Smoke transport in an aircraft cargo compartment

Ezgi Öztekin[*], Dave Blake[§] and Richard Lyon[§]

[*] Technology and Management International (TAMI), LLC

[§] Federal Aviation Administration (FAA) William J. Hughes Technical Center

International Aircraft Systems Fire Protection Working Group Meeting

22 - 23 May 2012

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
    - …

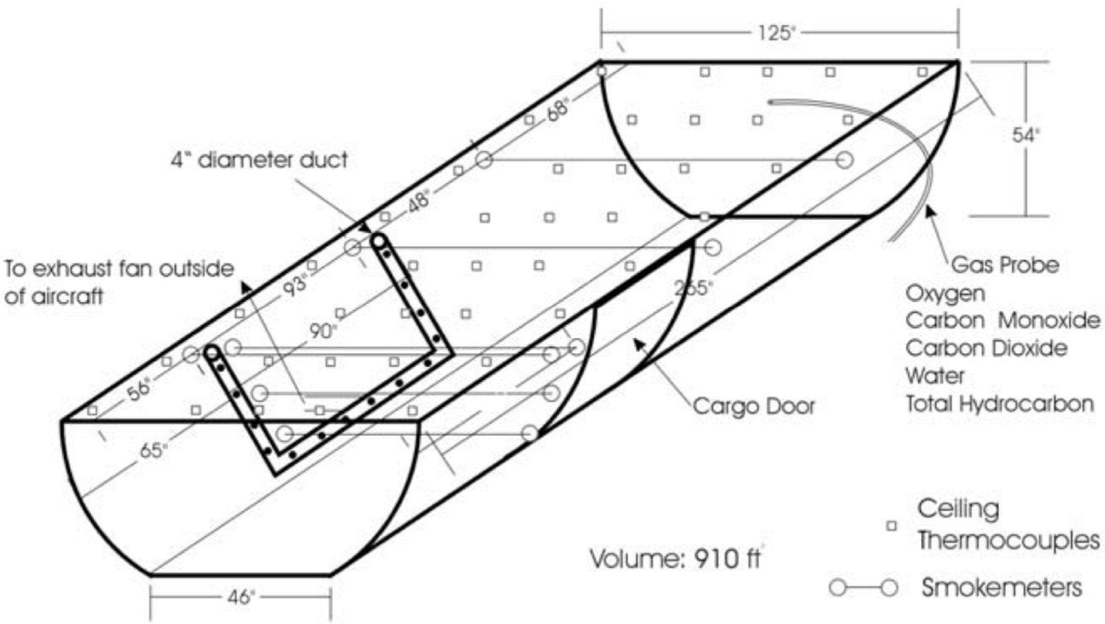
- Our criteria:
  - Reliable
  - Accessible
  - Robust
  - Fast turnaround time
  - User-friendly (pre/post–processing, installation, maintenance)
  - Free or available at a small cost
  - Inexpensive to use/maintain
  - Gradual learning curve

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.

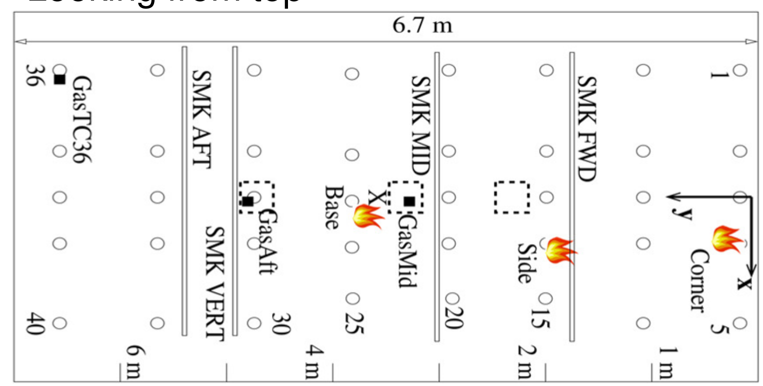
Methodology

- Type of Aircraft: Boeing-707



- narrow-body
- no ventilation
- negligible leakage

Looking from top



Ground test measurements: 15 tests with

- 40 thermocouples
- 6 smoke meters
- 3 gas analyzers

Three test cases (fire scenarios):

