A Loosely Coupled approach for the CFD code US3D and Radiation code NEQAIR

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Background

- A Thermal Protection System (TPS) is required to protect the vehicle from severe heating environments during high speed entries.
- The physics of the entry aeroheating is controlled by phenomenon like:
  - Convection (US3D/DPLR)
  - Radiation (NEQAIR)
  - Surface chemistry (FIAT/ICARUS)
  - In-depth conduction (FIAT/ICARUS)
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In reality, these processes are coupled due to the surface energy balance. Assumptions have to be made about their time/length scales. Thus, allowing the use of uncoupled approaches.
Motivation

• Main focus:

  **Fluid-dynamics and Radiation** coupling

• The amount of fluid-radiation coupling can be estimated by evaluating the **Goulard number** $(\Gamma)$:

  \[
  \Gamma = \frac{2q_{unc}^R}{\frac{1}{2} \rho_\infty u_\infty^3} = \frac{\text{Uncoupled radiative energy flux}}{\text{Total energy flux}}
  \]

• Different values for $\Gamma$:
  - FIRE II $^{[1]} \sim 0.01$ to 0.03
  - Galileo Probe $^{[8]} \sim 0.1$
  - Titan Aerocapture $^{[8]} \sim 0.4$

• An uncoupled solution over-predicts the total heating by almost 15% for FIRE II $^{[1]}$.

• For atmospheric conditions such as in Titan or during Jovian entry the fluid-radiation coupling becomes a must.
State of the Art

• Past work on fluid-radiation coupling have mainly used structured codes:
  – Palmer et al. [1] using DPLR-NEQAIR.
  – Johnston et al. [7] using LAURA-HARA.

• First attempt to use US3D an unstructured code.
  – US3D is developed by University of Minnesota in collaboration with NASA Ames and other partners.
  – Will be the next generation CFD tool for NASA Ames.
  – Important to have the capability of fluid-radiation coupling.

• Develop a loosely coupled methodology using US3D and NEQAIR.
Run the CFD simulation until convergence

*Obtain solution on a 3-D volume*

Extract flow data along Lines of Sight

Calculate the radiant energy source term

*Obtain solution on a 1-D Line of Sight*

Run the CFD simulation using the source term

**US3D**

**US3D post-par**

**NEQAIR**

**US3D**

One Coupling Iteration
Coupling Procedure

- Run the CFD simulation until convergence
  - Obtain solution on a 3-D volume
  - US3D

- Extract flow data along Lines of Sight
  - US3D post-par

- Calculate the radiant energy source term
  - NEQAIR

- Obtain solution on a 1-D Line of Sight

- Run the CFD simulation using the source term
  - US3D

One Coupling Iteration
Extracting LOS

- Challenging in an unstructured code.
- Connectivity not explicitly given using grid index.
- An efficient searching algorithm is required for searching nearest neighbors.
- The \textit{kd-tree algorithm} in US3D is used.
- It organizes data in a way that a large chunk of data points can be excluded during the search.
- A zeroth-order interpolation of flow data along the LOS.
Steps in LOS Extraction

1. Calculate metrics for the grid
   *Ex: Distance from wall, normal etc.*

2. Draw normal lines from wall face centers

3. Discretize the normal line from the wall to the outer boundary

4. Interpolate data along the LOS
   *Rate determining step - requires a search for cells in the whole domain*

Find the cell center on the outer boundary closest to the normal line.

Use the parametric equation of line to draw normals from the wall.
Serial code runs using the US3D post-processor.

Time required for extracting 100 lines with 100 points each:
- FIRE II grid \( \sim 10^4 \) cells = 1 sec.
- EAST grid \( \sim 10^6 \) cells = 60 sec.

User Inputs:
- Grid file - grid.h5, connectivity file - conn.h5 and solution file - data.h5
- No. of points to extract per line.
- The wall boundary name and gas file name used.

Outputs and Capabilities:
- Extract lines at any given point on the wall or between any two given points.
- Write LOS data in NEQAIR (.h5/.dat) or Tecplot readable (.dat) format.
- Mirror LOS data about the outer boundary (useful for shock tube problems).
Tangent Slab

- **Tangent Slab approximation:**
  - The radiation is along a line of sight normal to the wall.
  - Johnston et al. [4] showed that the tangent-slab assumption is sufficient to model the source term but not the radiative heating on surface.
    - Source term: under 3% - stagnation line & shoulder, 10% - afterbody.
    - Radiative heating: 11% - stagnation line, 17% - shoulder, 40% - afterbody.
### Flow Conditions

