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
  – Allow for improved detector alarm algorithms, thereby the reliability of the smoke detectors,
  – 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),
  • have 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

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

Fire source: Compressed plastic resin block
  • when burned yielding combustion products similar to actual luggage fires,
  • with imbedded nichrome wire to enable remote ignition,
  • with cone calorimetry test data (HRR, MLR, CO₂, CO, and soot).
## Methodology

### Validation Metrics

**A. Thermocouple temperature rise**
- from 0 to 60 seconds
- from 0 to 120 seconds
- from 0 to 180 seconds

**B. Light transmission**
- at 30 and 50 seconds (ceiling and vertical)
- at 60, 120 and 180 seconds (vertical – high, mid and low)

**C. Gas species concentration rise**
- at 60, 120 and 180 seconds
Methodology

Model set-up

Geometry, grid and materials:
- Rectilinear grids, single-domain solution
- Recessed areas are included in the flow domain
- Grid dimensions: 36x72x36 for 3.6x7.3x1.7m, maximum grid size = 0.1m, chosen according to

\[ D^* = \left( \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \]

where \( D^* \) is the characteristics fire diameter.
- Fiberglass epoxy resin:
  properties of woven glass with 30% vinyl ester

\[ \rho = 1683 \text{ kg/m}^3, \quad c_p = 1200 \text{ J/kgK}, \quad k = 0.3 \text{ W/mK} \]

§ "Measuring properties for Material Decomposition Modeling", C. Cain and B. Lattimer
Methodology

- **Model set-up**
  
  Model parameters:
  
  - Fire source: flaming resin block, no ventilation,
  - Radiation modeling, radiative fraction: 0.40,
  - Turbulence modeling: dynamic Smagorinsky,
  - Scalar transport using Superbee flux limiter.

  Reaction with a made up fuel using known yields of soot, CO, and CO₂.
  Heat of combustion = 21000 kJ/kg from known cone calorimetry data (MLR and HRR).
  Extinction coefficient = 8700 m²/kg (FDS default).
Results

B707 Baseline Fire

- Cone calorimetry data for mass loss rate (MLR) is used to represent the fire source in the model.
- Calculated heat release rate (HRR) is in agreement with the experimental data.
- Energy Budget shows the contribution of radiative and conductive heat losses.
Results

B707 Baseline Fire

A. Temperature comparisons

- Experimental uncertainty is \(~6 \, ^\circ\text{C}\) close to the fire source, and \(~2 \, ^\circ\text{C}\) away from the fire source.
- Temperature predictions are higher than the experimental mean but still within the experimental uncertainty.
- The difference between model estimates and measurements increases in time.
Results

B707 Baseline Fire

A. Temperature comparisons

- The difference between model estimates and measurements is the same everywhere (~3 °C).

![Measurements](image1)

![Model](image2)
Results

B707 Baseline Fire

B. Light transmission

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

- Light transmissions are predicted within 5% of measurements for the first 60 seconds of fire initiation.
- There is less smoke in the model (at Fwd, Mid and Aft smoke meter regions).
Results

B707 Baseline Fire

B. Light transmission

- Model predicts 5% less smoke at Fwd, Mid, Aft smoke meter regions at 120 and 180 seconds.

- Model vertical smoke meters at low and mid stations show 20% more smoke compared to the experiments.
Results

B707 Baseline Fire

B. Light transmission

- Vertical distribution of smoke is not in agreement with the experimental data.
- Ceiling smoke distribution is within 5% of the experiments.
**Results**

**B707 Baseline Fire**

**C. Gas Species concentration**

Both CO and CO$_2$ concentrations are low at $t=60$ s except for TC36, and increase to experimental values at $t=120, 180$ s.

![Graphs showing CO and CO$_2$ concentration over time for different gas probe numbers](image)
Results

B707 Baseline Fire

C. CO concentration
- The time lag for CO concentration at TC36 is almost 20 seconds.
Results

B707 Baseline Fire

C. CO$_2$ concentration

- Model data has a more gradual increase in the first 60 seconds.

![Chart showing CO$_2$ concentration over time for measurements and model data]
Conclusions

• Our preliminary results show:
  
  – **Temperature**
    • Temperatures are predicted within experimental uncertainty, however, heat losses must be examined further.
  
  – **Smoke**
    • Light transmissions are predicted within 5% close to the ceiling but 20% off in the lower regions and agreement deteriorates in time.
  
  – **Gas concentrations**
    • CO and CO\textsubscript{2} concentrations are predicted within experimental uncertainty, however, mass checks show added CO\textsubscript{2} to be well above that of the experiment.
Future Work

• Further examination and in-depth analysis is required,
  – check for energy and mass conservation, use of more accurate material properties.
• Model parameters must be examined
  – for radiation and turbulence modeling.
• Numerical error analysis must be done.
• If B707 baseline fire scenario is found to be successful,
  – Continue code validation for other B707 scenarios: attached-corner and attached-sidewall cases, and for DC 10 cargo compartment with all three fire scenarios.