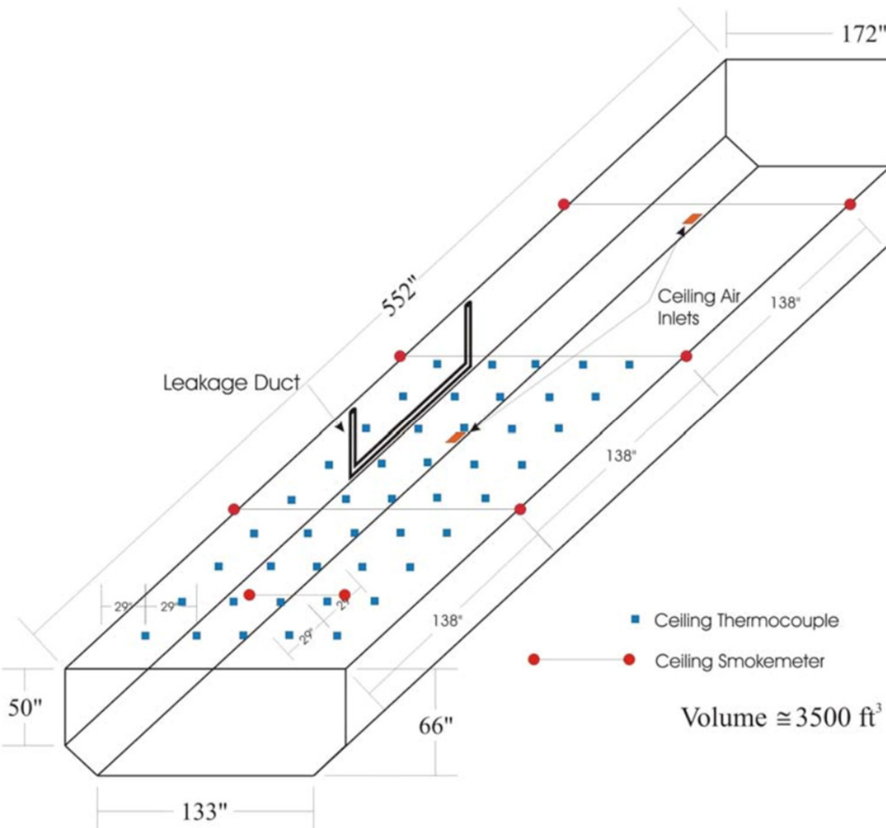
- **Test case 1:** Base fire
- **Test case 2:** Corner fire
- **Test case 3:** Side fire

* Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

Methodology

- Type of Aircraft: McDonnell Douglas DC10

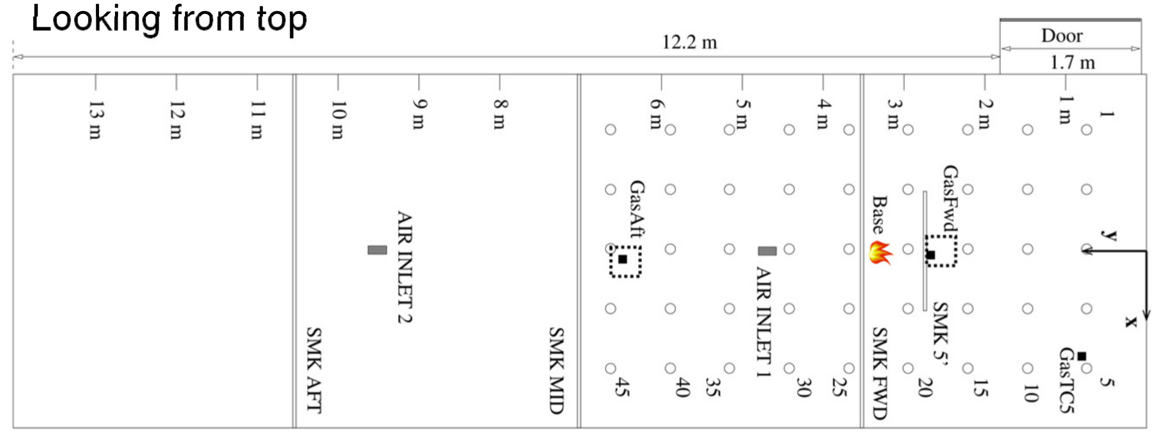
- wide-body
- forced ventilation
- leakage



Ground test measurements: 15 tests with

- 45 thermocouples
- 4 smoke meters
- 3 gas analyzers

Looking from top

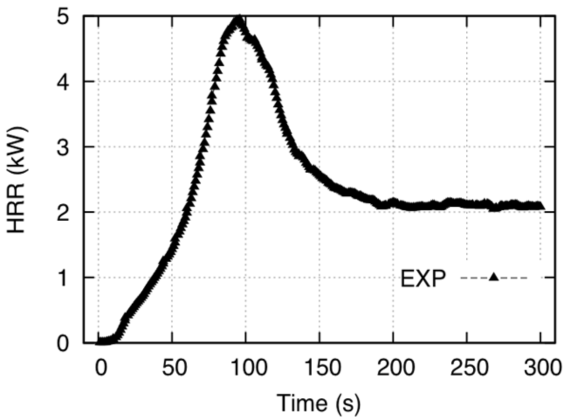


* Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

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 CO_2, CO, and soot were measured).



* Filipczak, R., Blake, D., Speitel, L., Lyon, R., and Suo-Anttila, J., Development and Testing of a Smoke Generation Source, Proceedings of the Fire and Materials Conference, San Francisco, California, 2001.

Methodology

- Validation Metrics*
  - In the first three minutes of fire initiation compare
    - Ceiling temperature rise
    - Light transmission change, $LT = exp(-K_m \sum_{i=1}^{N} \rho_{soot,i} \Delta x_i / L) \times 100\ (\%)$
    - Gas concentration rise.

