Smoke transport in an aircraft cargo compartment

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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 <u>one minute</u> after the start of fire.

  …

  d. The effectiveness of the detection system must be shown for <u>all</u> 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

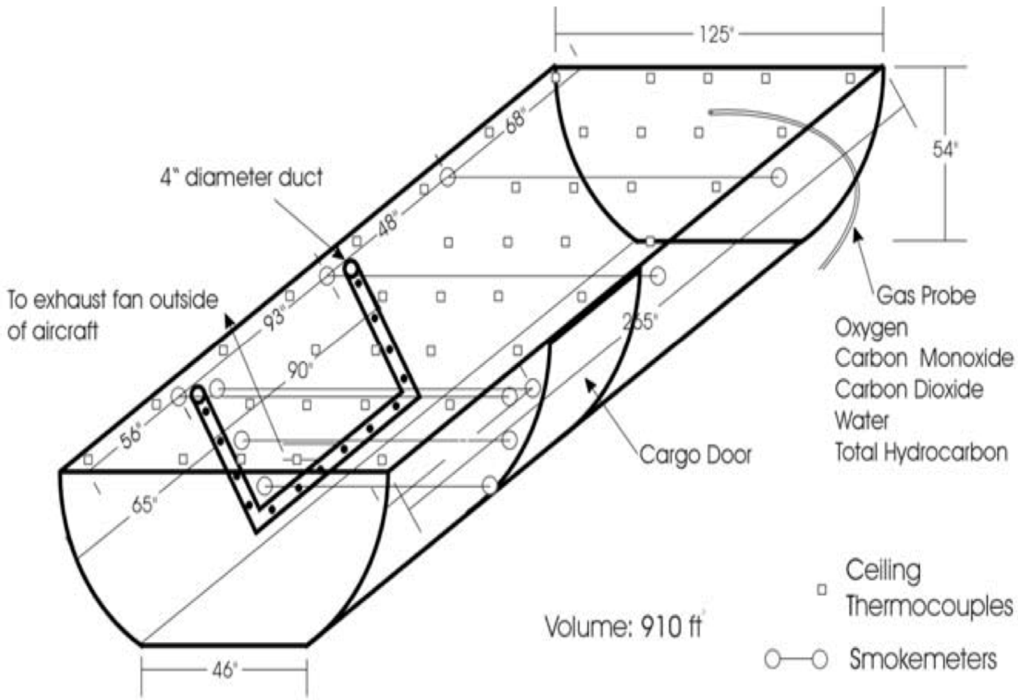
- CFD solver candidates:
  - Commercial solvers:
    - Fluent, …
  - Open source solvers:
    - FAA Smoke Transport Code
    - Fire Dynamics Simulator (FDS)
    - Code-Saturne
    - Jasmine
    - Sophie
    - FireFOAM-OpenFOAM
    - …
- Our criteria:
  - Reliable
  - Accessible
  - Robust
  - Fast turnaround 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

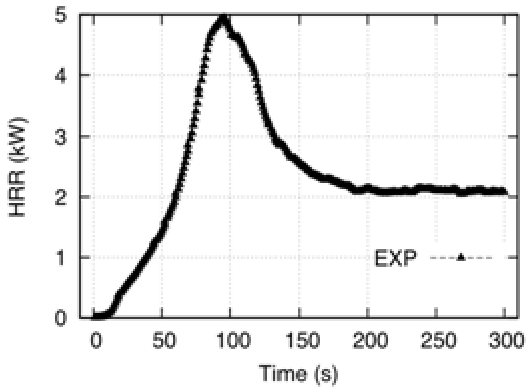


Ground test measurements: 15 tests with

- 40 thermocouples
- 6 smoke meters
- 3 gas analyzers

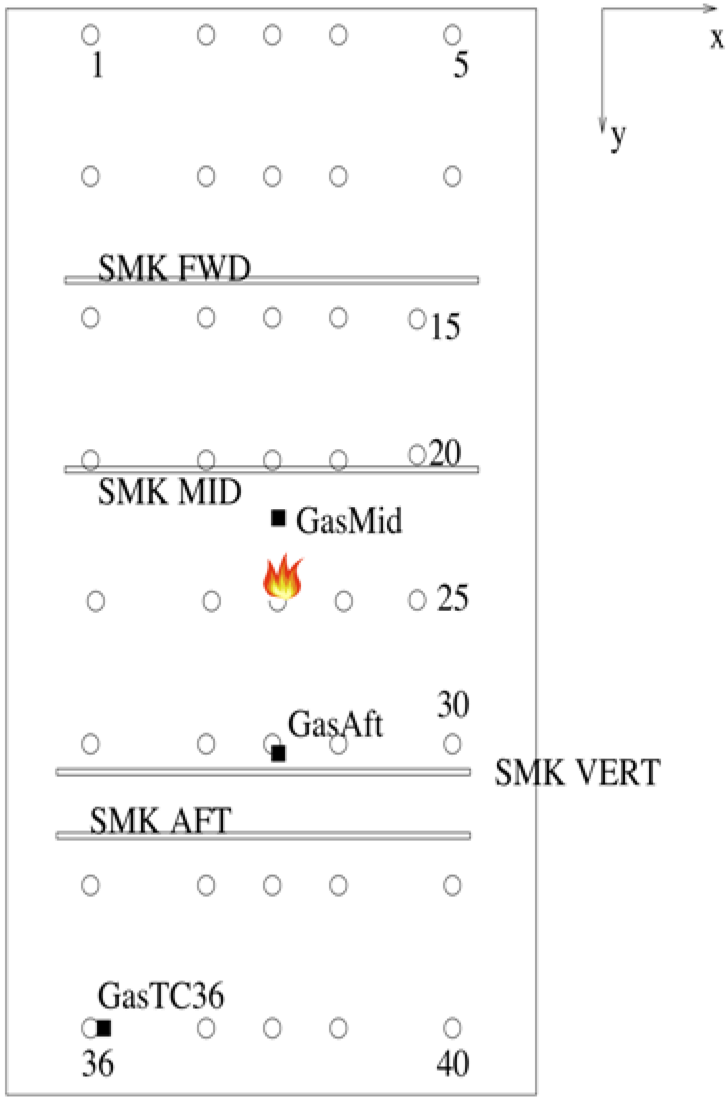
Fire source: Compressed plastic resin block

- when burned yielding combustion products similar to actual luggage fires,
- with imbedded nichrome wire to enable remote ignition,
- with cone calorimetry test data (HRR, MLR, CO_2, CO, and soot).

