Smoke transport in an aircraft cargo compartment

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Motivation

• FAA Federal Aviation Regulations (FAR) Part 25, Section 858:
  “If certification with cargo or baggage compartment smoke or fire detection provisions is requested, the following must be met ...
  
a. The detection system must provide a visual indication to the flight crew within one minute after the start of fire.
  
  ...
  
d. The effectiveness of the detection system must be shown for all approved operating configurations and conditions.”

• Smoke detectors have high false alarm rates.
• Standardization of certification process is necessary.
• Ground and in-flight tests required for the certification process are costly and time consuming.
Objective

- FAA aims to
  - improve the detector alarm algorithms, thereby the reliability of the smoke detectors,
  - provide guidelines for the certification process, and standardize the procedures to use,
  - reduce the total number of required tests,

by integrating computational fluid dynamics (CFD) in the certification process.

- The objective of the present study is to
  - assess predictive abilities of available CFD solvers for smoke transport when applied to aircraft cargo compartments.
Methodology

- CFD solver candidates:
  - Commercial solvers:
    - Fluent, ...
  - Open source solvers:
    - FAA Smoke Transport Code
    - Fire Dynamics Simulator (FDS)
    - Code-Saturne
    - Jasmine
    - Sophie
    - FireFOAM-OpenFOAM
    - ...

- Our criteria:
  - Reliable
  - Accessible
  - Robust
  - Fast turnaround time
  - User-friendly (pre/post-processing, installation, maintenance)
  - Free or available at a small cost
  - Inexpensive to use/maintain
  - Gradual learning curve
Methodology

• **Fire Dynamics Simulator (FDS)** developed at National Institute of Standards and Technology (NIST),
  
  • solves Navier-Stokes equations for low Mach number thermally-driven flow, specifically targeting smoke and heat transport from fires,
  
  • has a companion visualization program Smokeview (SMV),
  
  • has been verified/validated for a number of fire scenarios.

• **Validation**
  
  • FDS will be validated for three fire scenarios in an empty compartment: baseline, attached-sidewall, attached-corner.
  
  • Results will be compared with the full-scale FAA test measurements on two types of aircraft cargo compartments: Boeing-707, DC-10.
Methodology

- Type of Aircraft: Boeing-707
- narrow-body
- no ventilation
- negligible leakage

Ground test measurements: 15 tests with
- 40 thermocouples
- 6 smoke meters
- 3 gas analyzers

Three test cases (fire scenarios):
- **Test case 1**: Base fire
- **Test case 2**: Corner fire
- **Test case 3**: Side fire

Methodology

- **Type of Aircraft: McDonnell Douglas DC10**

**Ground test measurements:** 15 tests with
- 45 thermocouples
- 4 smoke meters
- 3 gas analyzers

**Methodology**

- A compressed plastic resin block was used as a **fire source***
  
  - When burned it yields combustion products similar to actual luggage fires,
  
  - It had imbedded nichrome wire to enable remote ignition,
  
  - Its burning was well-characterized with a set of cone calorimetry tests (heat release rate, mass loss rate, production rates of CO₂, CO, and soot were measured).

Methodology

• **Validation Metrics**
  - In the first three minutes of fire initiation compare
    - Ceiling temperature rise
    - Light transmission change,
    - Gas concentration rise.

\[ LT = \exp(-K_m \sum_{i=1}^{N} \rho_{soot,i} \Delta x_i / L) \times 100 \% \]

Table: Summary of experimental data

<table>
<thead>
<tr>
<th>Compartment type</th>
<th>Fire scenario</th>
<th>Total number of tests</th>
<th>Measurement type</th>
<th>Total number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>B707</td>
<td>Baseline</td>
<td>15</td>
<td>Ceiling Temperatures</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Side Corner</td>
<td>3</td>
<td>CO, CO₂ concentrations (5+5+5)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Smoke concentrations</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperatures in the vertical</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heat flux</td>
<td>2</td>
</tr>
<tr>
<td>DC10</td>
<td>Baseline</td>
<td>15</td>
<td>Ceiling Temperatures</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO, CO₂ concentrations (5+5+5)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Smoke concentrations</td>
<td>4</td>
</tr>
</tbody>
</table>

Model set-up

Model parameters:

- Fire source: flaming resin block,
- Ventilation
  - None for B707,
  - Forced ventilation with 400 CFM total volumetric flow rate for DC10,
- Radiation modeling, radiative fraction: 0.55,
- Turbulence modeling: dynamic-coefficient Smagorinsky,
- Scalar transport using Superbee flux limiter,
- Reaction defined
  - using heat of combustion calculated from the cone calorimetry data (MLR and HRR),
  - by simple chemistry from the measured species yields obtained from the cone calorimeter (CO, CO$_2$, soot),
- Extinction coefficient = 7600 m$^2$/kg.
Model set-up