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Altitude (km)</th>
<th>$U_\infty$ (km/s)</th>
<th>$T_\infty$ (K)</th>
<th>$\rho_\infty$ (kg/m$^3$)</th>
<th>$T_w$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1636</td>
<td>71.0</td>
<td>11.31</td>
<td>210</td>
<td>$8.57 \times 10^{-5}$</td>
<td>810</td>
</tr>
<tr>
<td>1643</td>
<td>53.0</td>
<td>10.48</td>
<td>276</td>
<td>$7.80 \times 10^{-4}$</td>
<td>640</td>
</tr>
<tr>
<td>1645</td>
<td>48.4</td>
<td>9.83</td>
<td>285</td>
<td>$1.32 \times 10^{-3}$</td>
<td>1520</td>
</tr>
</tbody>
</table>

### Computational Models

<table>
<thead>
<tr>
<th>Fluxes</th>
<th>Modified Steger-Warming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time integration</td>
<td>Data Parallel Line Relaxation (DPLR)</td>
</tr>
<tr>
<td>Gas</td>
<td>Air – 11 species</td>
</tr>
<tr>
<td>Reaction rates</td>
<td>Park two-temperature model</td>
</tr>
<tr>
<td>Vibrational-Electronic energy</td>
<td>NASA Lewis data fits</td>
</tr>
<tr>
<td>Transport properties</td>
<td>Gupta collision model</td>
</tr>
</tbody>
</table>
Coupling – FIRE II

Uncoupled Solution → LOS Extraction → Radiative Source Term → Coupled Solution
**Heating Rates**

\[ U_\infty = 10.48 \]

- The heating rates converged in 3-4 coupling iterations.
- Decrease in heating rates after coupling:
  - Convective - 6.5 %
  - Radiative - 23.5 %
Heating Rates

\[ U_\infty = 11.31 \]

\[ U_\infty = 10.48 \]

\[ U_\infty = 9.83 \]
Shock Movement

$U_\infty = 10.48$

- Decrease in bow shock stand-off distance.
- Decrease in temperatures inside shock layer.
Shock Movement

$U_\infty = 11.31$

$U_\infty = 10.48$

$U_\infty = 9.83$

Temperature (K)

x (m)

- Red: $T$, uncoupled
- Red dashed: $T_v$, uncoupled
- Blue: $T$, coupled
- Blue dashed: $T_v$, coupled
The radiative source term typically acts as an energy sink in the shock layer (due to emission) and a source in the boundary layer (due to absorption).
Radiative Cooling

- Net effect of the radiative source term:
  - Lowers convective and radiative heating rates at the wall.
  - Reduction in bow shock stand-off distance.
  - This effect is known as radiative cooling.

- Tauber and Wakefield \cite{2} derived an approximate relation for the ratio of the coupled radiative heating to the adiabatic one as a function of the Goulard number (where $\kappa = 3.45$).

$$\frac{q_{coup}^R}{q_{ad}^R} = \frac{1}{1 + \kappa \Gamma^{0.7}}$$

Fractional change in radiative heating:

<table>
<thead>
<tr>
<th>$U_\infty$ (m/s)</th>
<th>$\Gamma$</th>
<th>US3D-NEQAIR</th>
<th>Palmer et al. \cite{1}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T&amp;W</td>
<td>Results</td>
</tr>
<tr>
<td>11.31</td>
<td>0.036</td>
<td>0.748</td>
<td>0.793</td>
</tr>
<tr>
<td>10.48</td>
<td>0.031</td>
<td>0.767</td>
<td>0.765</td>
</tr>
<tr>
<td>9.83</td>
<td>0.011</td>
<td>0.872</td>
<td>0.842</td>
</tr>
</tbody>
</table>
• Developed a user module for US3D to perform fluid-radiation coupling simulations with NEQAIR.

• The coupling simulations were performed on the 2-D axisymmetric FIRE II grid for three different flow conditions.

• The effects of the fluid-radiation coupling were seen as a reduction in the convective/radiative heating rates and decrease in the shock stand-off distance.

• The reduction in radiative heating rates seems to be comparable to those predicted by Tauber-Wakefield [2].
Future Work

• Adding the capability in the LOS tool to extract lines any given angle.
  – Extract a no. of LOS within a given solid angle.

• Evaluate the effects of the Tangent-Slab assumption on the flow field.
  – Computationally very expensive as the radiation on every LOS emanating from the wall face needs to be computed.

• Better interpolation of source term into the domain.

• Comparison of US3D-NEQAIR simulations with those done from DPLR-NEQAIR.
Thank you
Any Questions?

Special Thanks to:
Joseph C. Schulz
Aaron M. Brandis
Khalil Bensassi
Brett A. Cruden
Suman Muppidi
David B. Hash
References