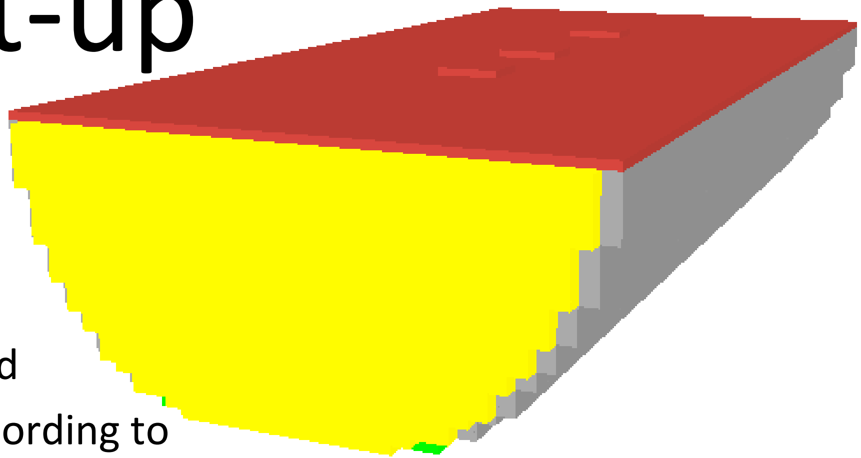


Methodology

- Validation Metrics
  - A. Thermocouple temperature rise
    - from 0 to 60 seconds
    - from 0 to 120 seconds
    - from 0 to 180 seconds
  - B. Light transmission
    - at 30 and 50 seconds (ceiling and vertical)
    - at 60, 120 and 180 seconds (vertical – high, mid and low)
  - C. Gas species concentration rise
    - at 60, 120 and 180 seconds



Model set-up



Geometry, grid and materials:

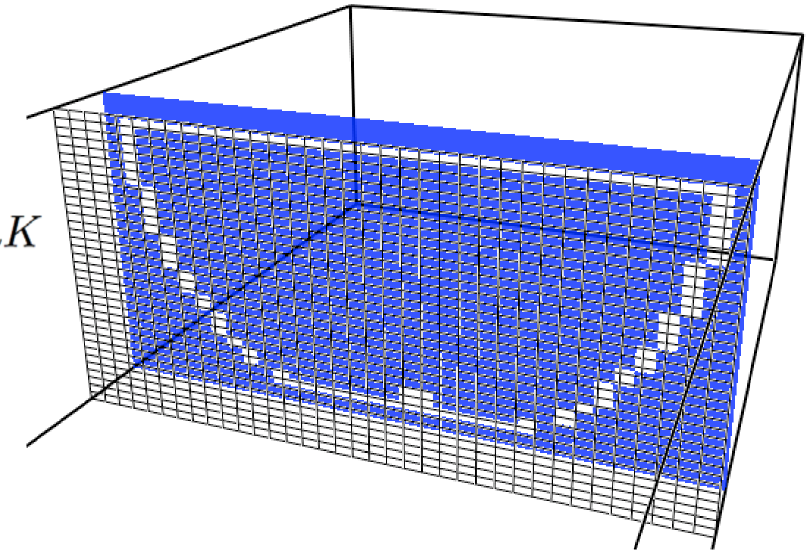
- Rectilinear grids, single-domain solution
- Recessed areas are included in the flow domain
- Non-uniform grid at three resolutions, maximum grid size = 0.04m for 3.2x6.7x1.5m geometry, chosen according to

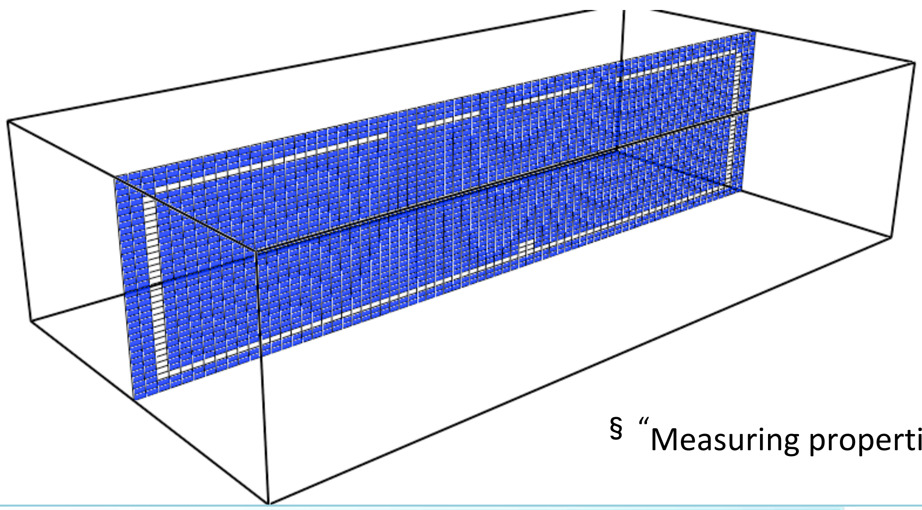
$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$$

where D* is the characteristics fire diameter.

- Fiberglass epoxy resin: properties of woven glass with 30% vinyl ester §

$$\rho = 1683\ kg/m^3,\ c_p = 1200\ J/kgK,\ k = 0.3\ W/mK$$



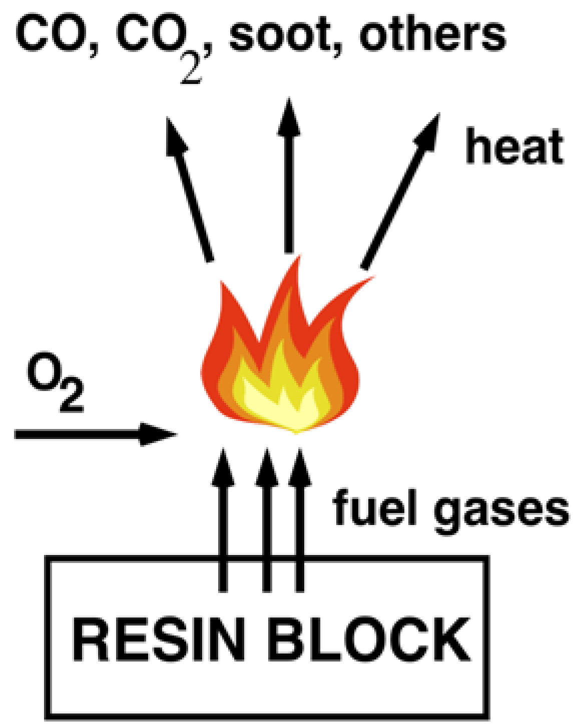


§ "Measuring properties for Material Decomposition Modeling", C. Cain and B. Lattimer

Model set-up

Model parameters:

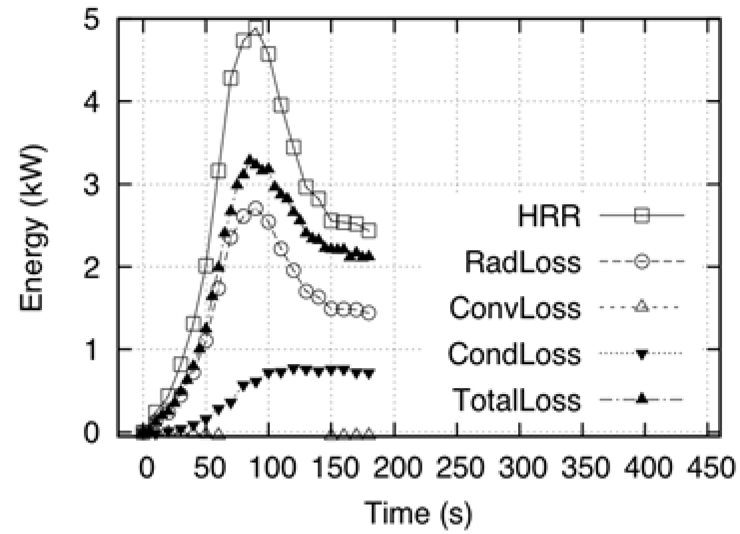
- Fire source: flaming resin block,
- No ventilation,
- Radiation modeling, radiative fraction: 0.55,
- Turbulence modeling: dynamic Smagorinsky,
- Scalar transport using Superbee flux limiter,
- Reaction with a made-up fuel and made-up heat of combustion only to provide heat input from the known cone calorimetry data (MLR and HRR),
- Yields of soot, CO, and CO_2 are input as gaseous leak into the compartment,
- Extinction coefficient = 8700 m^2/kg (FDS default),
- Three grid resolutions are run: Coarse, medium and fine with $D^*/\Delta x$ = 2, 5, 10.

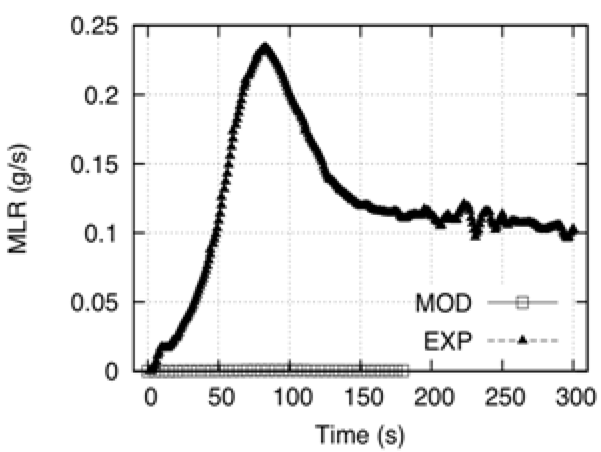


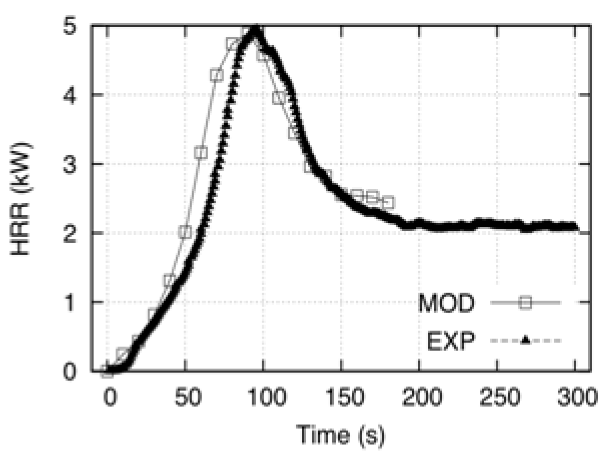
Results

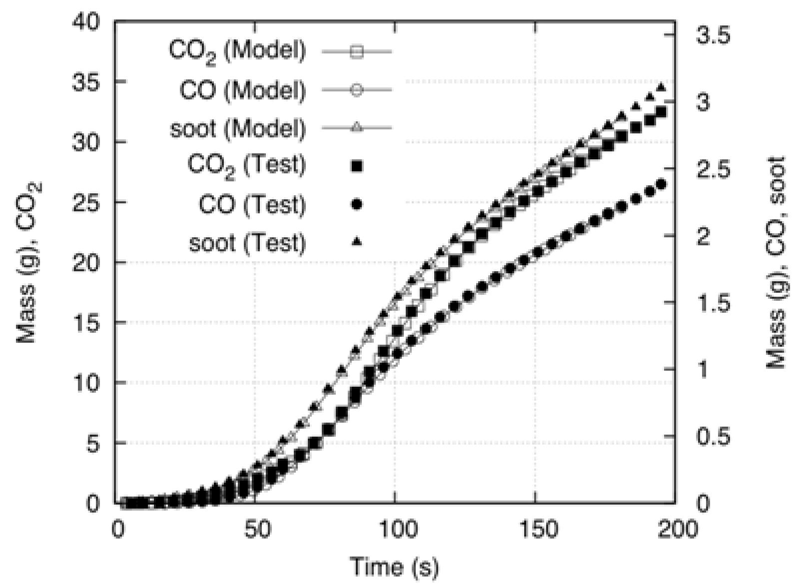
B707 Baseline Fire

- Cone calorimetry data for mass loss rate (MLR) is used to represent the fire source in the model.
- Calculated heat release rate (HRR) is in agreement with the experimental data.
- Energy Budget shows the contribution of radiative and conductive heat losses.

