Smoke transport in an aircraft cargo compartment

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Introduction

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.

Introduction

Objective

- FAA aims to
  - improve the detector alarm algorithms, thereby the reliability of the smoke detectors,
  - provide better guidelines for the certification process, and standardize the procedures to use,
  - reduce the total number of required tests,

  by integrating computational fluid dynamics (CFD) into 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

Solver selection

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
- Inexpensive/Free
- Gradual learning curve

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.

Methodology

Test setup – Boeing 707

Boeing 707

- narrow-body
- no ventilation
- negligible leakage

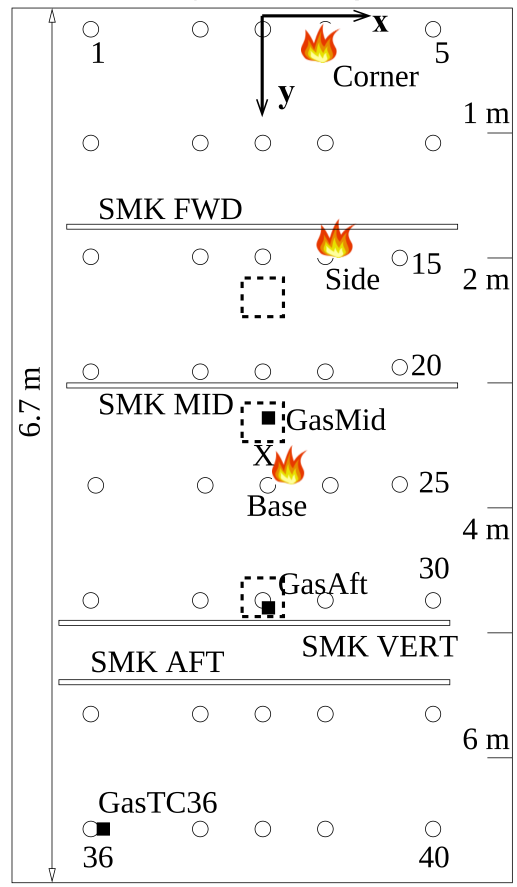
Three test cases (fire scenarios):

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

Ground test measurements: 15 tests with*

- 40 +4 thermocouples
- 6 smokemeters
- 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

Test setup – McDonnell Douglas DC10

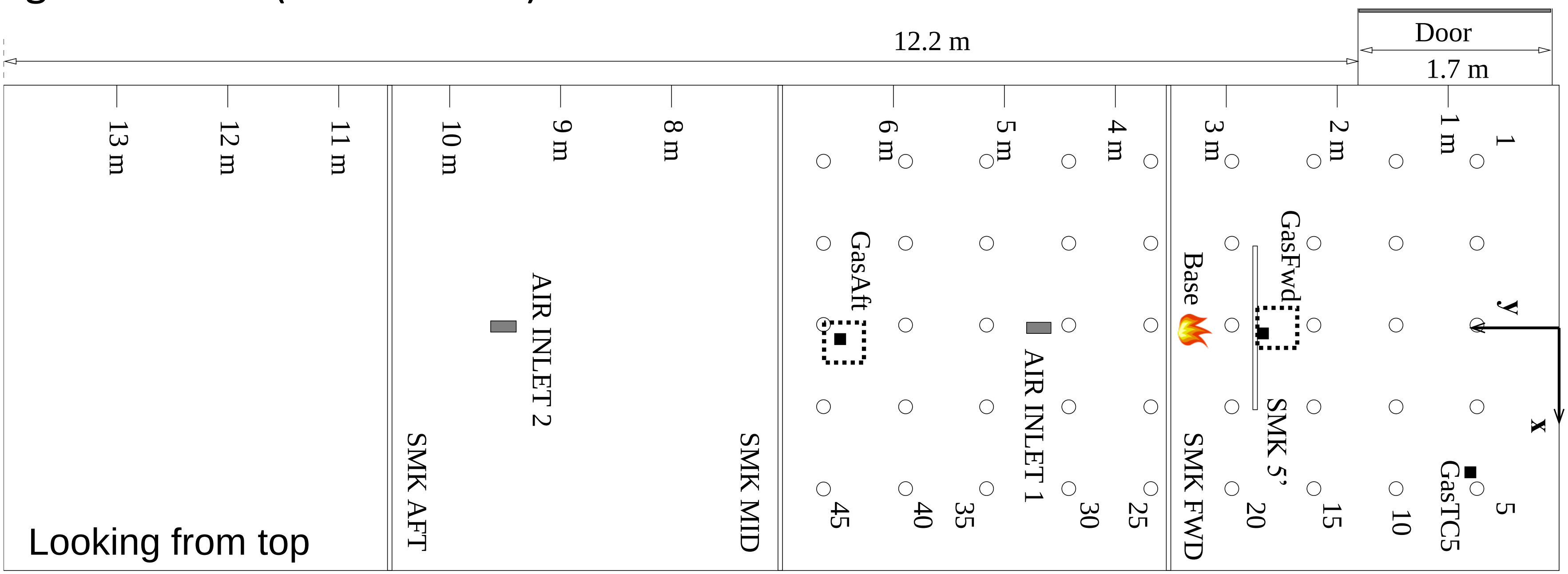
McDonnell Douglas DC10

- wide-body
- forced ventilation
- leakage through compartment door

Ground test measurements: 15 tests with*

- 45 thermocouples
- 4 smokemeters
- 3 gas analyzers

Single test case (fire scenario): **Test case 4:** Base fire

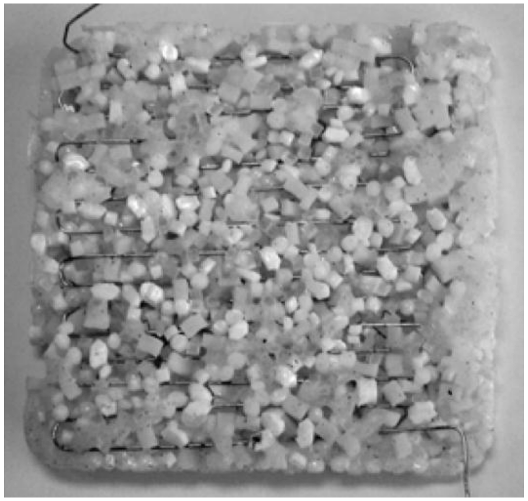


* Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

Methodology

Test setup – Fire source

A compressed plastic resin block was used as a fire source**



- When burned it yields combustion products similar to the 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

