How to assess fire safety designs based on CFD modelling?

Ensuring proper use of CFD models in Fire Safety Engineering

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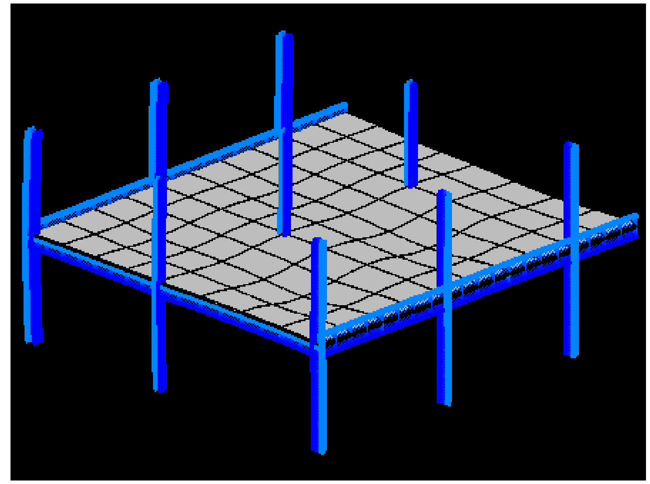
Prepared by Piotr Smardz

COMPUTER MODELLING IN FSE

Computer models are now used in the following areas of Fire Safety Engineering:

- Structural fire engineering (Vulcan, Safir, Ansys, Diana)
- Evacuation of buildings (Exodus, Simulex, Pathfinder)
- Spread of fire and smoke
  - Zone models
  - **CFD (field) models**
- Special purpose (DETACT)



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EMPIRICAL / ZONE / CFD MODELS

Tools for predicting smoke (and fire) spread can be split into 3 categories:

1. **Empirical** correlations
   - Very simple to use
   - Specific to a particular problem
   - Applicable to a limited range of conditions

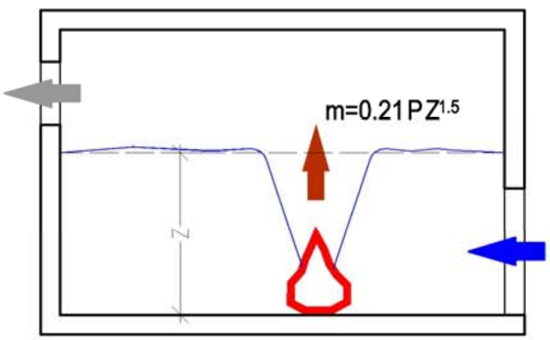
   Expl: Thomas' plume eqn

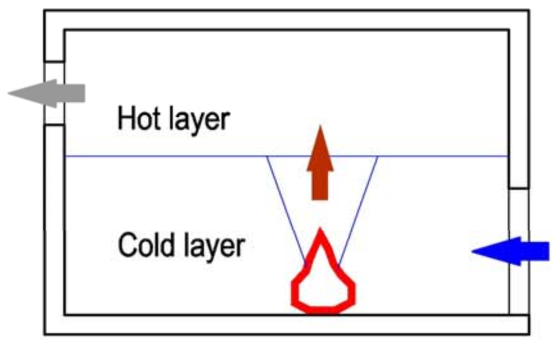
2. **Zone** models
   - Simple and fast to use
   - Application limits are defined
   - Several connected compartments can be modelled

   Expl: CFAST, OZone

3. **CFD** (field) models
   - Most sophisticated
   - Require expert knowledge
   - Provide "best picture" at the cost of long simulation times

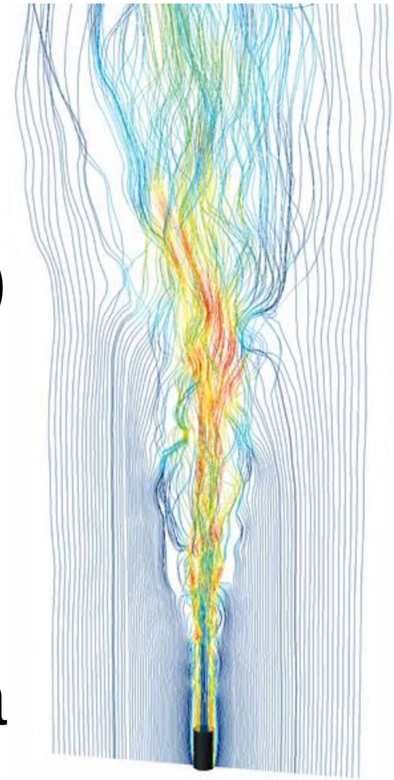
   Expl: FDS, Jasmine, Fluent





WHAT IS CFD?

The physics of fluid flow is described by a set of differential equations called the Navier-Stokes equations.