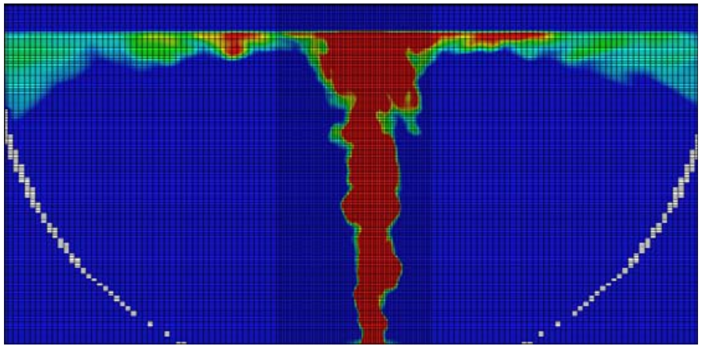








Results



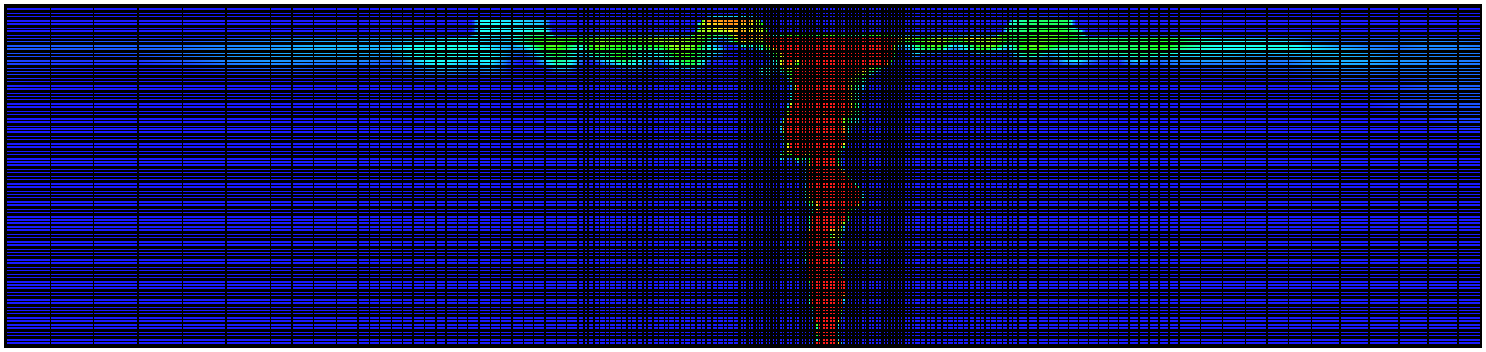
GL3

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	~0.25	~2	~4
GL2	132x144x68	0.022	~1	~5	~44
GL3	164x180x135	0.011	~4	~10	~270