Test setup – Validation metrics

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

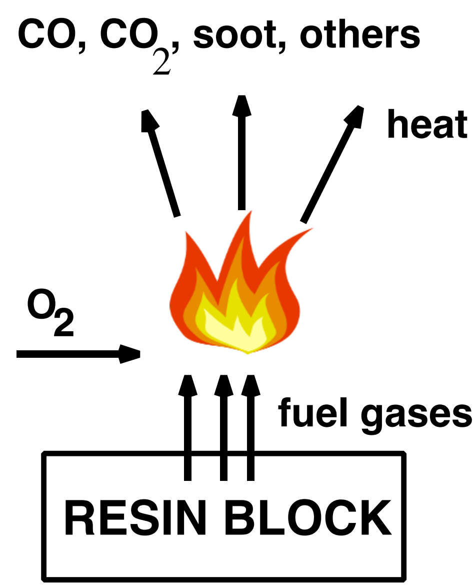
Compartment type	Fire scenario	Total number of tests	Measurement type	Total number of measurements
B707	Baseline Side Corner	15 3 3	Ceiling Temperatures CO, CO_2 concentrations (5+5+5) Smoke concentrations Temperatures in the vertical Heat flux	40 3 6 4 2
DC10	Baseline	15	Ceiling Temperatures CO, CO_2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

Methodology

Model setup – Numerical parameters

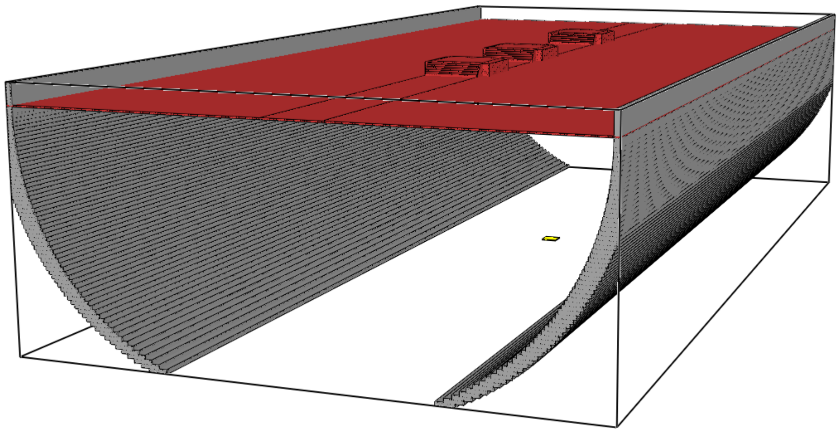
- Production rates are determined through mixture fraction formulation with a simple reaction of fuel and air, using the species-release rates measured in the cone calorimeter (CO_{yield} = 0.065, $Soot_{yield}$ = 0.125).
- Heat of combustion (HOC) is calculated from the recorded heat release and mass loss rates (HOC = 21 kJ/g).
- Radiation modeling, radiative fraction = 0.55.
- Turbulence modeling: dynamic-coefficient Smagorinsky.
- Scalar transport using Superbee flux limiter.
- Extinction coefficient = 7600 m^2/kg.
- Fire source: flaming resin block.
- Ventilation
  - None for B707,
  - Forced ventilation with 400CFM total volumetric flow rate for DC10.



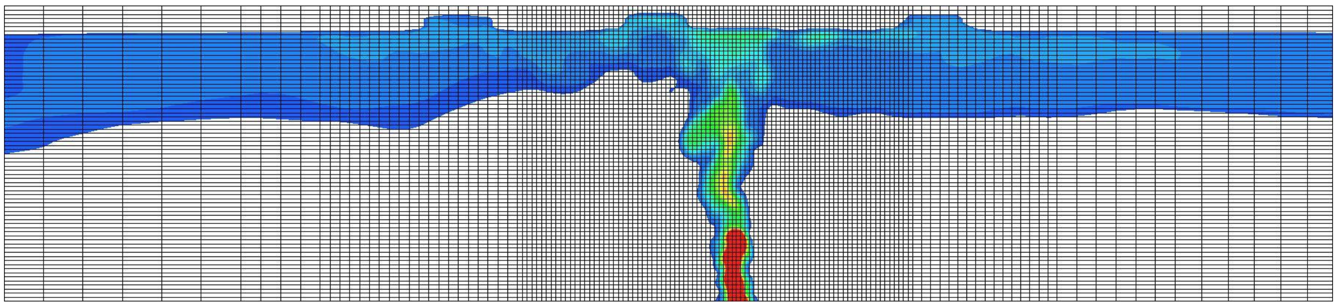
Methodology

Model setup: B707 - Geometry, grid & materials

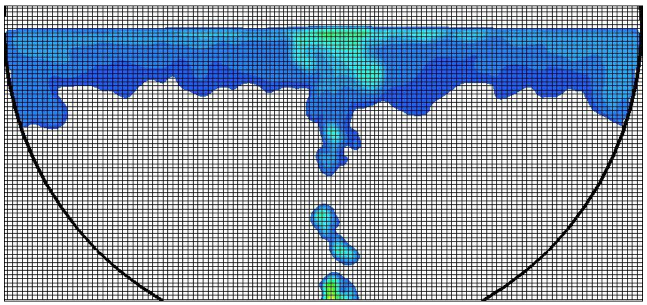
- Rectilinear grids, single-domain solution,
- Non-uniform grid chosen according to characteristic fire diameter: $D^* = (\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}})^{2/5}$
- Using D*/Δx=5, 3.2x6.7x1.4 m^3 volume represented by 132x144x72 grid points,
- Recessed areas are included in the flow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



