Modeling and Analysis of Realistic Fire Scenarios in Spacecraft

NASA John H. Glenn Research Center

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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
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

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

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

- 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

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

![Graph showing pressure and temperature over time for LCM and FDS models.](image-url)
Base Case – Isothermal Wall
Detailed Computation - Saffire

- 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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<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>
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<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>
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<tr>
<td></td>
<td>Saff. Flow = 0.104 m³/s</td>
<td>Gravity OFF</td>
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<tr>
<td></td>
<td>ECLSS = 0.0524 m³/s</td>
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<tr>
<td></td>
<td>Gas Vol. = 10.6 m³</td>
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</tbody>
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- 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

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FDS Saffire Computation Results

![Graph showing pressure and temperature over time with legends for Pressure, Average Temperature, Avionics Inlet Temperature, and ECLSS Inlet Temperature.]
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
- - Valves open at 30.0 sec
- - Valves open at 60.0 sec
- - Valves open at 120.0 sec
- - No CPE valve open

- MPCV Volume = 18.4 m³
- MPCV Surface Area = 23.5 m²
- Fire Growth Coefficient = 0.0586 kW/sec²
- Fire Growth Time = 30.0 sec
- Fire Constant Time = 130.0 sec
- Fire Decay Time = 15.0 sec
- Total Fuel Consumed = 0.501 kg
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