Virtual Fires via Computers

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Introduction

- Fire Statistics
- Rational Analysis and Fire Prediction Tools
  - Algebraic equations
  - Scale or Physical Modeling
  - Network Modeling for Pressurized Systems
  - CFAST (Consolidated Model of Fire Growth and Smoke Transport)
  - FDS (Fire Dynamic Simulator)
- Example calculation
Costs of Fire to the USA

- America's fire death rate is one of the highest per capita in the industrialized world.
- Fire kills over 4,000 and injures more than 23,000 people each year.
- Firefighters pay a high price for this terrible fire record as well; approximately 100 firefighters die in the line of duty each year.
- Direct property losses due to fire exceed $13 billion a year.
- Most of these deaths and losses can be prevented!
Rational Analysis

- 2006 IBC code requires consideration of specific effects on smoke control operation
  - Stack or buoyancy effects
  - Characteristics of design fire
  - Wind effects
  - HVAC system
  - Climate
  - Room to room and floor to floor variations
  - Elevator and stairwell effects
  - System activation sequence
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC

\[ \frac{z}{H} = 0.67 - 0.28 \ln \left( \frac{tQ^{1/3}}{H^{4/3}} \frac{A}{H^2} \right) \]
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling

NIST 4-story stairway fire model

Before fire

During fire
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM

Vents
Windows
Doors
Rooms
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM
- Zone Models
  - CFAST
Why CFAST?

- Program specifically designed for unsteady fire simulation in compartments.
- Program designed for fast execution.
How did they do it?

- Focus on the simplicity of the problem,
- Extensively use experimental data, and
- Focus on solving sets of ordinary differential equations (ODE).
Recognize simplicity of problem

- Divide flow regime into distinct zones (2 to 4),
- Assume flow within zones are well mixed,
- Replace complex processes with empirical algorithms.

![Diagram showing flow regimes and zones](image)
Typical Building Geometry

Room 1
(3 m x 4 m x 2.4 m)

Room 2
(3 m x 40 m x 2.4 m)

Room 3
(3 m x 4 m x 2.4 m)

Room 4
(3 m x 4 m x 2.4 m)

All doorways 1 m wide x 2 m high
All surfaces gypsum

Vertical flow vent
1 m diameter
Simplify physical processes

- Assume few zones per compartment is adequate to model physical situation,
- Solve for conservation of mass and energy over zone,
- Momentum equation only solved through Bernoulli equation for vent flows.
  - This eliminates acoustic waves and gravity waves.
Focus on very fast numerical solvers

- Equations formed by integrating conservation expressions over volume of zone, resulting in ODE,
- Solve sets of coupled ODE, no finite difference expressions,
- Use algebraic algorithms to describe fire processes,
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM
- Zone Models
  - CFAST
- CFD Models
  - FDS
Why FDS?

- Program specifically designed for unsteady fire simulation.
- Program designed for fast execution.
How did they do it?

- Recognize the complexity of the problem,
- Simplify physical processes, and
- Focus on very fast numerical solvers.
Recognize complexity of problem

- Bluff body aerodynamics,
- Multi-phase flow, (liquid or solid fuels, gaseous products)
- Turbulent mixing and combustion,
  - Ignition,
  - Pyrolysis,
  - Homogeneous and heterogeneous combustion possibilities,
- Radiative heat transfer, and
- Conjugate heat transfer (conduction & convection together).
Simplify physical processes

- Use LES (Large Eddy Simulation) approximation for turbulence,
- Use "low-Mach number" combustion equations,
- Divide continuum of physical space where fire flow occurs into a finite number of rectangular cells, inside of which all flow properties are uniform and change only with time, and
- Approximate complicated processes with "adequate" algorithms.
Focus on very fast numerical solvers

- Use a one step non-iterative method to invert Poisson equation associated with fluid pressures, which requires that one
- Limit grids to rectangular cells and rectangular grids.
CFAST vs FDS Comparison

- NUREG-1824 (2006), Vol. 1, 4, & 6
- Criterion 1 – Are the physics of the model appropriate for the calculation being made?
- Criterion 2 – Are there calculated relative differences outside the experimental uncertainty?
- Color Code for Criteria

**Green**: Both criteria are satisfied, model can be used with confidence

**Yellow**: 1st criterion is satisfied, but differences are outside experimental uncertainty with no pattern of over- or under-prediction.