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



Looking from the side

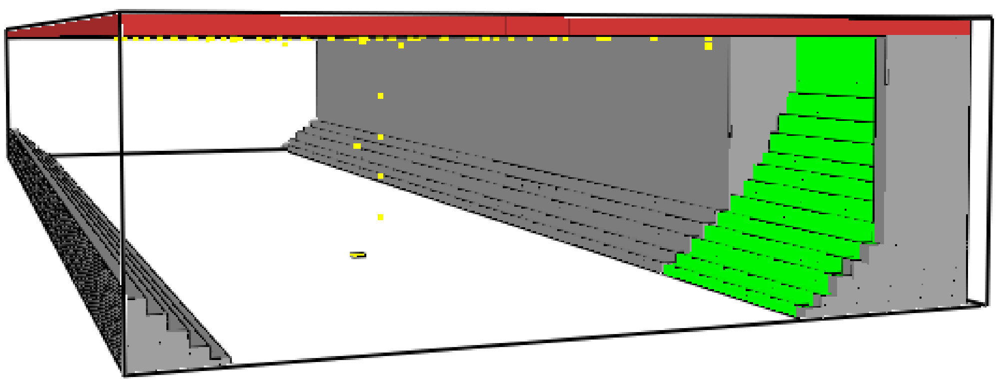


Looking from the front

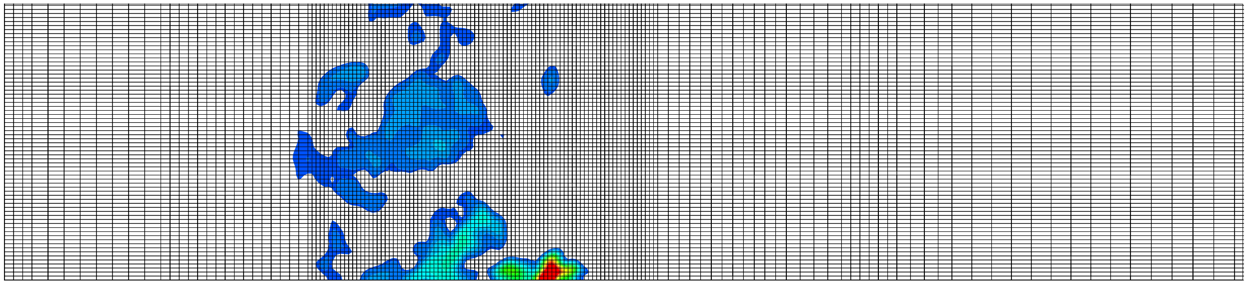
Methodology

Model setup: DC10 - Geometry, grid & materials

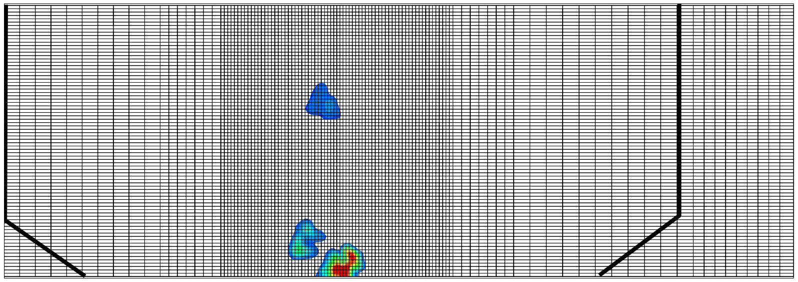
- 114x216x81 grid points are used to represent 5.2x14.0x1.8 m^3 volume,
- Forced ventilation with an inflow velocity of 4.6 m/s is specified at each air inlets (total volume flux is 400 CFM),
- Leakage area is determined so as to avoid pressure build-up in the compartment,
- Wall material (galvanized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



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



Looking from the side



Looking from the front

Methodology

Model setup – Radiative fraction

Empirical evidence suggests correlations between radiative heat of combustion and yields of CO and soot¶.

Table: Measured radiative fractions for selected fuels¶

Fuel	Ys (g/g)	Y_{CO} (g/g)	Heat flux (kW/m^2) q''_{rad}	q''_{conv}	q''_{chem}	χ_R
Thiophenol	0.122	0.045	13.6	11	24.6	0.55
1-3 Butadiene	0.125	0.048	18.2	15.4	33.6	0.54
Aniline	0.120	0.044	13.5	11.1	24.6	0.55
Polyethylene with Chlorine	0.115	0.042	12.6	10.0	22.6	0.56
FAA standardized fire source	0.125	0.065	-	-	5.0	-

¶ A. Tewarson, Smoke Point Height and Fire Properties of Materials, NIST-GCR-88-555, National Institute of Standards and Technology, Dec 1988.

Methodology

Model setup – Grid sensitivity

- 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 converge solutions D*/Δx must be at least 5 (around 2 million grid points),
- The computational expense are over 40 hours for B707 cases and over 240 hours for DC10 case#.
- 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.

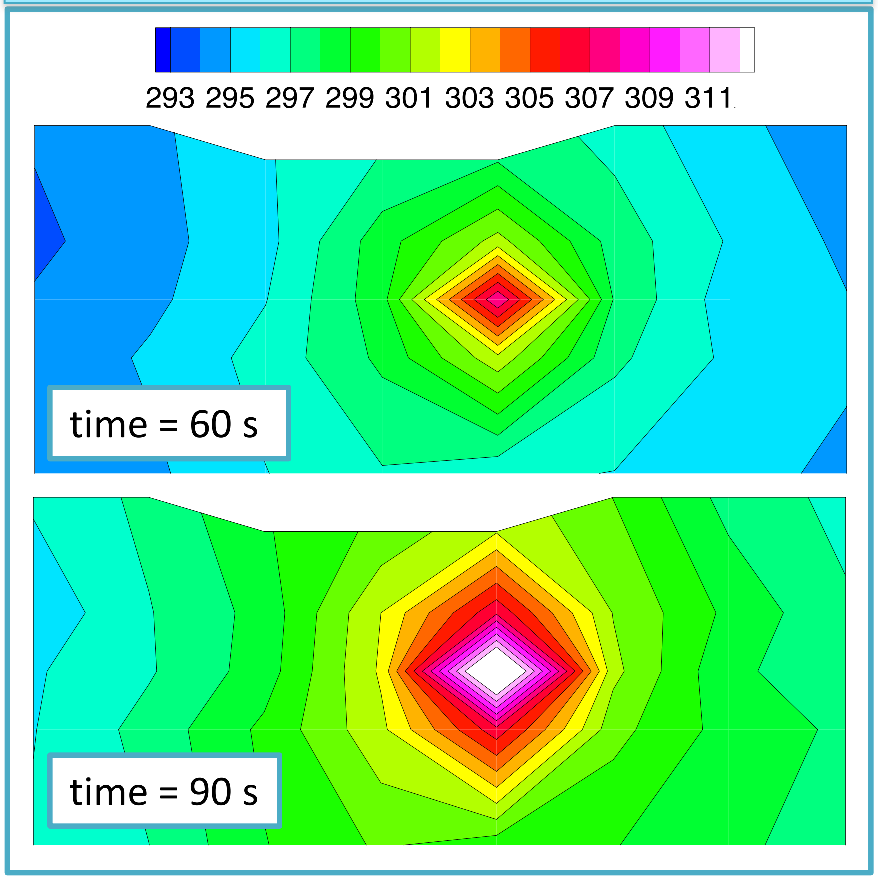
#OpenMP-runs using 6 processors on 2x2.93 GHz 6-Core Intel Xeon with 16GB memory.

Results

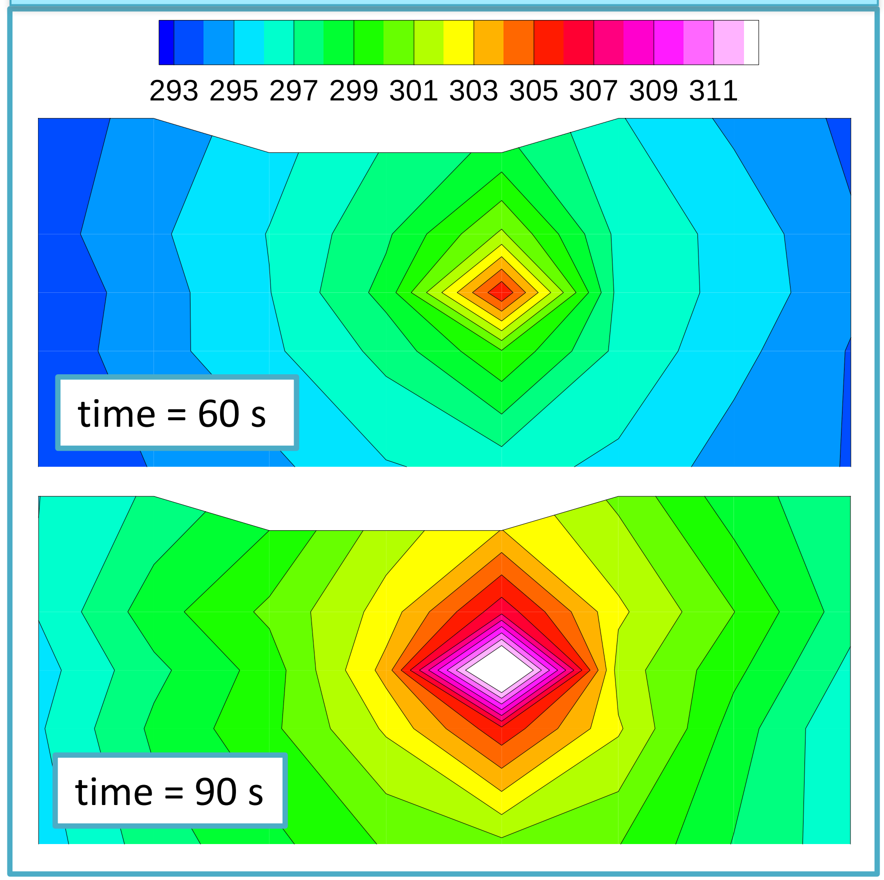
Temperature comparisons: Test case 1 - B707 Base fire