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

GL3

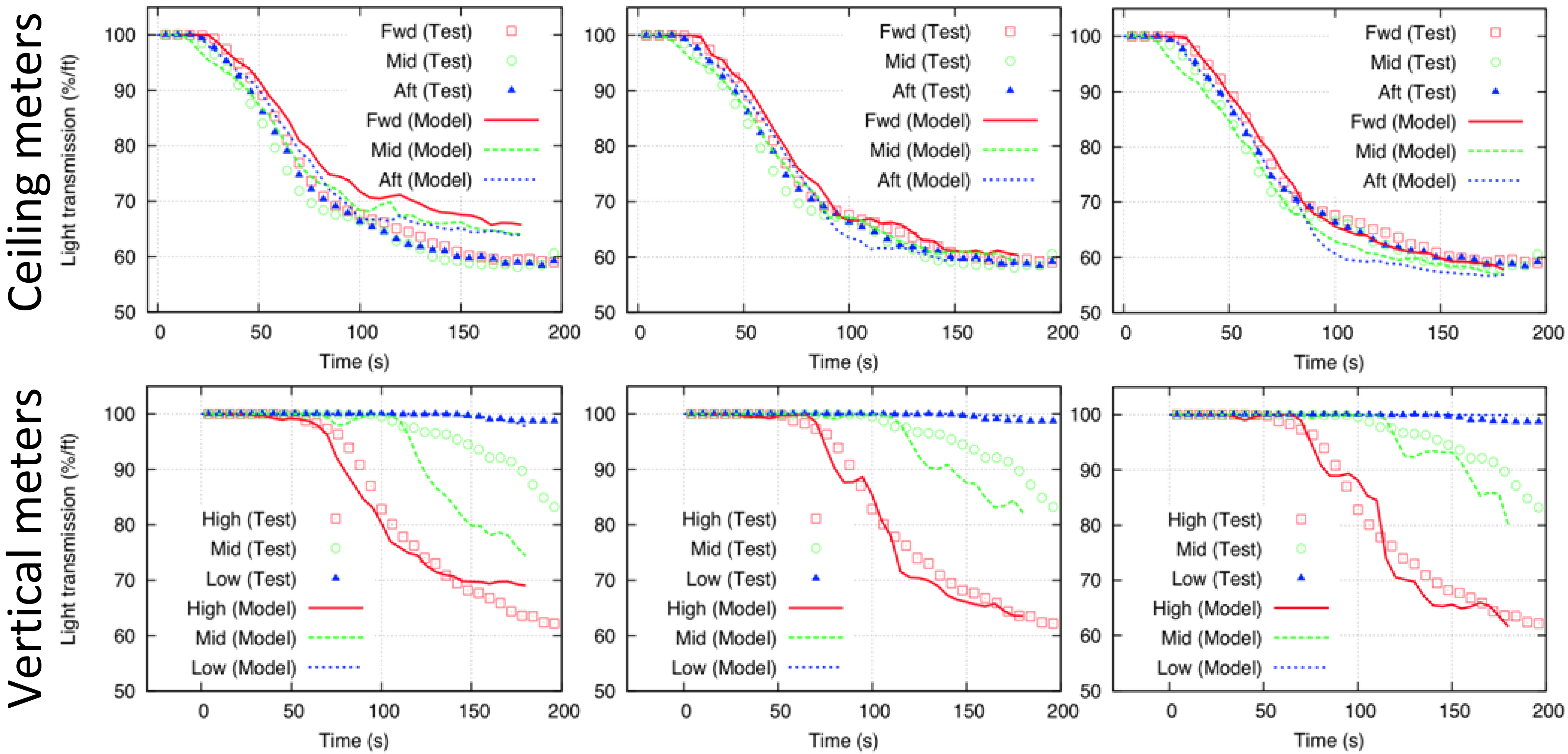


Results

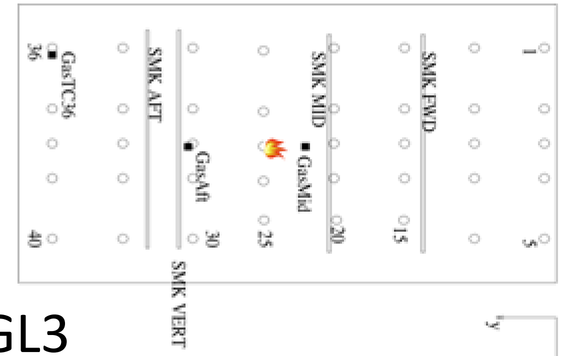
B707 Baseline Fire – Light Transmission

$$LT = exp(-K_m \sum_{i=1}^{N} \rho_{soot,i} \Delta x_i) \times 100\ (\%)$$

GL1 GL2 GL3



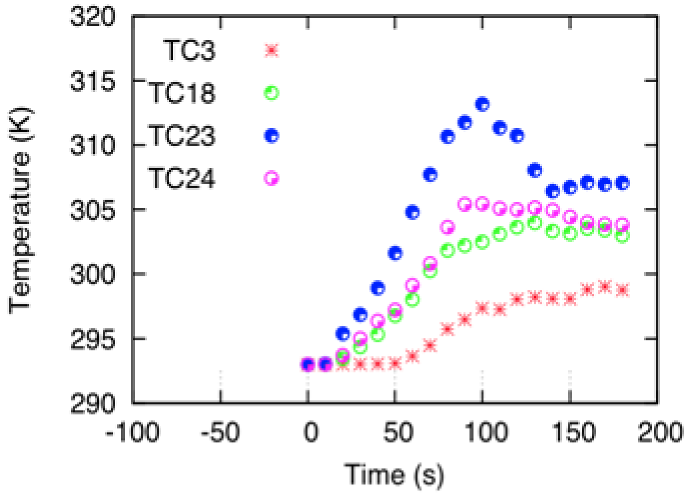
Results



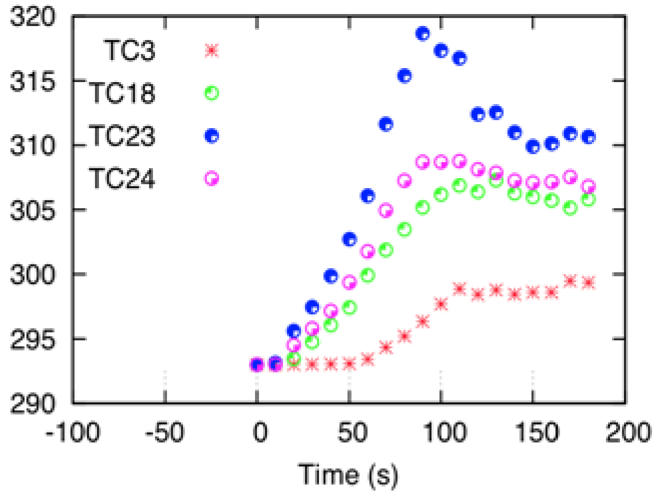
B707 Baseline Fire – Temperature comparisons

Model

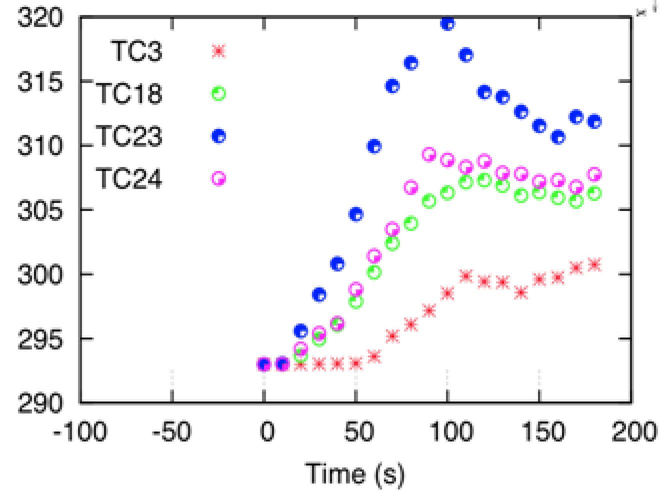
GL1



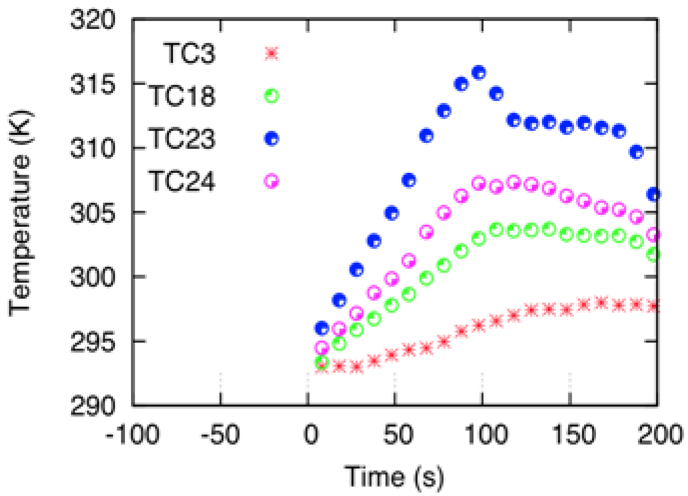
GL2



GL3



Measurements



- Experimental uncertainty is ~6 °C close to the fire source, and ~2 °C away from the fire source*,

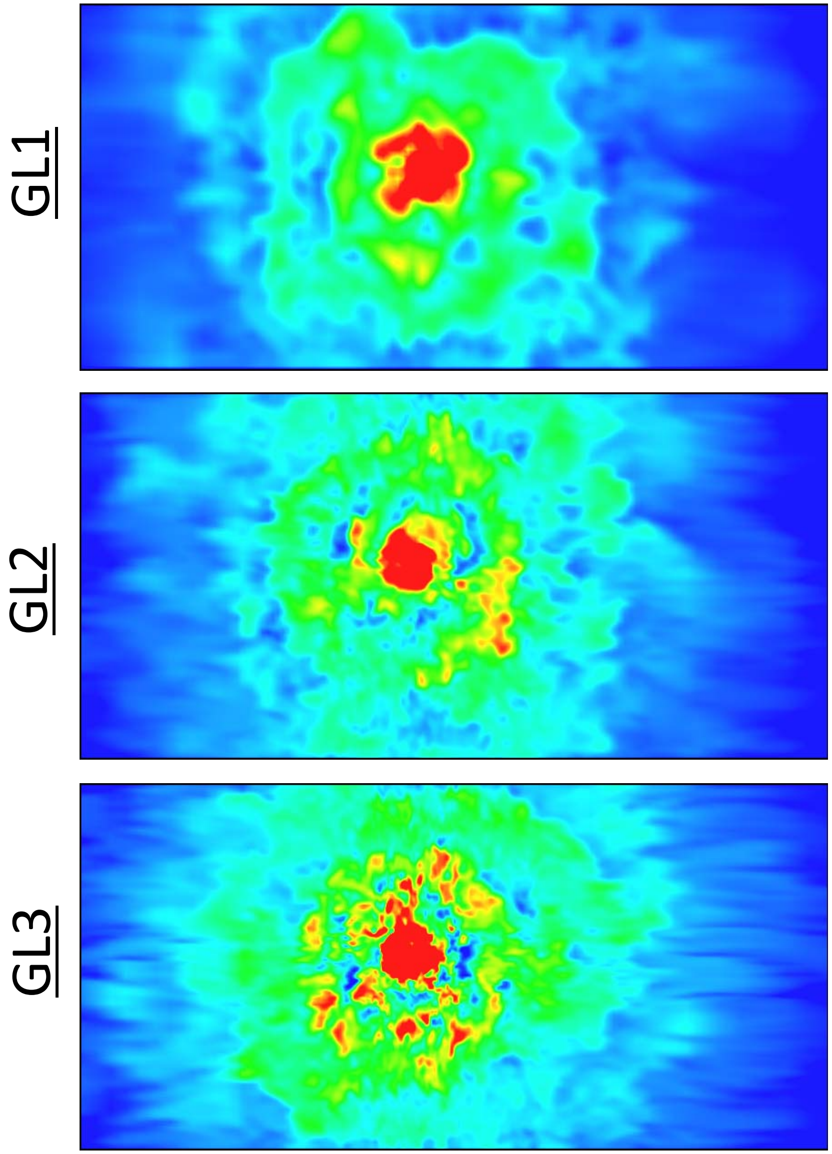
- The difference between model estimates and measurements increases in time and it is the same everywhere (~3 °C),