Table: Summary of experimental data

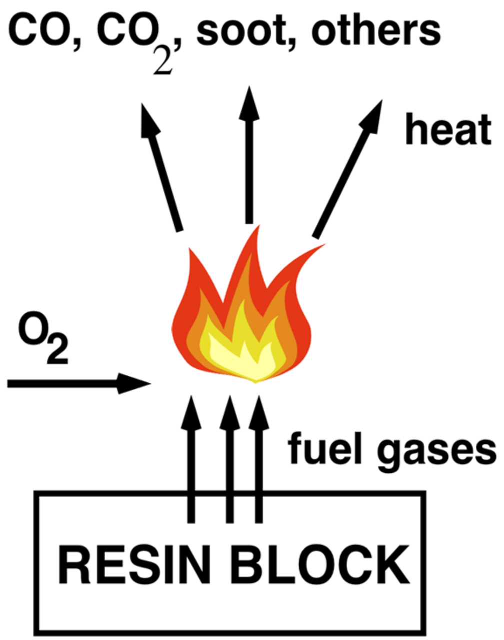
Compartment type	Fire scenario	Total number of tests	Measurement type	Total number of measurements
B707	Baseline Side Corner	15 3 3	Ceiling Temperatures CO, CO_2 concentrations (5+5+5) Smoke concentrations Temperatures in the vertical Heat flux	40 3 6 4 2
DC10	Baseline	15	Ceiling Temperatures CO, CO_2 concentrations (5+5+5) Smoke concentrations	45 3 4

* Suo-Anttila, J., Gill, W., Luketa-Hanlin, A., and Gallegos, C., Cargo Compartment Smoke Transport Computational Fluid Dynamics Code Validation, DOT/FAA/AR-07/27, Federal Aviation Administration, July 2007.

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.

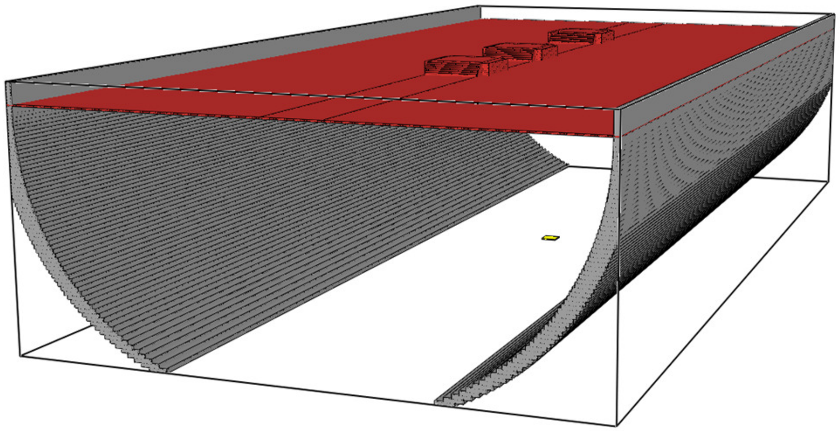


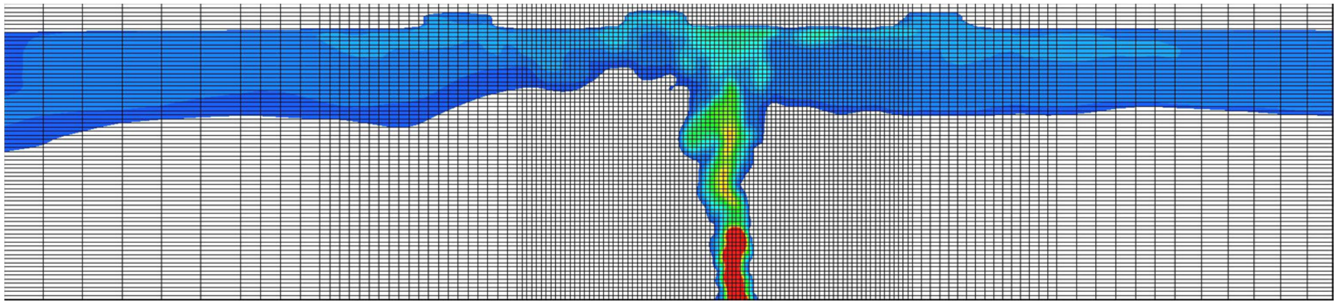
Model set-up

Geometry, grid and materials: B707

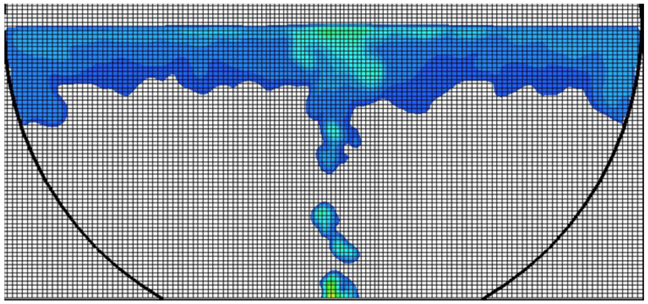
- Rectilinear grids, single-domain solution,
- Non-uniform grid chosen according to characteristic fire diameter: $D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$
- Using D*/Δx=5, 3.2x6.7x1.4 m^3 volume represented by 132x144x72 grid points,
- Recessed areas are included in the flow domain,
- Wall material (cargo liner) is tested and have the following property set:

$$\rho = 1694\ \mathrm{kg/m^3},\ c_p = 1000\ \mathrm{J/kgK},$$
$$k = 0.25\ \mathrm{W/mK}.$$