Contourplots of ceiling temperatures at 60 and 90 seconds show that model predictions agree with the test data and are within experimental uncertainty.

TEST DATA



MODEL SOLUTION

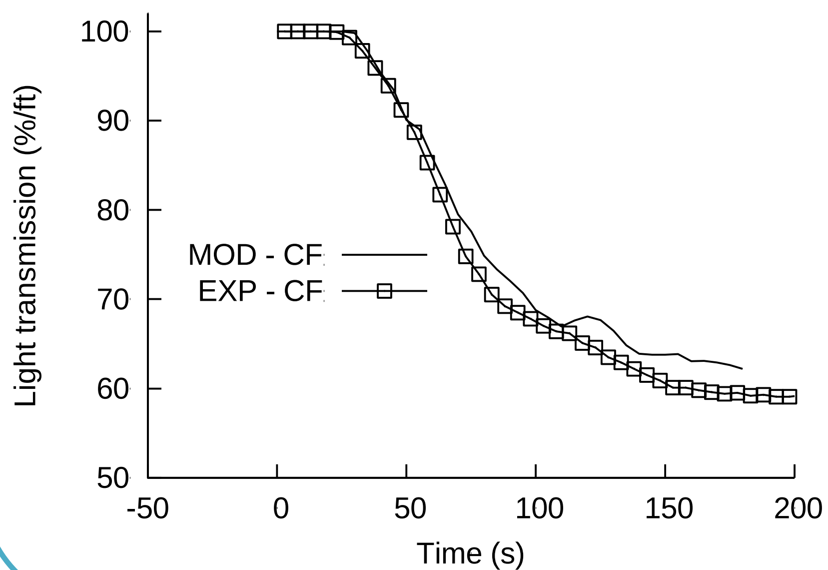


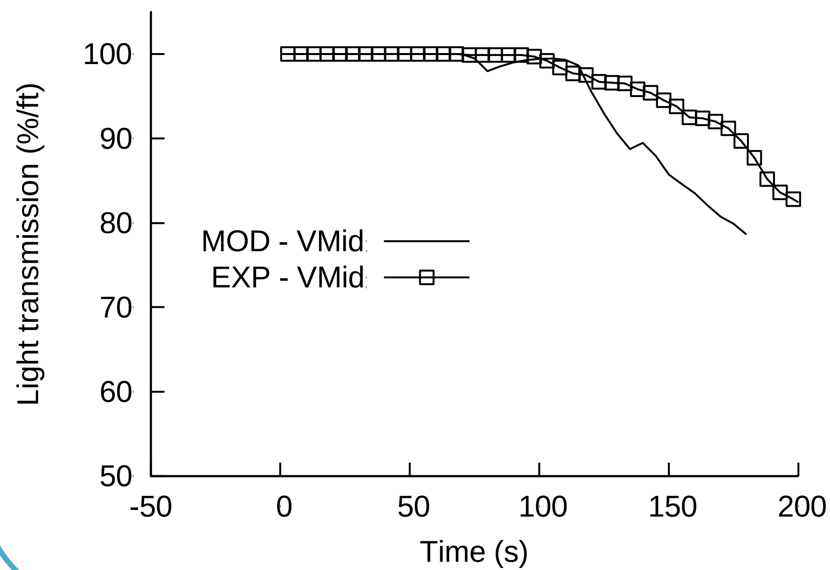
Results

Concentration comparisons: Test case 1 - B707 Base fire

Predicted ***light transmissions*** are generally in good agreement with the measured values. An example is shown below for the ceiling-forward beam detector (CF).

The worst comparison for light transmissions is obtained at the vertical-mid (VMid) beam detector as shown.