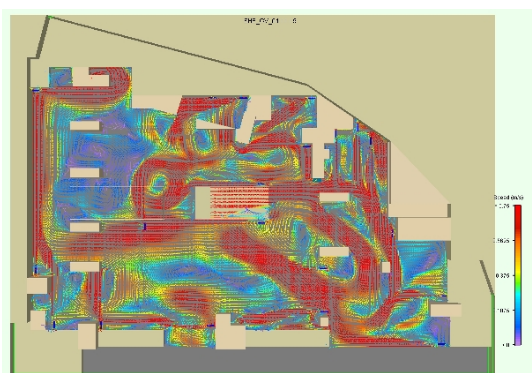
Computational Fluid Dynamics (CFD) is a numerical technique of solving these equations.

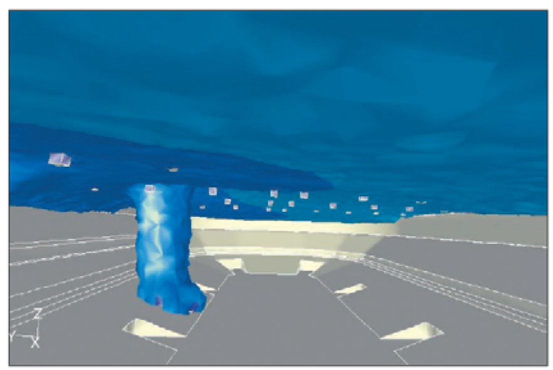
CFD is therefore a useful tool in investigating any process involving a motion of gas or liquid.

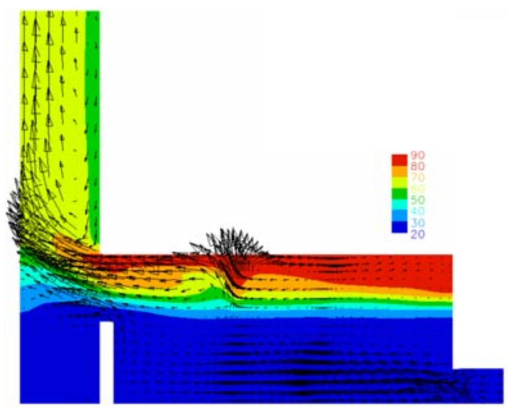
APPLICATIONS IN FSE

CFD modelling can be used in:

- Design of smoke control systems (also jet fan ventilation)
- Assessment of conditions for evacuation
- Assessment of thermal conditions in fire compartment
- Fire investigations (King's Cross, WTC)
- Research (BRE)







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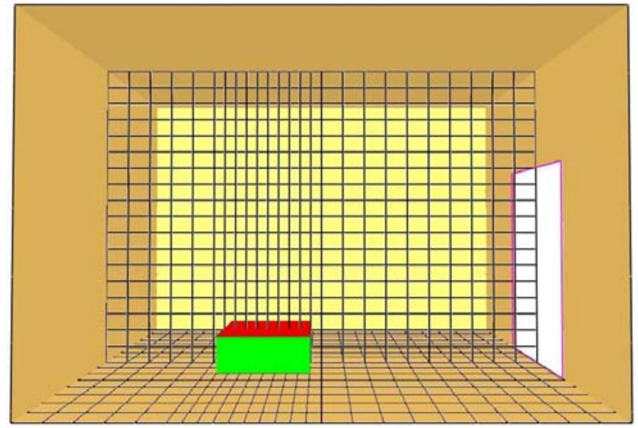
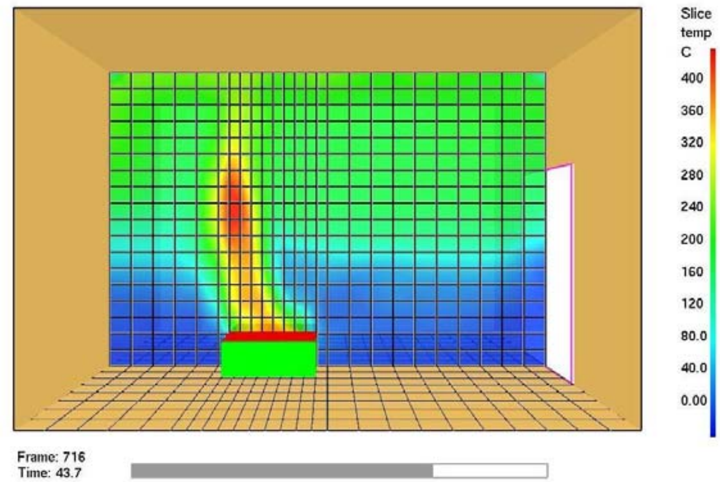
PRINCIPLES OF CFD (1)

- Computational domain is divided into a large number of control volumes (called the computational grid).
- Cells do not need to be uniform
- Obstructions, vents must conform to the grid
- Temperature, pressure etc. are uniform within each cell
- Boundary conditions are applied to define vents, extract fans, fire etc.