Looking from the side

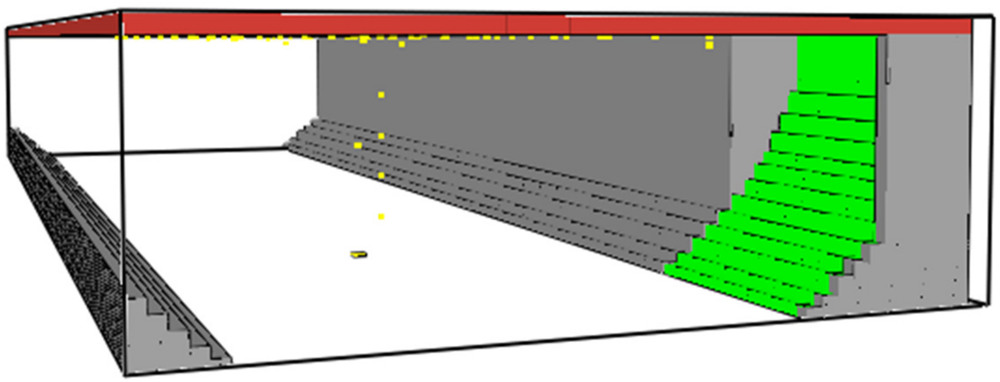


Looking from the front

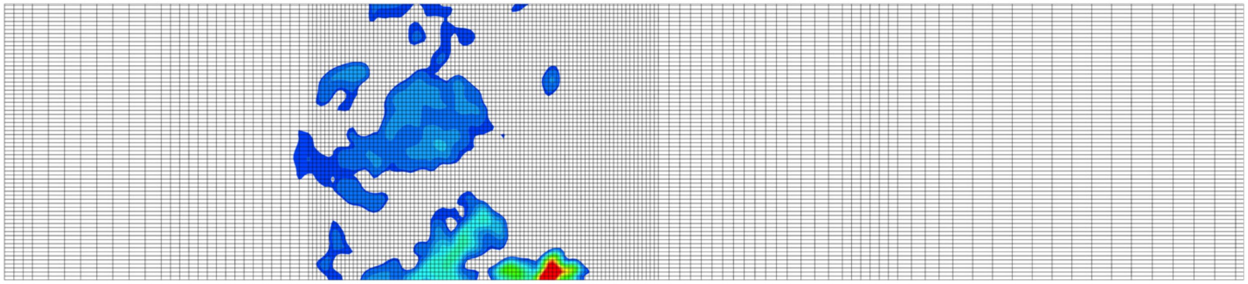
Model set-up

Geometry, grid and materials: DC10

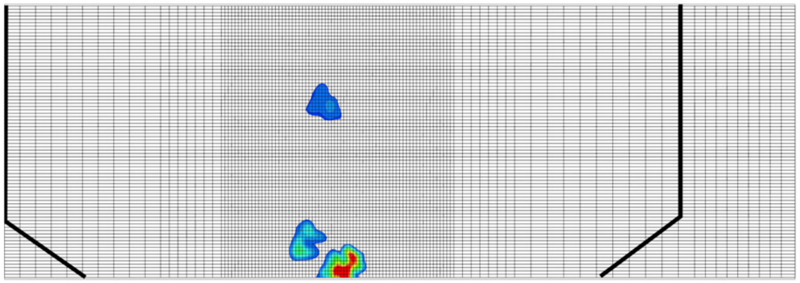
- 114x216x81 grid points are used to represent 5.2x14.0x1.8 m^3 volume,
- Forced ventilation with an inflow velocity of 4.6 m/s is specified at each air inlets (total volume flux is 400 CFM),
- Leakage area is determined so as to avoid pressure build-up in the compartment,
- Wall material (galvanized steel) is assumed to have following property set:



$$\rho = 7850 \text{ kg/m}^3, \; c_p = 460 \text{ J/kgK}, \; k = 46 \text{ W/mK}.$$



Looking from the side



Looking from the front

Results

Grid Sensitivity Analysis:

B707 Baseline Fire – Grid Resolutions

Levels	$N_x x N_y x N_z$	Δx_{min} (m)	N_{total} (million)	$D^*/\Delta x_{min}$	Time# (hrs)
GL1	75x100x36	0.042	~0.3	~2.0	~3
GL2	132x144x68	0.022	~1.4	~5.0	~40
GL3	164x180x135	0.011	~4.0	~10.0	~203

DC10 Baseline Fire – Grid Resolutions

Levels	$N_x x N_y x N_z$	Δx_{min} (m)	N_{total} (million)	$D^*/\Delta x_{min}$	Time# (hrs)
GL1	54x108x20	0.088	~0.2	~1.3	~5
GL2	80x150x40	0.044	~0.5	~2.5	~21
GL3	114x216x81	0.022	~2.0	~5.0	~234

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

Results

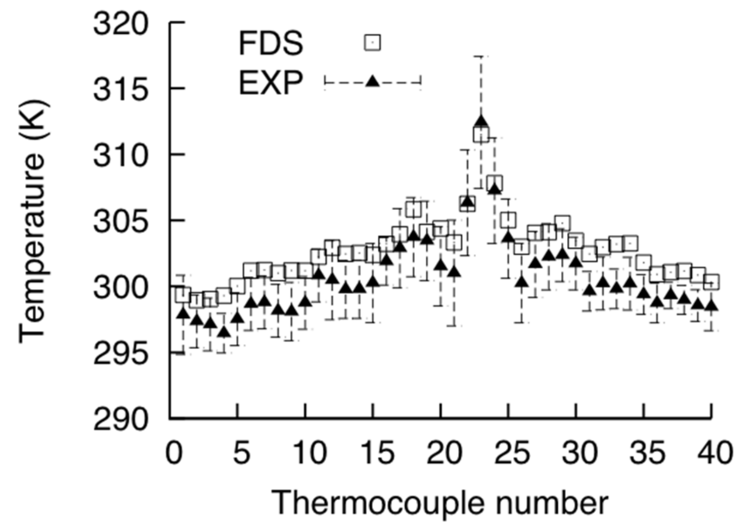
Grid Sensitivity Analysis:

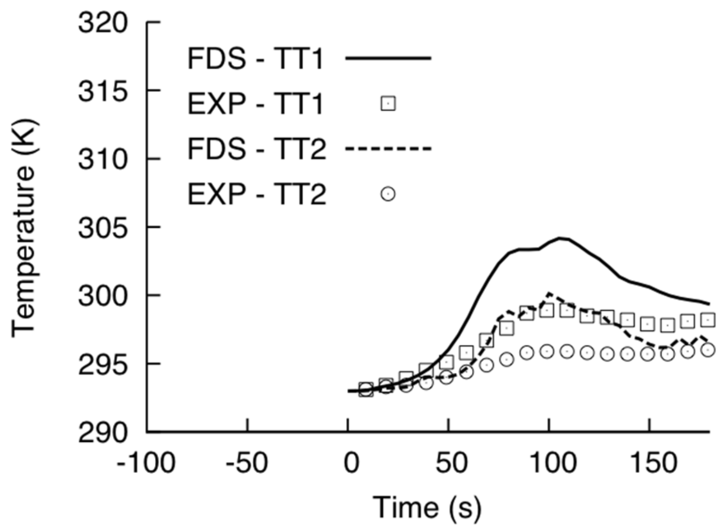
- Only the flow field where gradients are expected are further resolved,
- The flow quantities of interest (selected temperatures and species concentrations) are examined,
- For grid convergence $D^*/\Delta x$ must be at least 5,
- DC10 test case is computationally more expensive as it has
  - a larger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