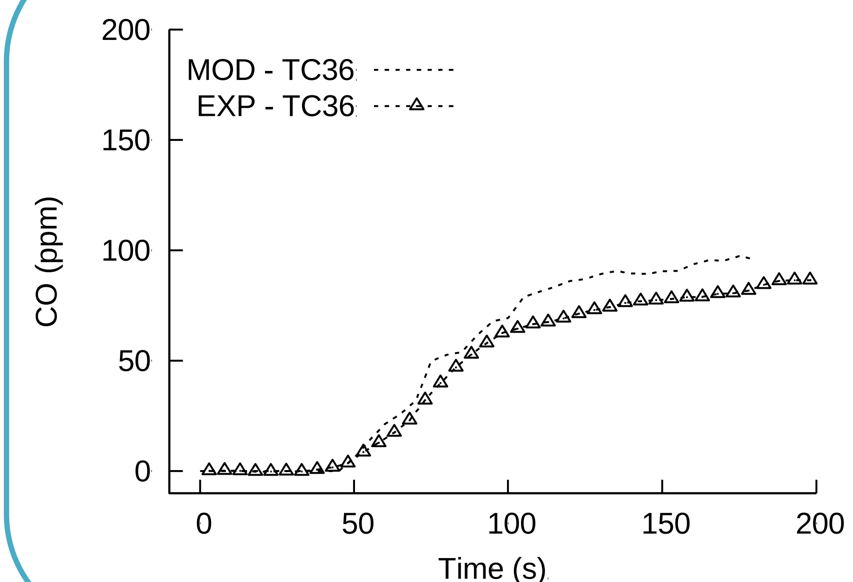


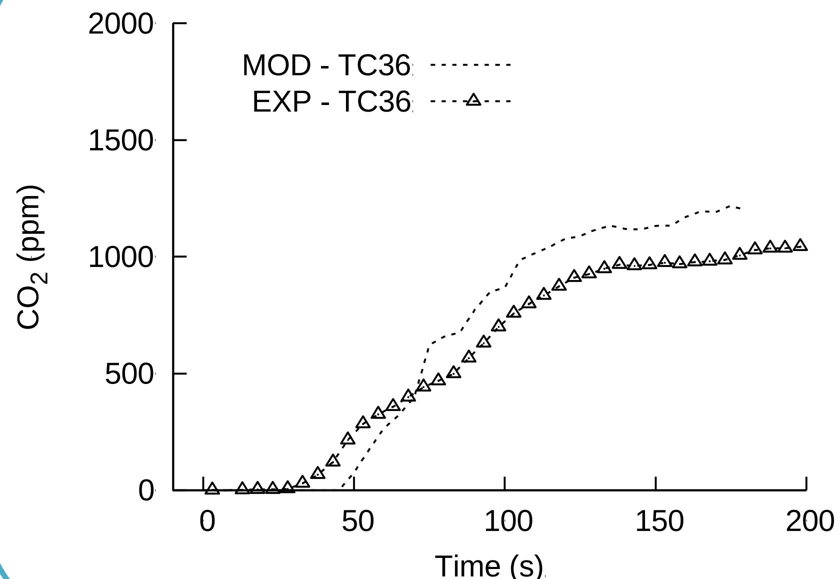


Results

Concentration comparisons: Test case 1 - B707 Base fire

Predictions both for ***CO and CO_2*** follow the experimental mean very closely except for those at gas analyzer TC36. CO and CO_2 concentrations at this location are slightly overestimated.

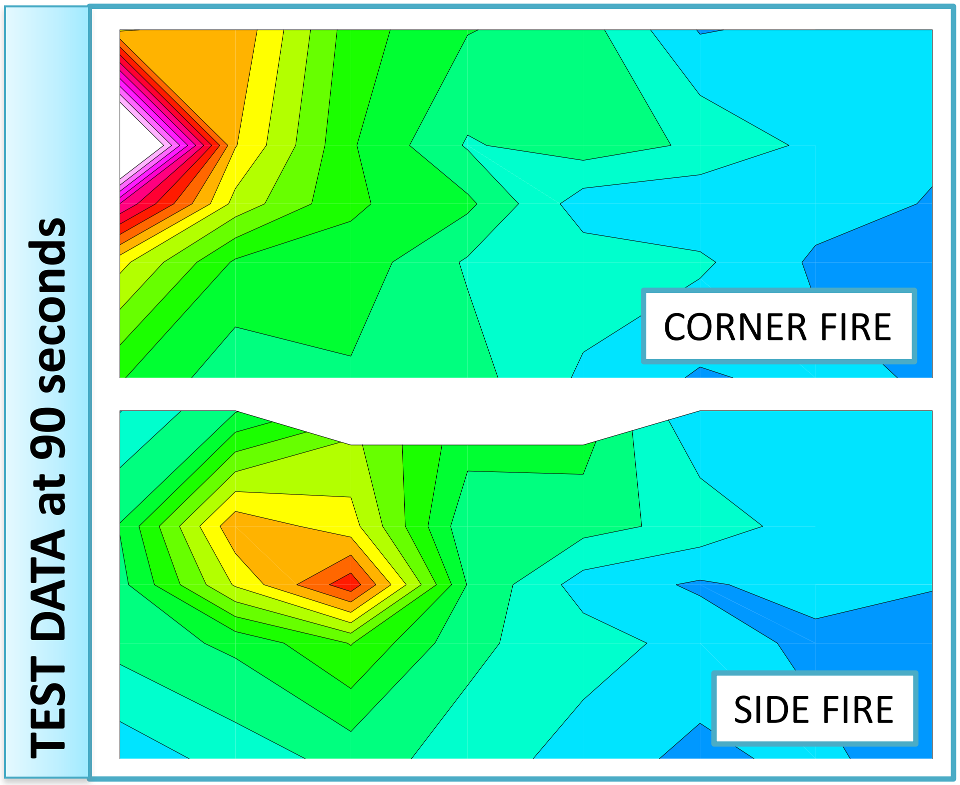


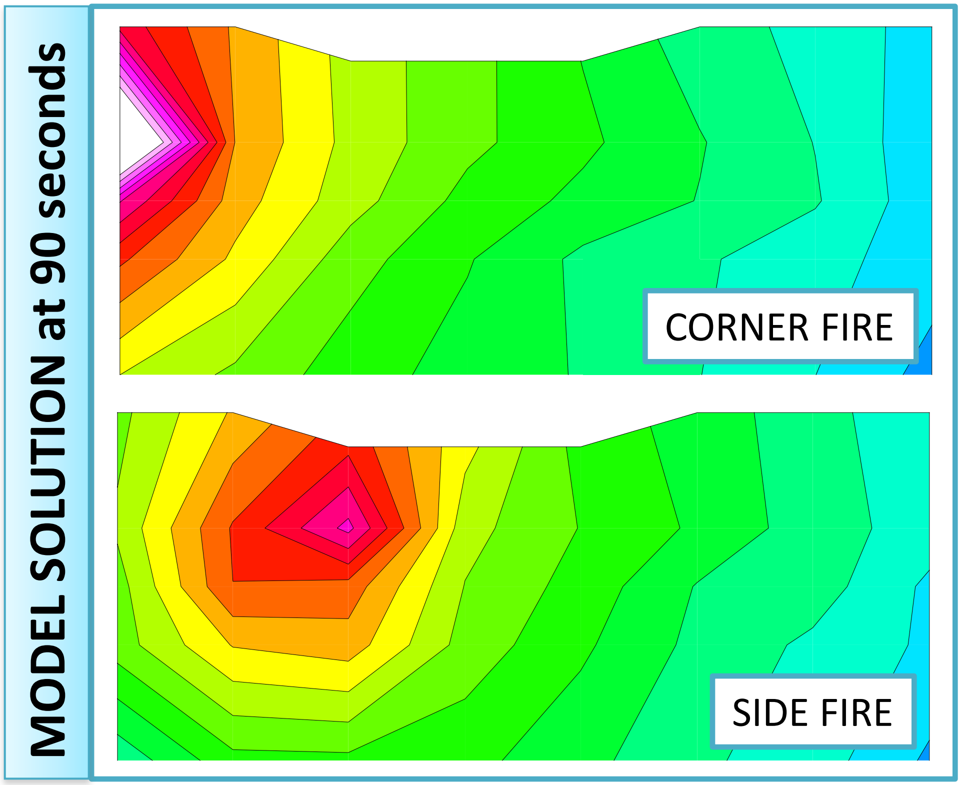


Results

Temperature comparisons: Test cases 2 & 3 - B707 Corner & Side fires

- For test case 2, ***corner fire***, ceiling temperatures are higher in comparison to the test data.
- For test case 3, ***side fire***, they are noticeably overpredicted, but more importantly the location of maximum temperature is different. It is possible that the fire source had been located further down than what was recorded.