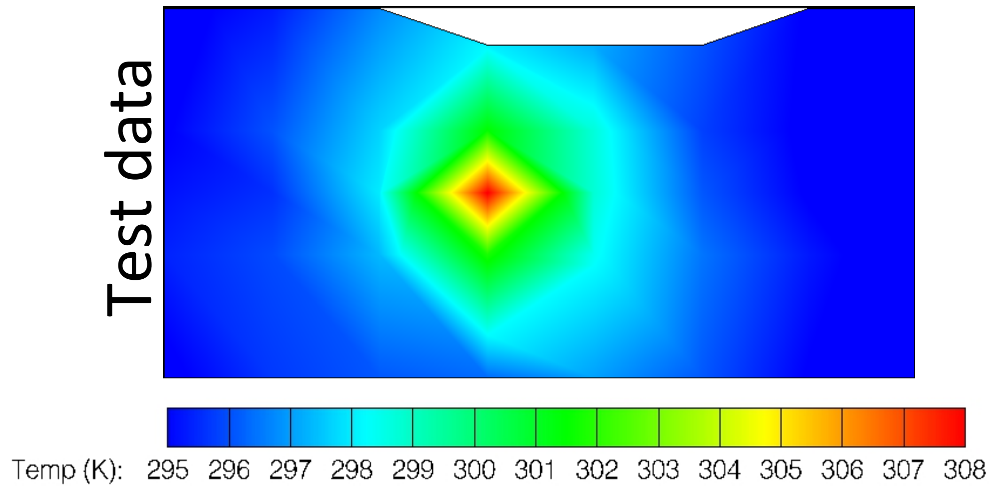
- Temperature predictions are higher than the experimental mean but still within the experimental uncertainty.

*"Cargo compartment smoke transport CFD code validation", J. Suo-Anttila *et al.*

Results

B707 Baseline Fire – Ceiling temperatures (60s)



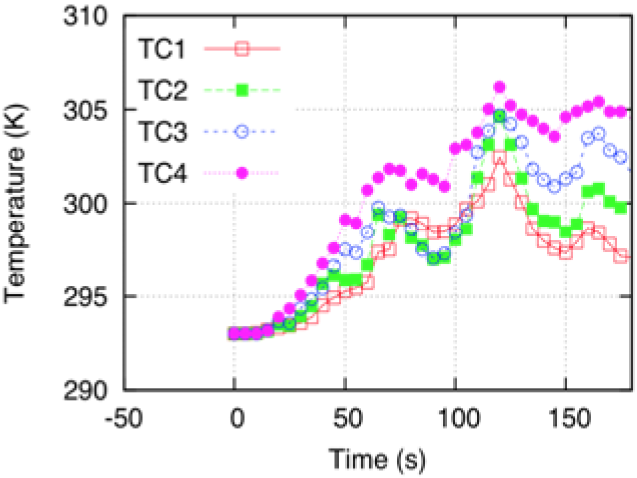


Results

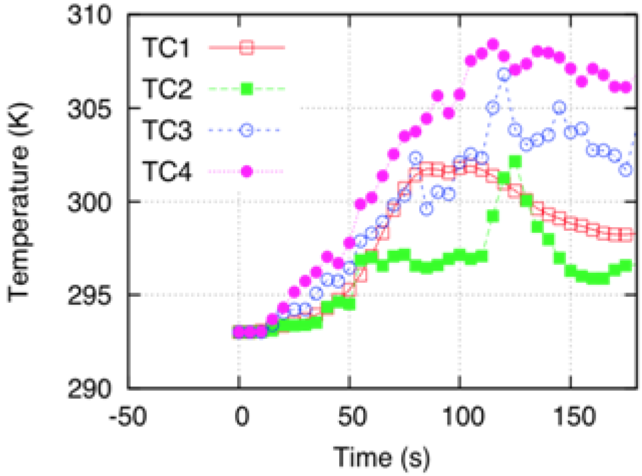
B707 Baseline Fire – Temperatures in vertical

Model

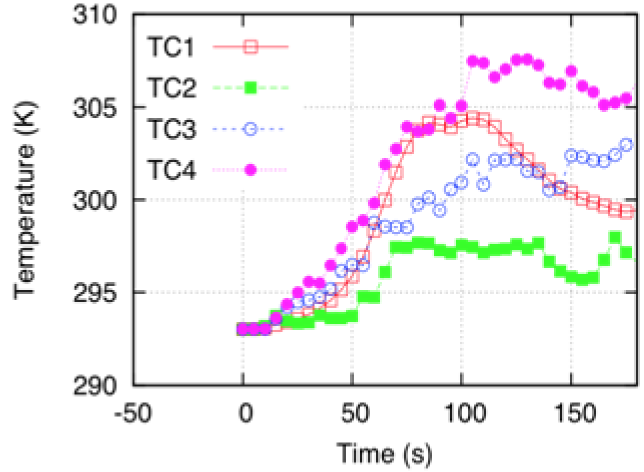
GL1



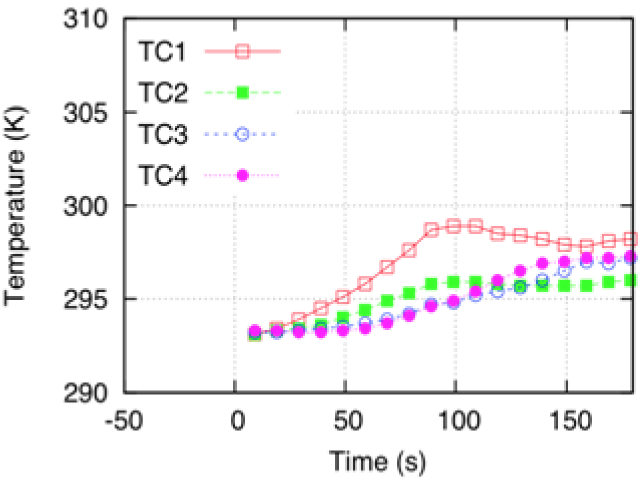
GL2



GL3



Test data



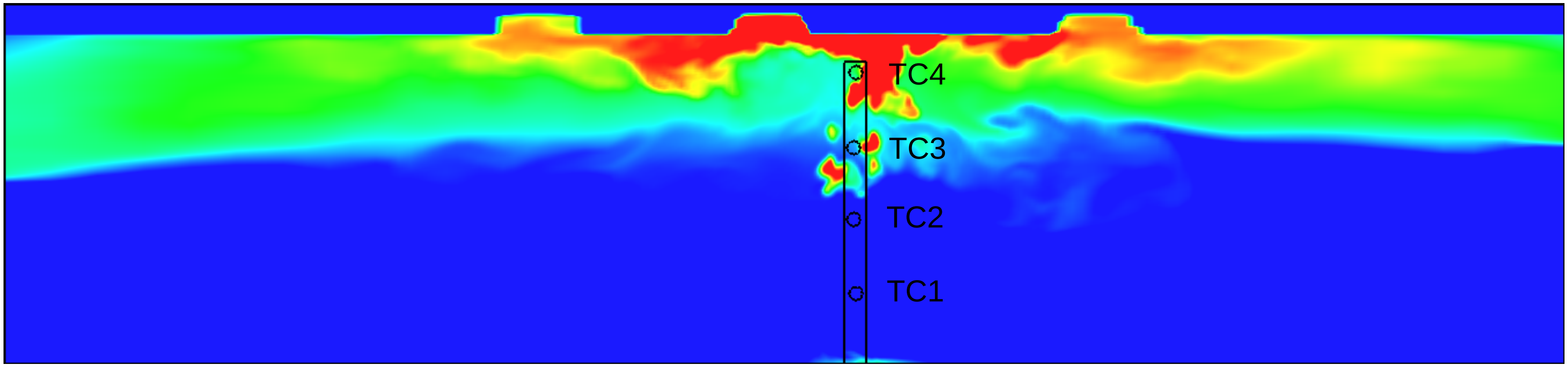
- Temperature measurements in the vertical are lower than the model estimates.