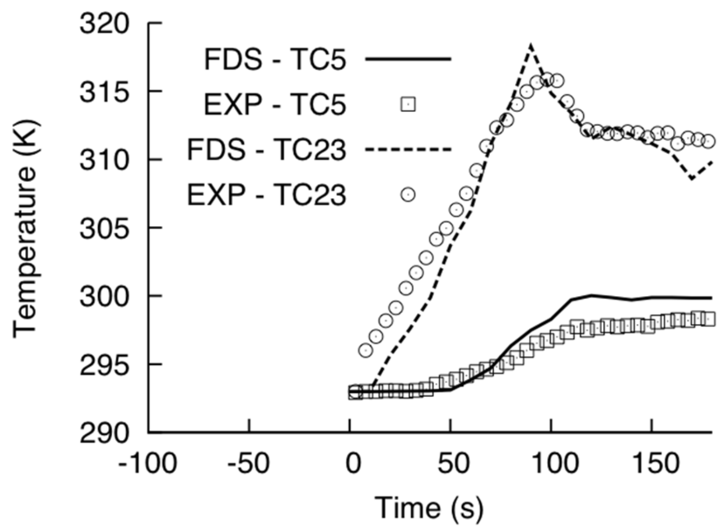
Results

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,



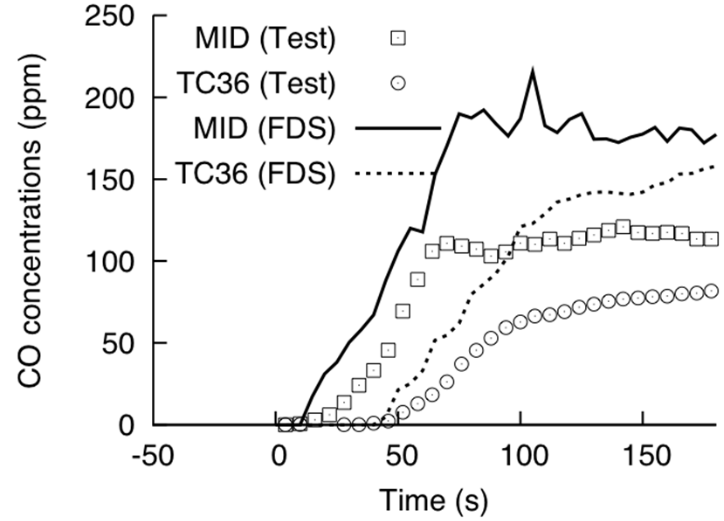


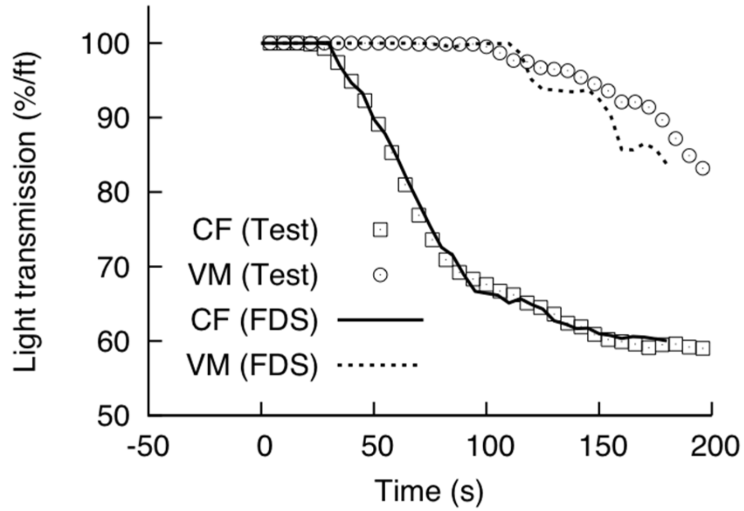


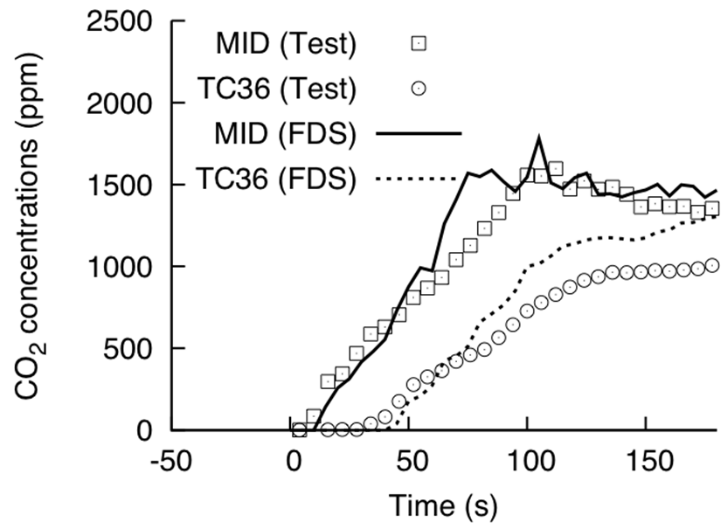
Results

Test case 1: B707 Baseline fire:

- Model predictions for smoke and CO_2 concentrations are good,
- However, CO concentrations are highly overestimated.