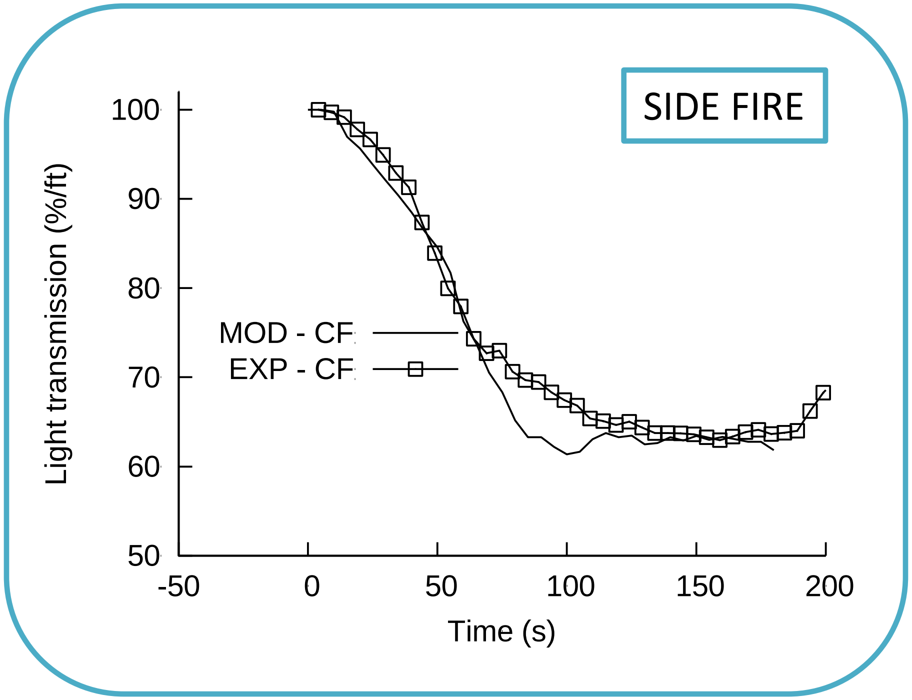


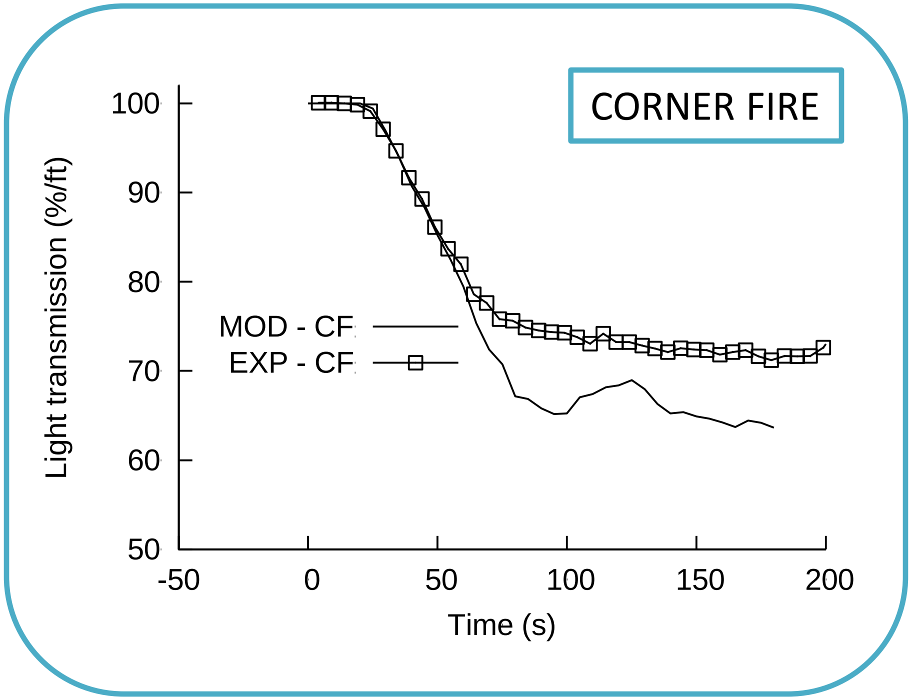


Results

Concentration comparisons: Test cases 2 & 3 - B707 Corner & Side fires

- ***Light transmissions*** at the ceiling forward (CF) beam detector display the worst comparisons for both side and corner fire cases (shown below).