**Red**: 1st criterion is not satisfied.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CFAST</th>
<th>FDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot gas layer temperature (&quot;Upper Layer Temperature&quot;)</td>
<td>Room of origin</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>Adjacent room</td>
<td>Yellow ±30%</td>
</tr>
<tr>
<td>Hot gas layer height (&quot;Layer interface height&quot;)</td>
<td></td>
<td>Green</td>
</tr>
<tr>
<td>Ceiling jet temperature (&quot;Target/Gas temperature&quot;)</td>
<td>Yellow -16 to +100%</td>
<td>Yellow ±20%</td>
</tr>
<tr>
<td>Plume temperature</td>
<td>Not calculated</td>
<td>Green</td>
</tr>
<tr>
<td>Flame Height</td>
<td>Green</td>
<td>Yellow 1</td>
</tr>
<tr>
<td>Oxygen concentration</td>
<td>Yellow ±20%</td>
<td>Yellow ±20%</td>
</tr>
<tr>
<td>Smoke Concentration</td>
<td>Yellow-35 to +450%</td>
<td>Yellow -33 to +400%</td>
</tr>
<tr>
<td>Room pressure</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Target temperature</td>
<td>Yellow ±50%</td>
<td>Yellow ±30%</td>
</tr>
<tr>
<td>Radiant heat flux</td>
<td>Yellow-50 to +150%</td>
<td>Yellow ±50%</td>
</tr>
<tr>
<td>Total heat flux</td>
<td>Yellow -90 to +70%</td>
<td>Yellow ±30%</td>
</tr>
<tr>
<td>Wall temperature</td>
<td>Yellow ±60%</td>
<td>Yellow ±50%</td>
</tr>
<tr>
<td>Total heat flux to walls</td>
<td>Yellow -70 to +90%</td>
<td>Yellow ±30%</td>
</tr>
</tbody>
</table>
Fire Management Methods

- Conventional wisdom uses sprinklers to suppress smoke and fire,
- Revised goal: maintain a lower “smoke free layer” for evacuation
- Smoke management used in atria
  - Smoke filling.....let it burn and smoke rise
  - Gravity venting...let buoyancy remove smoke through vents
  - Smoke exhaust...use fans to exhaust smoke
Fill, Natural Vent, Exhaust

No Smoke Control
Smoke Filling

Natural Venting = Gravity Venting

Forced Venting = Smoke Exhaust
CFD & CFAST Simulation of a Three Story Building
Test Building Configuration
Design Fire: Upholstered Chair

Heating Release Rate, HRR (kW)

Time (sec)
Including Wind Field Results in CFAST

- User specifies wind speed and direction for CFAST at openings to calculate exterior pressures.
- These are used with empirical pressure coefficients to adjust inflow and exhaust rates through windows, doors, and vents.

\[ Q = C_D C_V A \sqrt{\frac{\Delta p}{2\rho}} \]

- \( C_D \) = opening discharge coefficient
- \( C_V \) = Wind pressure and direction correction
  - 0.5 - 0.6 for perpendicular winds, and
  - 0.25 - 0.35 for oblique winds
Including Wind Field Results in FDS

- FDS calculates explicitly the exterior flow fields, associated secondary flows and pressure fields.
- Interior flows are directly coupled to exterior through openings.

\[ U = 11.2 \text{ m/s} @ 10 \text{ m} \]
\[ n = 0.12 \]
FDS Calculated Pressure Fields
Temperature Fields CFAST

No Fire

Fire Main Level

Fire 2nd Level

Fire 3rd Level
Velocity & Temperature Fields FDS
Obscuration vs Visibility

Graph showing the relationship between Obscuration (%) and Visibility (ft).