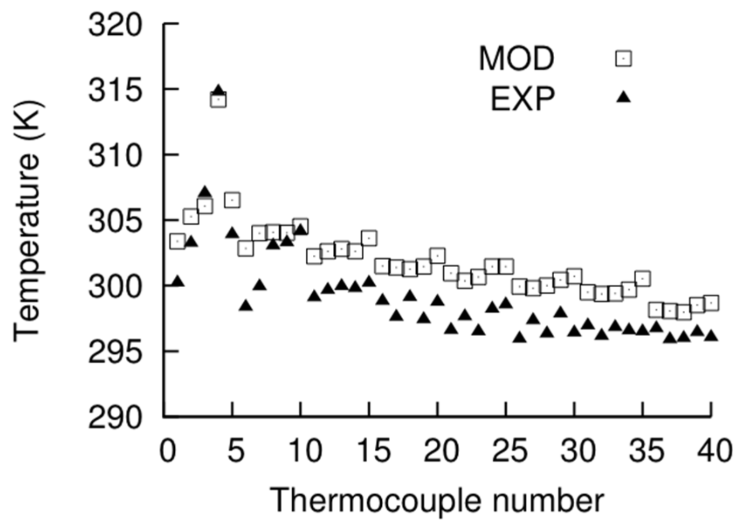


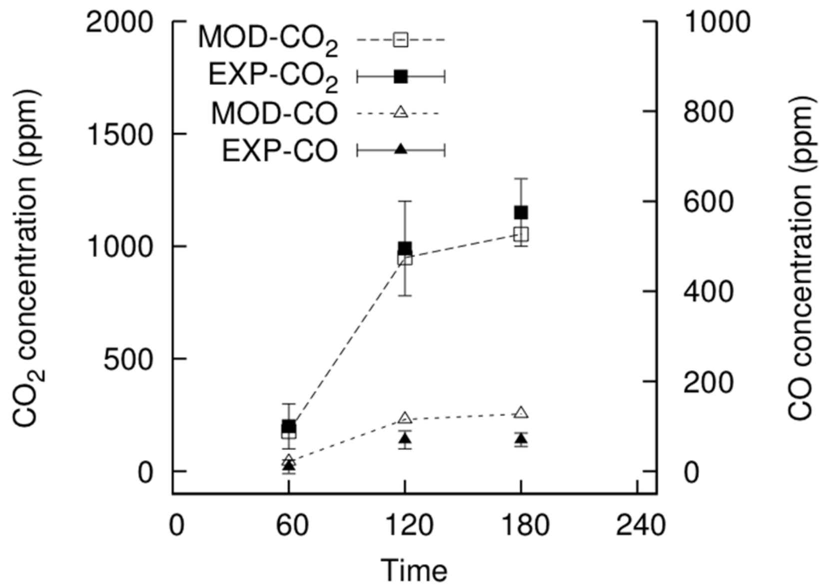
Results

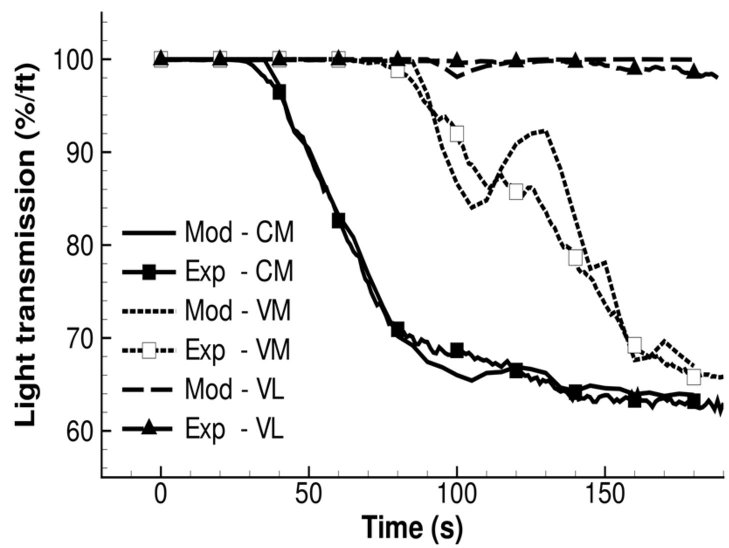
Test case 2: B707 Corner fire:

For **Corner** fire, similar to baseline fire

- Ceiling temperatures are slightly high compared to test data,
- 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.





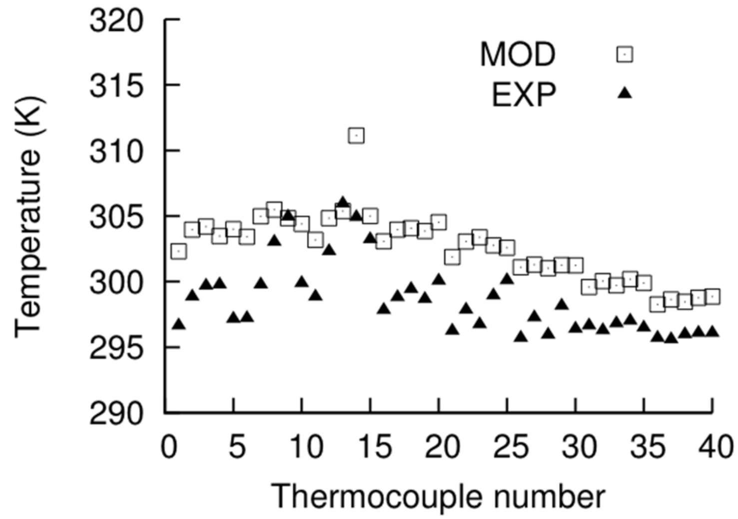


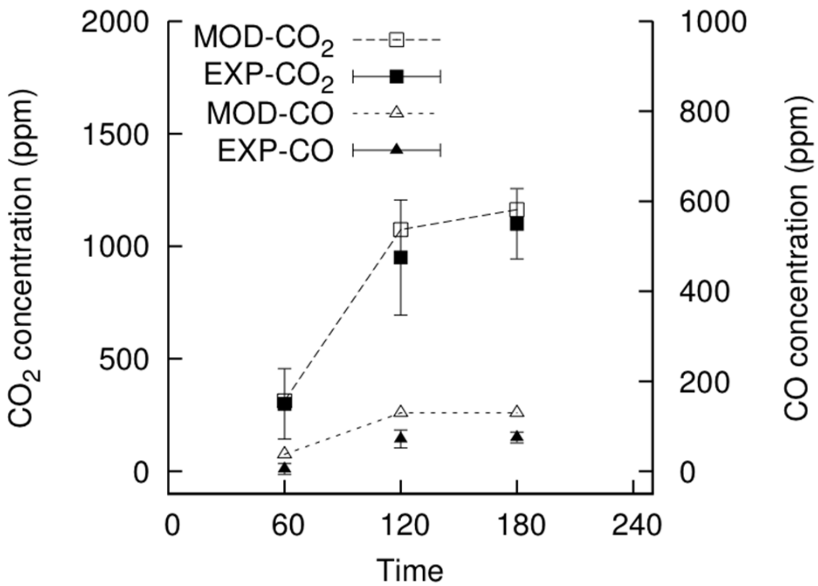
Results

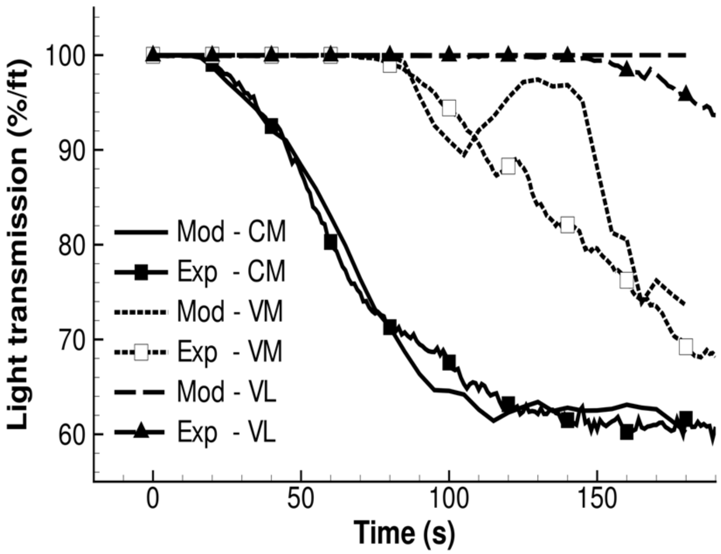
Test case 3: B707 Side fire:

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.