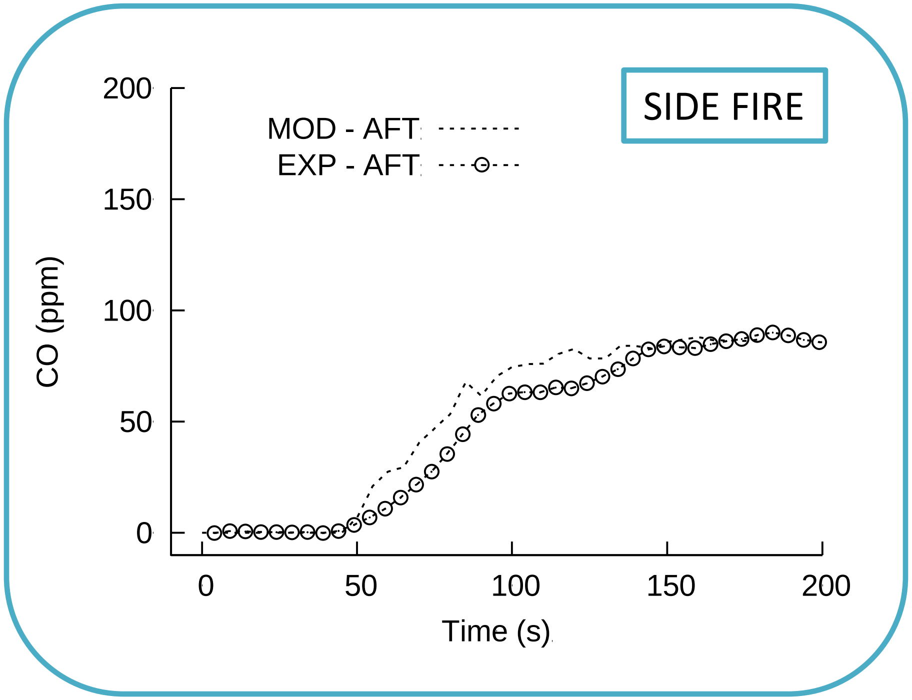


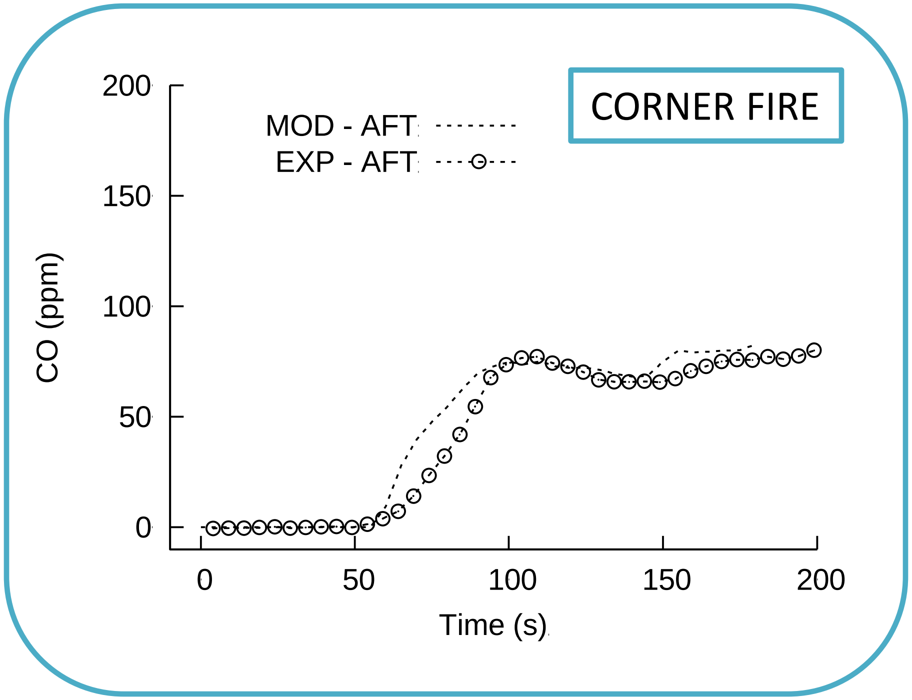
- Considering that the experimental uncertainty increases for light transmissions below 80% the results are good.

Results

Concentration comparisons: Test cases 2 & 3 - B707 Corner & Side fires

- ***CO gas concentrations*** for both test cases (corner and side fires) are predicted very close to the experimental mean.





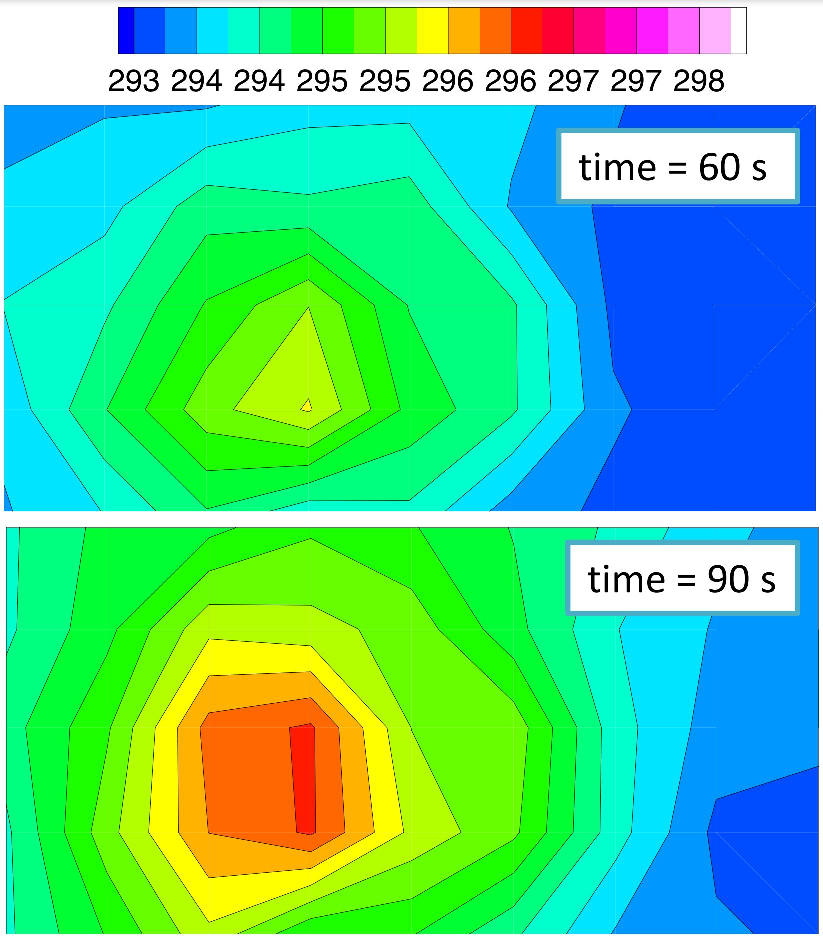
- A similar comparison is observed for CO_2 gas concentrations (not shown).

Results

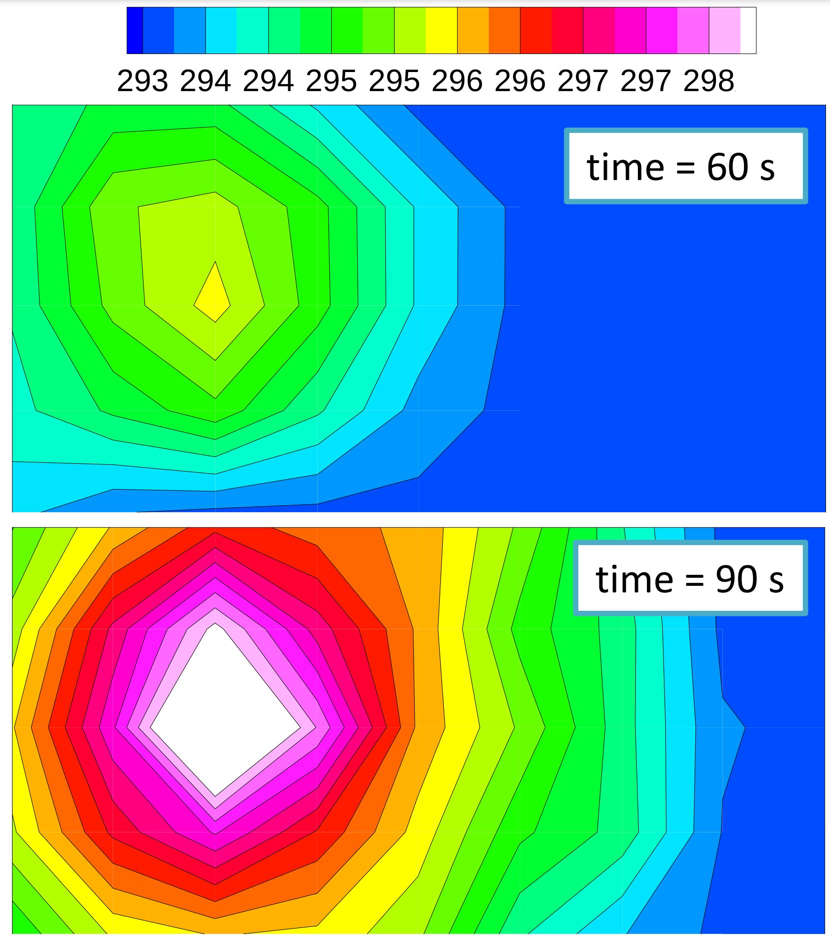
Temperature comparisons: Test case 4 – DC10 Base fire

Ceiling temperatures are consistently higher for DC10 test case.

