td>
<td>5.2</td>
<td>4.4</td>
</tr>
<tr>
<td>$L/\text{m}$</td>
<td>2.408</td>
<td>2.407</td>
<td>2.395</td>
<td>2.422</td>
<td><strong>2.809</strong></td>
<td>2.440</td>
<td><strong>2.342</strong></td>
<td>2.393</td>
<td>2.404</td>
<td>2.403</td>
</tr>
<tr>
<td>$H_0/\text{MJ.kg}^{-1}$</td>
<td>0.47</td>
<td>1.31</td>
<td>0.49</td>
<td>1.41</td>
<td>1.96</td>
<td>0.76</td>
<td>2.65</td>
<td>0.88</td>
<td>1.64</td>
<td>2.37</td>
</tr>
<tr>
<td>$h_w/H_0$</td>
<td>0.64</td>
<td>0.23</td>
<td>0.62</td>
<td>0.21</td>
<td>0.15</td>
<td>0.40</td>
<td>0.11</td>
<td>0.34</td>
<td>0.18</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**Wall enthalpy comparable to total enthalpy => sensitivity to wall temperature**

**Cases 45 & 43: Inferred characteristic length at variance with cone axial length of 2.353 m**

**Real-gas effects, if any, probably limited to change in $\gamma$, i.e., no chemistry**
Transition Locations for Blind Study Matrix

Locations corresponding to $\text{Re}_\theta = 600$ used for all blind study cases (since SST used)
Sample Result: Run 37 (Mach 7)

Grid tailored to outer shock including the shock interaction region

Separated flow seen at the foot of the flare
Sample Result: Run 37 (Global View)

Only SST computations performed for full configuration
Transition location at $\text{Re}_0 = 600$
No laminar or Baldwin-Lomax turbulent solution for full configuration!!!
Sample Result: Run 37 (Local View)

Pressure

Heat Flux

Only SST computations performed for full configuration

Transition location at $Re_0 = 600$

No laminar or Baldwin-Lomax turbulent solution for full configuration!!!
How Good is the $Re_\theta = 600$ Transition Criterion?

**Answer:** Good only for one HIFiRE-1 case, but not applicable across all cases!!

**Additional cases from AIAA 2013-2836**
- Experimentally determined transition locations available for some cases
  - For Runs 1, 4, 5, 9, and 10 transition location available
  - For Run 11, flow transitioned before first sensor location (174 mm)
- These additional cases have been computed as well

**Results from additional calculations can be used to construct a model to make predictions of onset of transition (at least for the cone-flare geometry)**
- Details will be in the written paper
- Applicability to the cylinder-flare configuration remains to be seen
$x_{tr} \text{ vs } Re_\theta \text{ from Additional Computations}$

<table>
<thead>
<tr>
<th>Run #</th>
<th>1</th>
<th>4</th>
<th>5</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt.</td>
<td>$x_{tr}/mm$</td>
<td>174</td>
<td>404</td>
<td>253</td>
<td>480</td>
<td>454</td>
<td>?</td>
</tr>
<tr>
<td>CFD</td>
<td>$Re_\theta$</td>
<td>349</td>
<td>372</td>
<td>503</td>
<td>331</td>
<td>617</td>
<td>?</td>
</tr>
</tbody>
</table>
Transition Onset Predictions for Blind Study Cases

- \( \text{Re}_\theta \neq 600 \) in all cases
- In most cases, transition occurs earlier
- Cases have not been recomputed with new onset locations

<table>
<thead>
<tr>
<th>Run #</th>
<th>26</th>
<th>28</th>
<th>33</th>
<th>34</th>
<th>45</th>
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<th>40</th>
<th>41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{tr} )/mm</td>
<td>61</td>
<td>145</td>
<td>215</td>
<td>169</td>
<td>353</td>
<td>181</td>
<td>796</td>
<td>223</td>
<td>631</td>
<td>918</td>
</tr>
</tbody>
</table>
Concluding Remarks