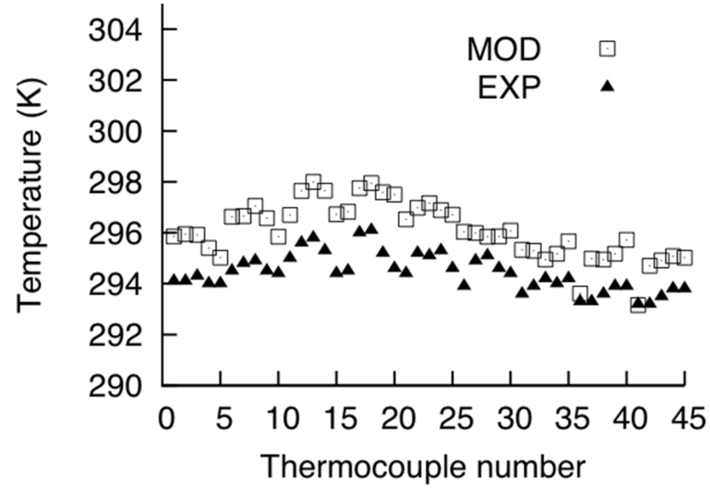


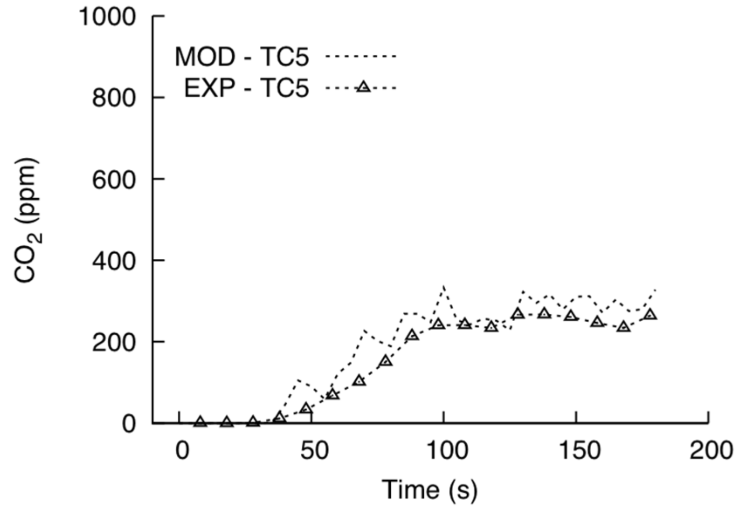
Results

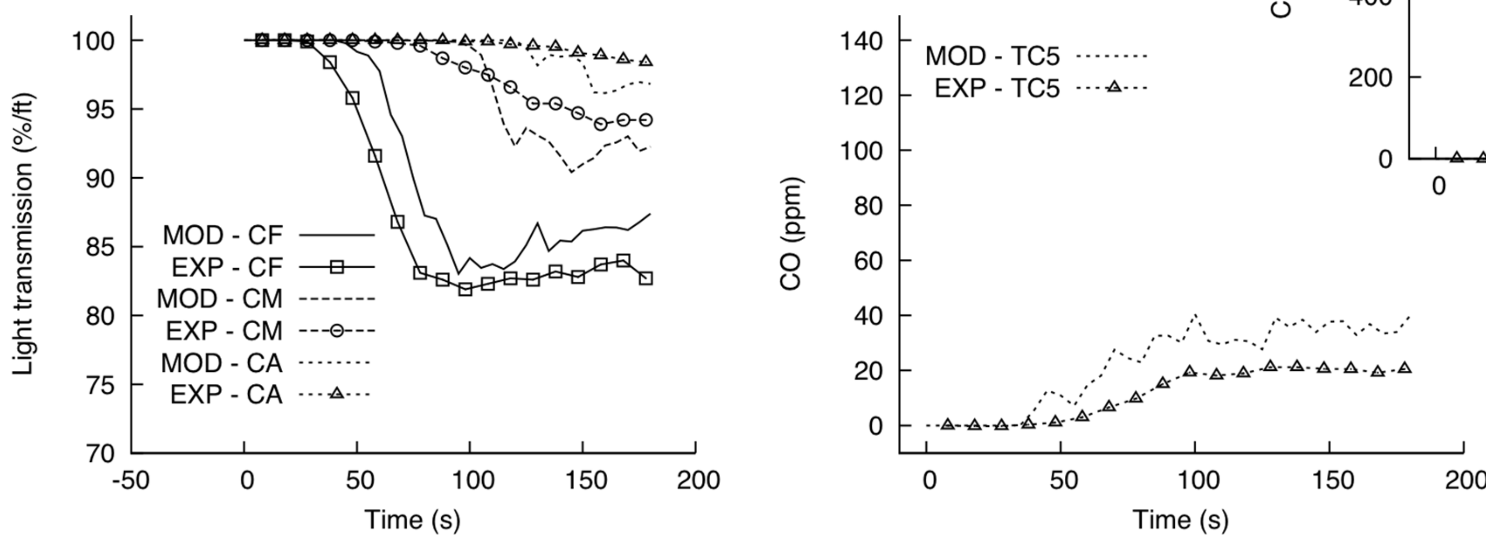
Test case 4: DC10 Baseline fire:

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.