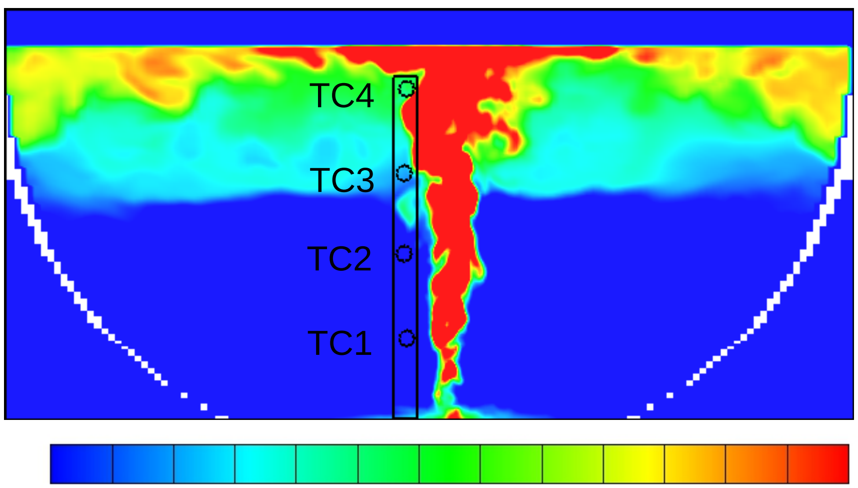
- Heat flux sensor readings are higher than the model heat fluxes.

Results

B707 Baseline Fire – Temperatures (120s)

