Modeling and Analysis of Realistic Fire Scenarios in Spacecraft

NASA John H. Glenn Research Center

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Introduction

- Fire is a significant hazard to both crew and vehicle on exploration missions
- On long-duration missions abandoning the vehicle and a rapid return to earth are not possible
- Fire requires fuel, oxidizer and an ignition source
  - All three present by necessity on manned spacecraft
- Large-scale fires are very complex:
  - Turbulent, chemically reacting flow
  - Complex chemical kinetics involving large hydrocarbon molecules, solid and gas phases and chlorinated or fluorinated species
Uniqueness of Microgravity

- Flame characteristics and flammability limits change
  - Low-speed, sub-buoyant flows
  - Normal gravity testing not necessarily worst-case

- Particulate size and transport changes
  - Terrestrial standards for detection not necessarily applicable

- Small, sealed, confined volume with limited egress

- Terrestrial large-scale fire models and experiments are of limited utility
  - Upcoming Saffire experiments are largest to date in microgravity

- Must rely on numerical models validated and calibrated against the very limited experimental data
Overall FPDS Approach

Develop a comprehensive modeling capability

1. Large Eddy Simulation (LES) CFD models:
   - Builds off of efforts to model ISS fire detection
   - Detailed treatment of flow inside the vehicle
   - Computationally intensive for realistic spacecraft configurations involving chemically reacting flows

2. Lumped Capacity Models (LCM):
   - Builds off of efforts to estimate survivable fires for spacecraft
   - Not as detailed as LES, but more amenable to parametric studies
Lumped Capacity Models (LCM)

- Treat the spacecraft volume as a single ‘zone’
  - Can be extended to multiple zones
- Assume each zone has a uniform temperature and species concentration
- Solve for energy and species conservation in each zone with a prescribed fire

\[
\left( \frac{dQ}{dt} \right)_{\text{loss}} + \left( \frac{dQ}{dt} \right)_{\text{fire}} + \left[ \sum_i \dot{n}_i h_i - \sum_e \dot{\bar{n}}_e h_e \right] = \frac{dU_{cv}}{dt}
\]

\[
\frac{dn_i}{dt} = (n_i)_{\text{gen}} - (n_i)_{\text{con}}
\]

- Creates a system of ODEs quickly solved by a range of open-source and commercial solvers
Base Case Comparison

- Empty, sealed cubic volume 3 \( m \) on a side
- Prescribed heat input
  1. Adiabatic wall
     - All energy transferred to gas
  2. Isothermal wall
     - Heat transfer to the wall

\[ \alpha t^2 \text{ growth first 34 s (} \alpha = 5.1 \times 10^{-3} \text{ kW/s}^2) \]
\[ \text{Constant fire for next 126 s} \]
\[ \text{Linear decay to 0 for 10 s} \]
\[ \text{Approximates expected profile from Saffire I} \]
Base Case – Adiabatic Walls

![Graph showing the relationship between pressure, temperature, and time in an adiabatic case. The graph compares LCM and FDS results with pressure and temperature data points marked over time.](image)
Base Case – Isothermal Wall

![Graph showing pressure and temperature over time](image)

- Pressure (atm)
- Time (sec)
- Average Gas Temperature (K)

Legend:
- LCM
- FDS
- Pressure
- Temperature

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Saffire experiment will be conducted in Orbital Cygnus Pressurized Cargo Module after de-mating from ISS (still in LEO)

- Use FDS to simulate the flow and heat transfer in the PCM while the large fuel sample is burned in Saffire