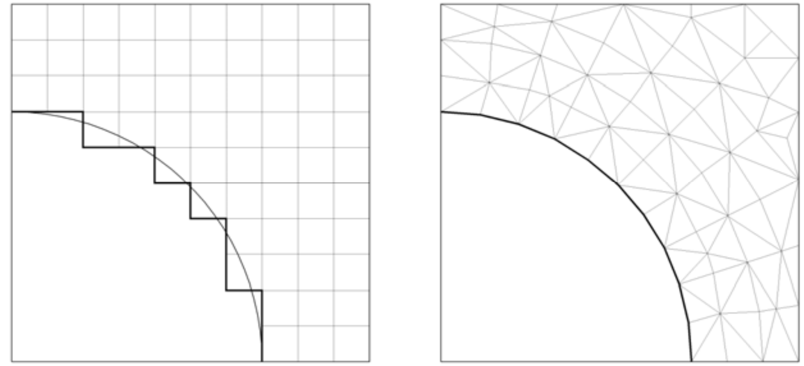




PRINCIPLES OF CFD (2)

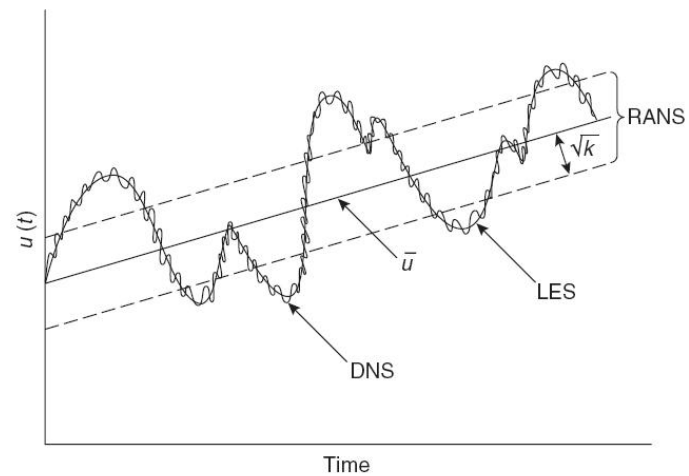
Computational mesh:

- Structured
- Unstructured



Physical sub-models for:

- Turbulence
  - ➢ RANS k-ε (most codes so far)
  - ➢ LES (FDS)
  - ➢ DNS (not applicable)
- Combustion
  - ➢ Heat source
  - ➢ One-step reaction
  - ➢ Multiple-step reaction
- Radiation (Six flux, Monte Carlo)



CFD PROGRAMS

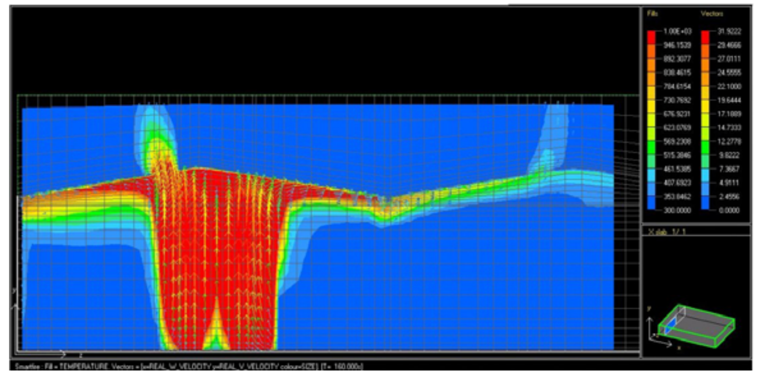
General purpose CFD codes:

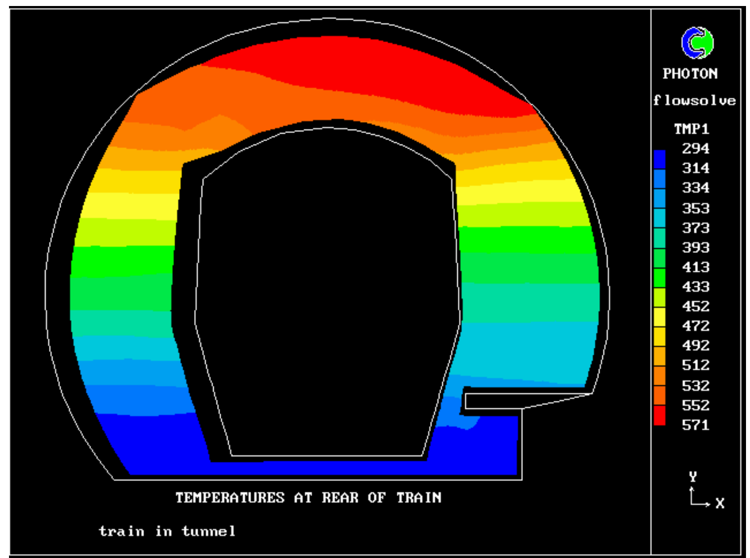
- Fluent
- Ansys CFX
- Phoenics / FLAIR
- STAR-CD v4