TEST DATA



MODEL SOLUTION

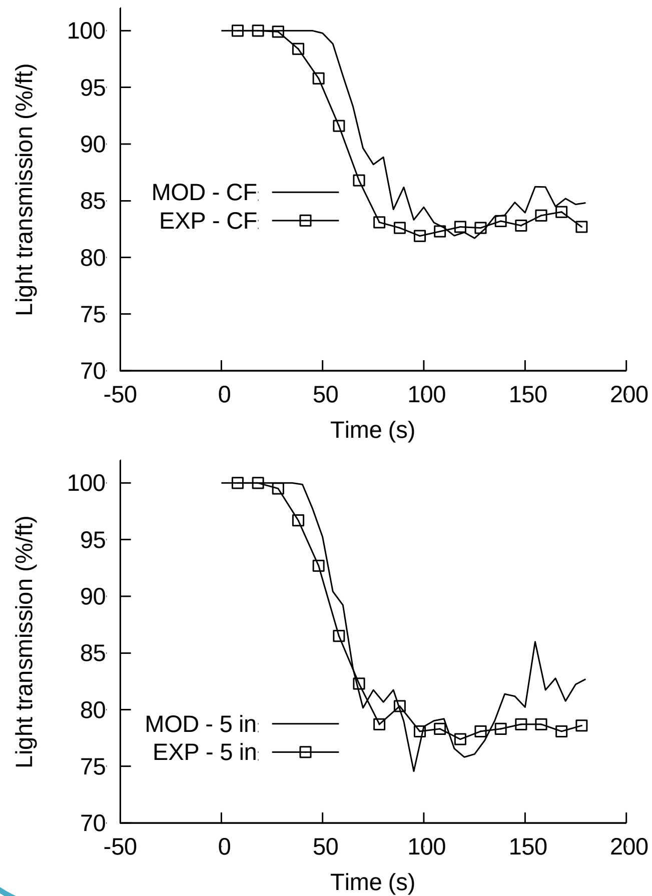


Results

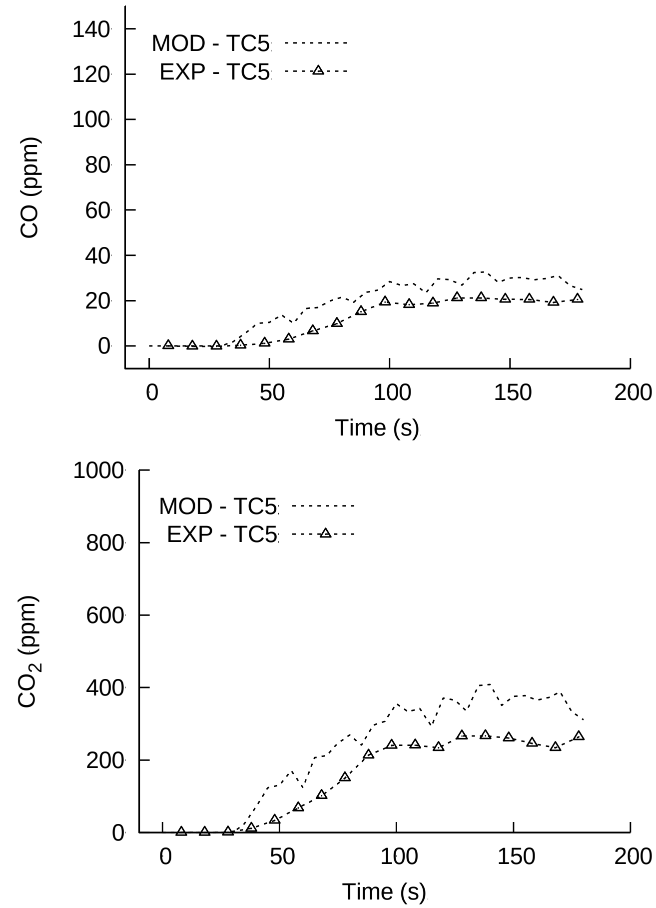
Concentration comparisons: Test case 4 – DC10 Base fire

Light transmissions and gas concentrations are predicted reasonably well.

Light transmissions



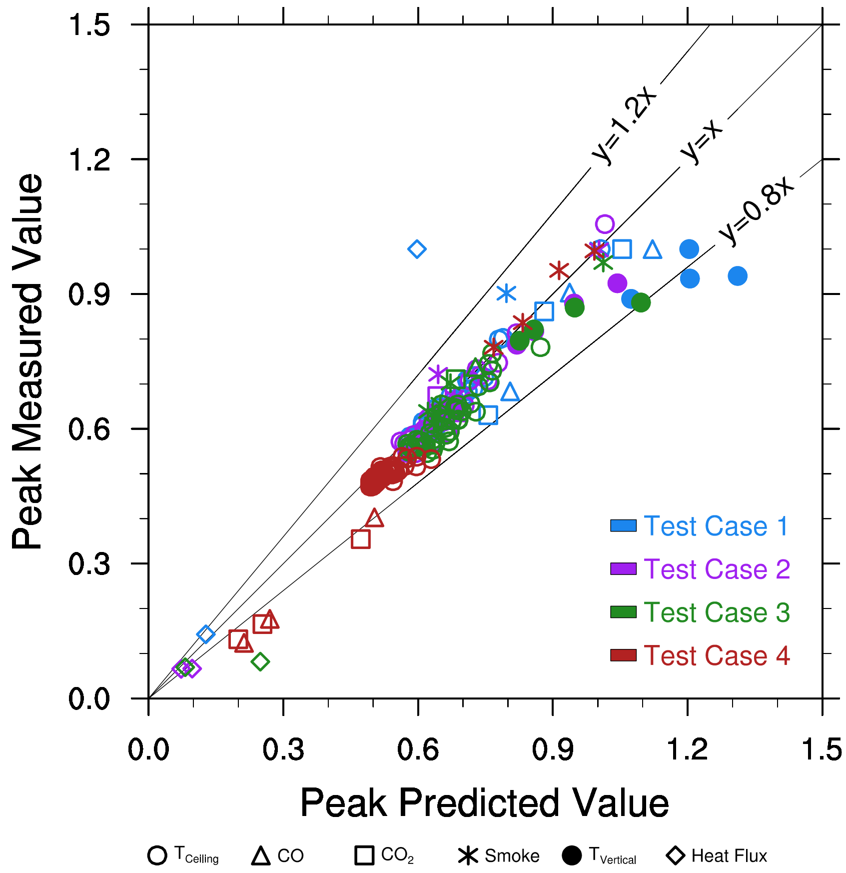
Gas concentrations



Results

Summaryplot

- In general the agreement between the model and the experiments is within ~20% margin (if not better).
- However, vertical temperatures (shown in filled circles) and heat fluxes (shown in diamonds) are consistently out of this error margin.
- This is most probably due to the under-resolved boundary layers on the walls.



Conclusions

- For **all** four test cases model solutions are:
  - in good agreement with the test data for light transmissions, CO and CO_2 concentrations,
  - slightly high for ceiling temperatures in comparison to the test data but still within reported experimental uncertainty,
  - much higher for temperatures in the vertical in comparison to the test data.
- The overestimation of temperatures are possibly due to
  - the under-resolved boundary layers on the walls,
  - the treatment of the radiation source term in the solver.
- Improving temperature predictions would require considerable increase in computational time.
- In the evaluation of the model performance, possible systematic errors associated with the test data must also be taken into consideration.
- It is important to measure critical model input data, such as radiative fraction.