<table>
<thead>
<tr>
<th>Initial Conditions</th>
<th>Simulation Conditions</th>
<th>FDS Parameters</th>
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</thead>
<tbody>
<tr>
<td>20 C</td>
<td>Isothermal Shell 20 C</td>
<td>Radiative Frac = 0</td>
</tr>
<tr>
<td>1.0 atm</td>
<td>Adiabatic Solid Objects</td>
<td>Suppression OFF</td>
</tr>
<tr>
<td>Air (0.21/0.79)</td>
<td>Heat Release at 30 s</td>
<td>Radiation OFF</td>
</tr>
<tr>
<td></td>
<td>Fuel Mass = 0.0541 kg</td>
<td>Stratification OFF</td>
</tr>
<tr>
<td></td>
<td>Saff. Flow = 0.104 m³/s</td>
<td>Gravity OFF</td>
</tr>
<tr>
<td></td>
<td>ECLSS = 0.0524 m³/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas Vol. = 10.6 m³</td>
<td></td>
</tr>
</tbody>
</table>

- Observe flow and heat transfer in realistic Saffire/PCM configuration
FDS Configuration - Saffire

Saffire Experiment (cargo pallet not shown)

CAD Shell (partial shown)

Disposal Cargo (FWD-PORT standoff) BC: adiabatic surface

CAD Cargo Pallet (FWD Bay 1) BC: adiabatic surface

Environmental Control and Life Support System (ECLSS) BC: adiabatic surface

+Z (FWD) -Y (PORT) O (NADIR) X (ZENITH) +Y (STBD) -Z (AFT)
FDS Saffire Computation Results

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MPCV Hatch Re-Design Study

- MPCV considered hatch re-design to save weight
- Needed to understand how accidental fire (launchpad) would impact crew/vehicle
- Assess the efficacy of the Cabin Pressure Equalization Valve (CPE)
- Perform parametric studies for different fire scenarios, CPE actuation, vehicle interiors.
MPCV Parametric Study

Pressure Temperature
- Valve Open at 30.0 sec
- Valve Open at 60.0 sec
- Valve Open at 120.0 sec
- No CPE valve open

MPCV Volume = 18.4 m$^3$
MPCV Surface Area = 23.5 m$^2$
Fire Growth Coefficient = 0.0586 kW/sec$^2$
Fire Growth Time = 30.0 sec
Fire Constant Time = 130.0 sec
Fire Decay Time = 15.0 sec
Total Fuel Consumed = 0.501 kg

Average Cabin Temperature (K)
450
400
350
300
250
200
150
100
50
0

Cabin Pressure (atm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0

Time after fire start (sec)
300 sec
250 sec
200 sec
150 sec
100 sec
50 sec
0 sec

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Discussion

- FDS can perform high-fidelity simulations of flows inside spacecraft with fires/heat release.
  - Can show localized results for combustion product accumulation, oxygen depletion, etc.
  - Simulations can take days for long simulation times and/or complex geometries for a single configuration (vehicle interior and flow condition)

- LCM more amenable to large-scale parametric studies
  - Can easily run hundreds of simulations over wide-ranging conditions such as vehicle volumes, fire sizes, relief valve sizes, etc.
  - Lack the localized fidelity present in LES

- Use FDS to calibrate or tune the parameters in the LCM for better fidelity

- Currently both models use a prescribed fire. Eventually need models to make \textit{a-priori} predictions of fire based on vehicle interior contents

- Models can be extended to include ECLSS scrubbing and flows
Conclusions

♦ FPDS pursuing two model approaches to fire in spacecraft
  • CFD simulations using FDS build on efforts to model fire detection in ISS.
  • LCM models treat spacecraft as a single volume and build off of efforts to define and predict a survivable fire in a spacecraft

♦ The complexity of real fires necessitate this approach
  • CFD provides detailed predictions in realistic geometries but requires large computational time – not amenable to parametric studies
  • LCM models suited for parametric studies and engineering evaluation of evolving spacecraft designs

♦ Demonstrated compatibility of model approaches in simple configuration and capability of both models
  • Used FDS to simulate flows inside of Orbital Cygnus during Saffire
  • Used LCM to assist in the evaluation of hatch re-design in the MPCV

♦ FPDS will continue to develop both model approaches
  • Incorporate detection into both models
  • Develop the capability to make a priori predictions of fire