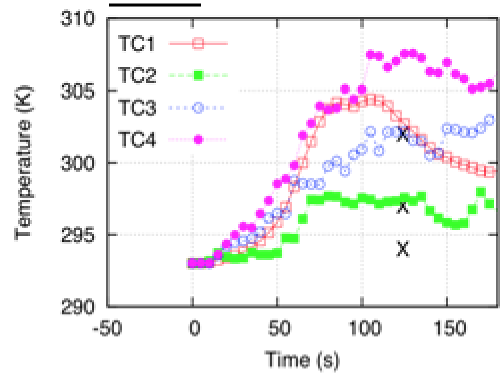
GL3



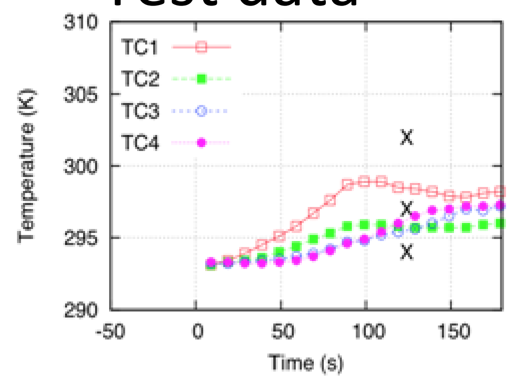


Temp (K): 295 296 297 298 299 300 301 302 303 304 305 306 307 308

GL3

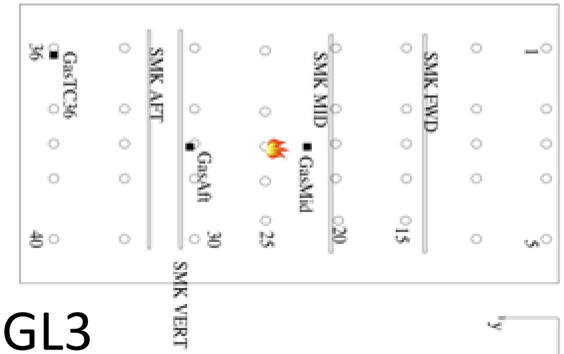


Test data



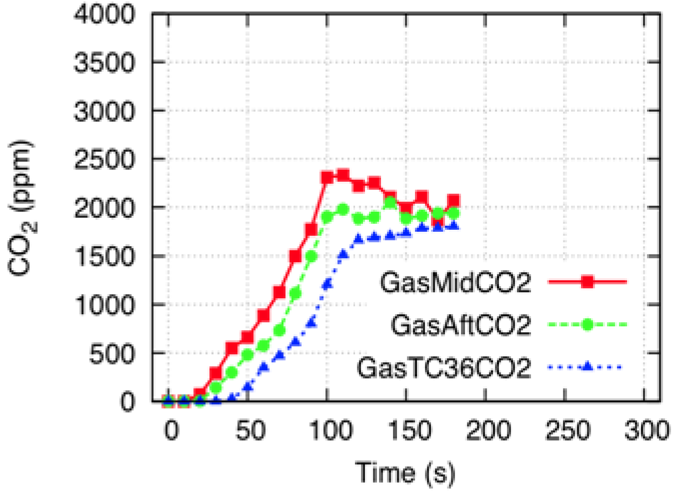
Results

B707 Baseline Fire – CO_2 concentrations

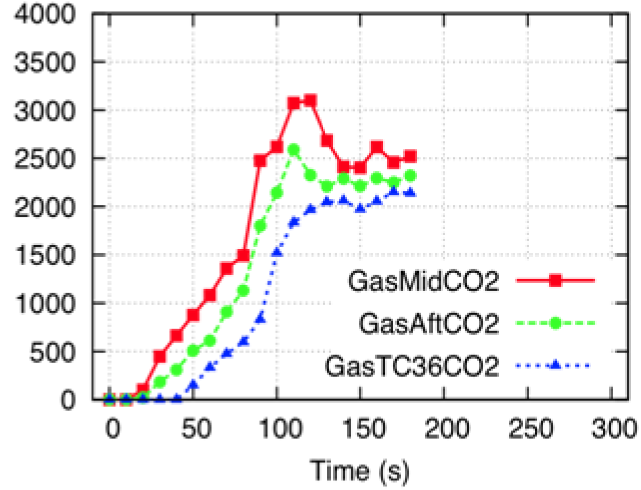


GL1

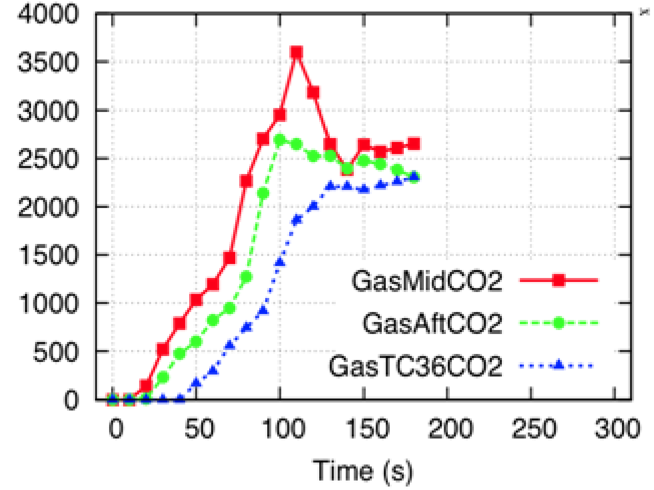
Model



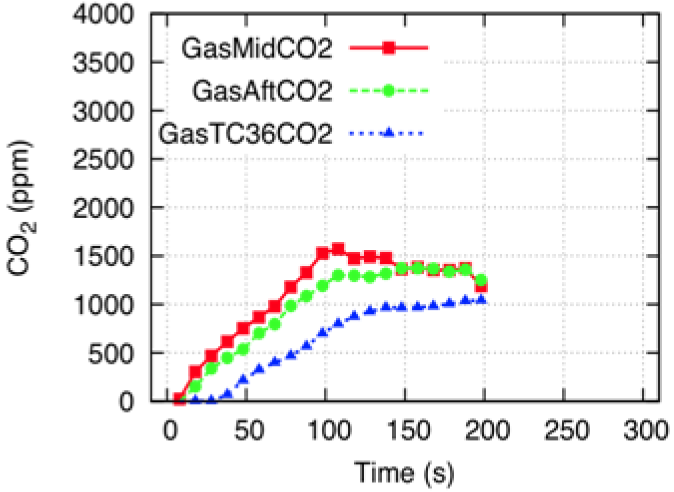
GL2



GL3



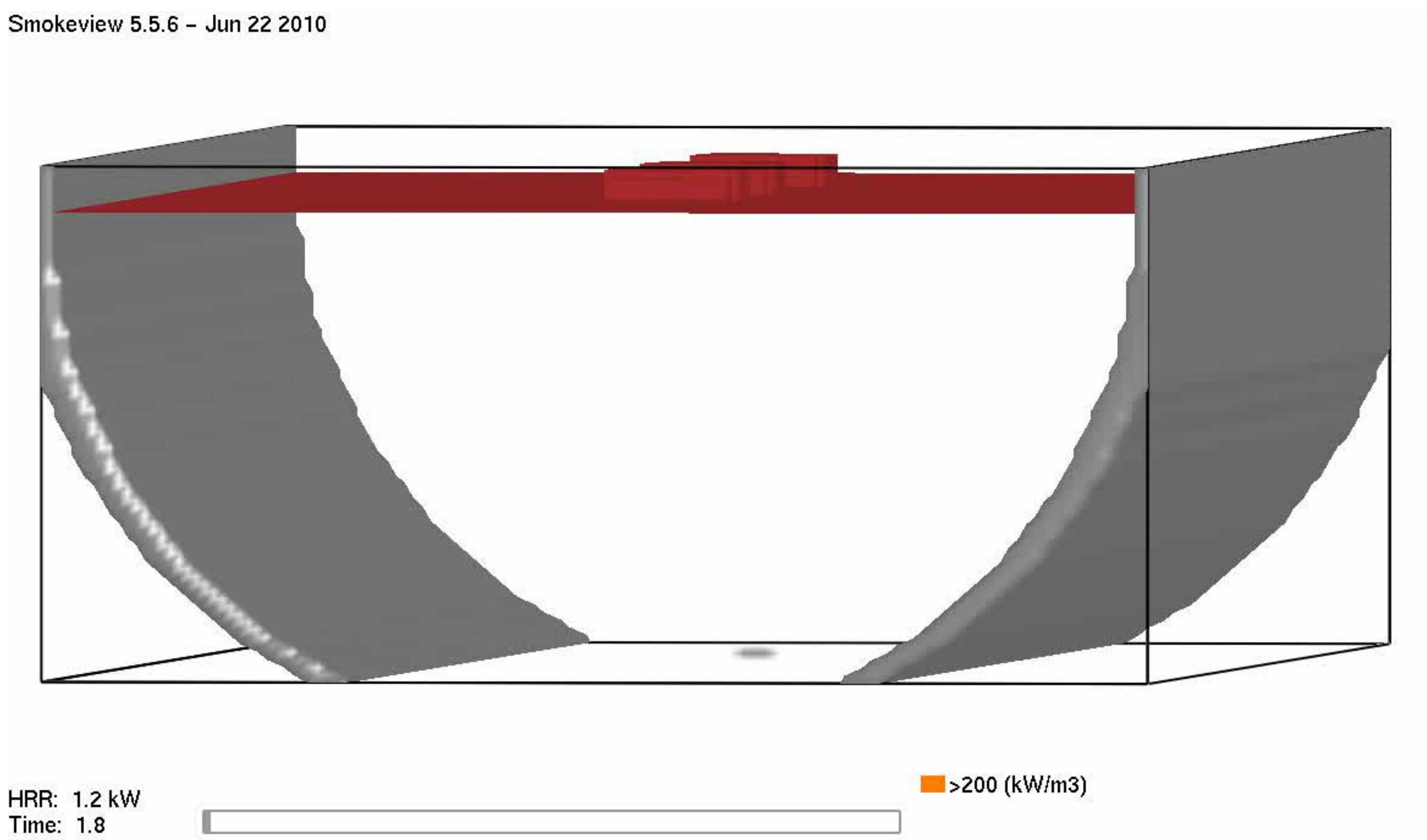
Measurements



- Concentrations are estimated higher than the test data. Model predictions are almost twice as high as the measured values.

Results

B707 Baseline Fire



Conclusions

<u>B707 Baseline Fire</u>

- Model solutions are
  - in good agreement with the test data for light transmissions,
  - high for ceiling temperatures,
  - much higher for temperatures in vertical, CO/CO_2 concentrations,
  - much lower for heat flux above the fire.
- The discrepancy may be due to
  - experimental uncertainty,
  - numerical model,
  - chosen model parameters.

Future Work

- Continue with further examination,
- Investigate model parameters for radiation and turbulence modeling,
- If B707 baseline fire scenario is found to be successful,
  - Continue code validation for other B707 scenarios: attached-corner and attached-sidewall cases, and for DC 10 cargo compartment with all three fire scenarios.