Geometry, grid and materials: B707

- Rectilinear grids, single-domain solution,
- Non-uniform grid chosen according to characteristic fire diameter:
  \[ D^* = \left( \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \]
- Using \( D^*/\Delta x=5 \), 3.2x6.7x1.4 m\(^3\) volume represented by 132x144x72 grid points,
- Recessed areas are included in the flow domain,
- Wall material (cargo liner) is tested and have the following property set:
  \[ \rho = 1694 \text{ kg/m}^3, \quad c_p = 1000 \text{ J/kgK}, \quad k = 0.25 \text{ W/mK}. \]
Geometry, grid and materials: DC10

- 114x216x81 grid points are used to represent 5.2x14.0x1.8 m³ volume,
- Forced ventilation with an inflow velocity of 4.6 m/s is specified at each air inlets (total volume flux is 400 CFM),
- Leakage area is determined so as to avoid pressure build-up in the compartment,
- Wall material (galvanized steel) is assumed to have following property set:

\[ \rho = 7850 \text{ kg/m}^3, \quad c_p = 460 \text{ J/kgK}, \quad k = 46 \text{ W/mK}. \]
Results

Grid Sensitivity Analysis:

B707 Baseline Fire – Grid Resolutions

<table>
<thead>
<tr>
<th>Levels</th>
<th>N_x x N_y x N_z</th>
<th>Δx_{min} (m)</th>
<th>N_{total} (million)</th>
<th>D^*/Δx_{min}</th>
<th>Time# (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL1</td>
<td>75x100x36</td>
<td>0.042</td>
<td>~0.3</td>
<td>~2.0</td>
<td>~3</td>
</tr>
<tr>
<td>GL2</td>
<td>132x144x68</td>
<td>0.022</td>
<td>~1.4</td>
<td>~5.0</td>
<td>~40</td>
</tr>
<tr>
<td>GL3</td>
<td>164x180x135</td>
<td>0.011</td>
<td>~4.0</td>
<td>~10.0</td>
<td>~203</td>
</tr>
</tbody>
</table>

DC10 Baseline Fire – Grid Resolutions

<table>
<thead>
<tr>
<th>Levels</th>
<th>N_x x N_y x N_z</th>
<th>Δx_{min} (m)</th>
<th>N_{total} (million)</th>
<th>D^*/Δx_{min}</th>
<th>Time# (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL1</td>
<td>54x108x20</td>
<td>0.088</td>
<td>~0.2</td>
<td>~1.3</td>
<td>~5</td>
</tr>
<tr>
<td>GL2</td>
<td>80x150x40</td>
<td>0.044</td>
<td>~0.5</td>
<td>~2.5</td>
<td>~21</td>
</tr>
<tr>
<td>GL3</td>
<td>114x216x81</td>
<td>0.022</td>
<td>~2.0</td>
<td>~5.0</td>
<td>~234</td>
</tr>
</tbody>
</table>

#OpenMP-runs using 6 processors on 2x2.93 GHz 6-Core Intel Xeon with 16GB memory.
Results

Grid Sensitivity Analysis:
- Only the flow field where gradients are expected are further resolved,
- The flow quantities of interest (selected temperatures and species concentrations) are examined,
- For grid convergence $D^*/\Delta x$ must be at least 5,
- DC10 test case is computationally more expensive as it has
  - a larger flow domain (i.e., more number of grid points are required),
  - and additional time-step constraints due to forced ventilation.
Results

Test case 1: B707 Baseline fire:

- Ceiling temperatures are slightly over-predicted, particularly away from the fire source,
- Temperatures in the vertical are high in comparison to the test data,
Test case 1: B707 Baseline fire:

- Model predictions for smoke and CO\textsubscript{2} concentrations are good,
- However, CO concentrations are highly overestimated.
Results

Test case 2: B707 Corner fire:

For Corner fire, similar to baseline fire

- Ceiling temperatures are slightly high compared to test data,
- \( \text{CO}_2 \) concentrations and light transmissions are reasonably well predicted,
- but \( \text{CO} \) concentrations and temperatures in the vertical are much higher in comparison to test data.
Results

Test case 3: B707 Side fire:

For Side fire, similar to baseline fire

- Ceiling temperatures are slightly high compared to test data,
- CO\(_2\) concentrations and light transmissions are reasonably well predicted,
- but CO concentrations and temperatures in the vertical are much higher in comparison to test data.
Results

Test case 4: DC10 Baseline fire:

For DC10 basefire, similar to B707 cases

- Ceiling temperatures are 2 degrees higher,
- CO\(_2\) concentrations and light transmissions are reasonably well predicted,
- but CO concentrations are over-predicted in comparison to test data.
Conclusions

- For **all** four test cases model solutions are
  - in good agreement with the test data for light transmissions and CO$_2$ concentrations,
  - slightly high for ceiling temperatures but still within reported experimental uncertainty,
  - much higher for temperatures in the vertical, and CO concentrations.
### Future Work

- Results will be documented in a technical note.