At 30' of visibility, the graph indicates a 95% obscuration.
Visibility (S vs $T_{\text{smoke}}$)

- Visibility is a function of smoke particle loading
- Particle density can be related to mass and type of fuel, HRR
- Typical criteria is visibility $S > 25$ ft (7.6 m) the min distance to see a reflective unlit sign

<table>
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<tr>
<th>Material</th>
<th>Obscuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic</td>
<td>7.6</td>
</tr>
<tr>
<td>Poly Foam</td>
<td>9.4</td>
</tr>
<tr>
<td>Silicone Rubber</td>
<td>9.4</td>
</tr>
<tr>
<td>Douglas Fir</td>
<td>7.6</td>
</tr>
</tbody>
</table>

![Graph showing Visibility (S vs $T_{\text{smoke}}$) for different materials](image)
ULT, LLT & SLH on 1st floor

Level 1

Temperature in °C

CFAST Summer  |  CFAST Winter  |  CFAST Summer West Wind  |  FDS Summer West Wind  |  FDS Summer No Detectors  |  FDS Summer Detectors Operating

Layer Height in meters

SLH Limit  |  ULT Limit

Legend:
- LLT
- ULT
- SLH
ULT, LLT, & SLH on 2\textsuperscript{nd}, 3\textsuperscript{rd} floor and stairs
Summary

- CFAST provides a fast screening model.
  - Flexibility and speed permits many alternative scenarios to be examined quickly.

- FDS produces detailed spatial information, but at a cost in time and computer resources.
  - Simulations follow fire development realistically and permit great visualization.
The End: Thank you for your attention
Il Fuoco: Fire

- Giuseppe Arcimboldo (1527-1593)
- Court painter to Hapsburg Emperor Rudolph II
- One of most bizarre and distinctive painters of art history producing composite heads of variety of objects, natural and man-made
Limitations of CFAST

- Requires an a priori specification of the temporal behavior of a fire;
- Limited by assumptions in the zone model formulation of the conservation equations;
- Limited to low-Mach number situations (i.e., no acoustic waves, detonations, explosions, etc.);
- Momentum is not explicitly considered in the conservation equations;
- Does not model all mitigative systems;
- It has limited chemical source term generation and transport capabilities;
- Does not output all important variables; and,
- Limited access to modeled variables.
Size Limitations CFAST

- Maximum simulation time (sec or hr) 86,400 or 24
- Maximum number of compartments 30
- Maximum number of fires in a single test case 31
- Maximum HRR (MW/m^3) 1
- Maximum number of thermal property definitions 125
- Maximum number of slabs in a wall 3
- Total number of ducts 60
- Total number of connections between rooms 62
- Ratio of area vents/room volume < (m^{-1}) 2
- Maximum number of mechanical driven vents 15
- Maximum number of targets 90
- Maximum number of data points in spread sheet 900
Limitations of FDS

- **Low-speed flow assumption** –
  - No sonic effects, no choking due to speed of sound limitations, no explosions, detonations, i.e.
  - Mach < 0.3.

- **Rectilinear Geometry** –
  - Fast, direct solver for pressure field REQUIRES rectilinear mesh,
  - NO exceptions.

- **Fire Growth and Spread** –
  - Model works best when HRR is specified and heat and exhaust products are calculated, T and V are then accurate to 10-20%.
  - If HRR is predicted then uncertainty in flow and transport is larger; because, a) properties of fuels are uncertain, and b) numerical methods are more sensitive to physical conditions.
Limitations of FDS (concld.)

- **Combustion** –
  - Mixture-fraction-based model assumes combustion is mixture controlled, and infinitely fast regardless of temperature. For well-ventilated fires this is a good assumption.
  - If fire is under-ventilated, CO₂ is introduced, or fuel and oxygen do not burn, then program uses empirical criteria to approximate suppressing effects which introduces greater uncertainty.

- **Radiation** –
  - Gray gas model does not allow for actual very complex interaction of radiation with composition and temperature.
  - Typically, only a finite number of angles are considered, which introduces errors for targets at large distances.
CFD as an Art

“Considering that application of CFD is an art and that the turbulence models are approximate, simulations need to (be) compared to experimental data. ... If a simulation is similar in most respects to others that have been experimentally verified, further experimental verification is not necessary.”

- John H. Klote (1994) NISTIR 5516, p. 84.
Sofa Burn
Video: Steve Kerber
Tree Fire
Video: William “Ruddy” Mell