• Accomplishments
  – All cases computed for both configurations
  – Transition imposed at $\text{Re}_\theta = 600$ for all cases
    • Unfortunately this criterion is solely for the HIFiRE-1 case
  – An attempt made to predict transition onset for the 7° sharp cone
    • Cases have not been recomputed with predicted onset locations

• Things still left to do
  – Recompute all cases with predicted onset locations
  – Reconcile differences between SST and B-L for transition onset
  – Grid convergence and wall temperature sensitivity studies
  – Choice of turbulence models such as Spalart-Allmaras, Lag, …
    • Can be a collaborative effort with Overflow especially since flow medium is ideal gas ($\gamma = \text{constant}$)
  – Real-gas effects, esp. at Mach 7 or 8
    • Most likely to be purely a variable $\gamma$ effect, but …

• Open issue (in the view of the author)
  – 3D vs Axisymmetric, but 3D is resource intensive
Backup
Hollow Cylinder-Flare Model

Cone-flare model has a sharp tip

7° cone is identical to that of HIFiRe-1 Configuration

HIFiRE-1 had a cylindrical section before the flare and the tip was blunt (2.5 mm radius)

All linear dimensions are in mm
## Test Matrix for Cone-Flare Geometry

<table>
<thead>
<tr>
<th>Case</th>
<th>17</th>
<th>16</th>
<th>11</th>
<th>13</th>
<th>18</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Mach 6</td>
<td>Mach 7</td>
<td>Mach 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho / \text{g.m}^{-3}$</td>
<td>109</td>
<td>213</td>
<td>52.6</td>
<td>158</td>
<td>45.9</td>
<td>23.1</td>
</tr>
<tr>
<td>$V / \text{m.s}^{-1}$</td>
<td>1.46</td>
<td>1.45</td>
<td>1.70</td>
<td>1.68</td>
<td>2.09</td>
<td>2.17</td>
</tr>
<tr>
<td>$T / \text{K}$</td>
<td>214</td>
<td>212</td>
<td>202</td>
<td>193</td>
<td>224</td>
<td>184</td>
</tr>
<tr>
<td>$Re \times 10^{-6}$</td>
<td>11.3</td>
<td>22.2</td>
<td>6.7</td>
<td>20.5</td>
<td>6.6</td>
<td>4.1</td>
</tr>
<tr>
<td>$L / \text{m}$</td>
<td><strong>2.858</strong></td>
<td><strong>2.846</strong></td>
<td>2.596</td>
<td>2.596</td>
<td>2.590</td>
<td>2.590</td>
</tr>
<tr>
<td>$H_0 / \text{MJ.kg}^{-1}$</td>
<td>1.27</td>
<td>1.26</td>
<td>1.64</td>
<td>1.59</td>
<td>2.41</td>
<td>2.53</td>
</tr>
<tr>
<td>$h_w / H_0$</td>
<td>0.24</td>
<td>0.24</td>
<td>0.18</td>
<td>0.19</td>
<td>0.13</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**Wall enthalpy comparable to total enthalpy => sensitivity to wall temperature?**

**Inferred characteristic length for Cases 16 & 17 differs from the others**

**Real-gas effects probably limited to change in $\gamma$**
Transition Locations for Blind Study Matrix

Locations corresponding to $\text{Re}_\theta = 600$ used for all blind study cases (since SST used)
LE shock and flare shock do not interact
Separated flow seen at the foot of the flare
Sample Result: Run 18 (Global View)

Only SST computations performed for full configuration
Transition location at \( \text{Re}_0 = 600 \)
No laminar or Baldwin-Lomax turbulent solution!!!
Sample Result: Run 18 (Local View)

Only SST computations performed for full configuration
Transition location at $Re_0 = 600$
No laminar or Baldwin-Lomax turbulent solution!!!