Fire specific CFD codes:

- **FDS (NIST)**
- SmartFire (FSEG)
- SOFIE (CU)
- Jasmine (FRS)
- Kobra-3D (IST GmbH)
- Solvent (for tunnel fires)

See also www.firemodelsurvey.com





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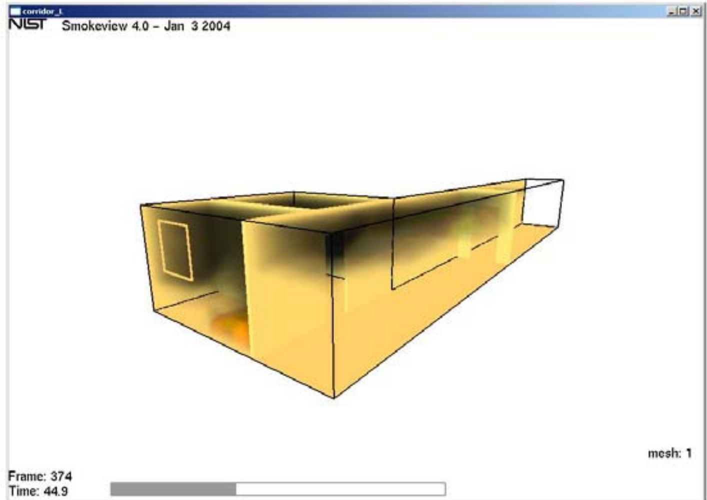
FDS – MAIN FEATURES

- Developed by NIST
- Sub-models for:
  - ➢ Turbulence (LES/DNS)
  - ➢ Heat transfer (FVM)
  - ➢ Combustion (mixture fraction)
- Multi-block, rectilinear grids
- Smokeview for viewing of results



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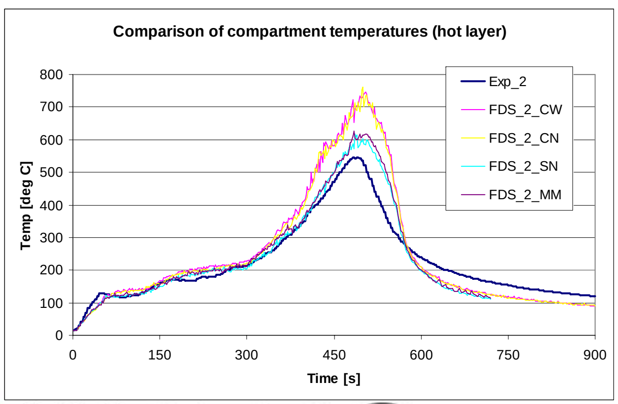
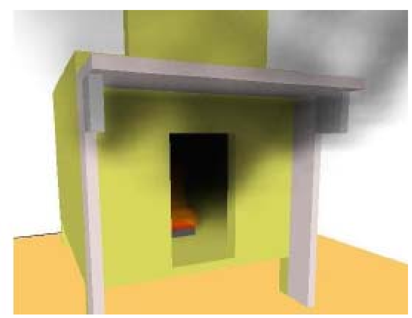
VALIDATION OF CFD SOFTWARE

Example - validation of FDS:

- Experimental
  - Large scale tests by NIST and VTT, including WTC fire experiments
  - Small scale tests
- Comparison with standard fire tests (e.g. room corner test)
- Comparison with documented fires





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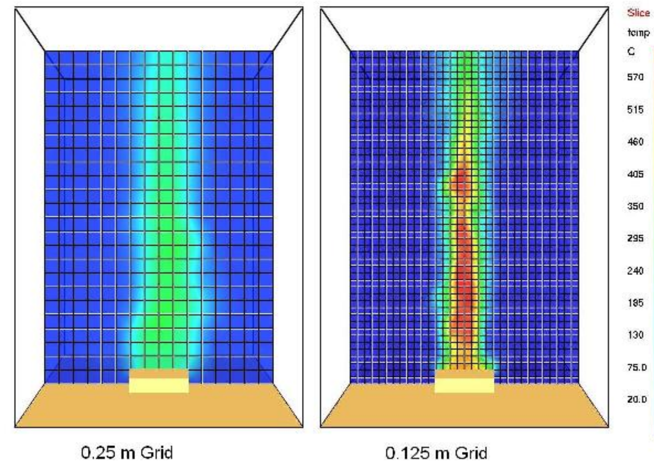
CFD - GOOD PRACTICE

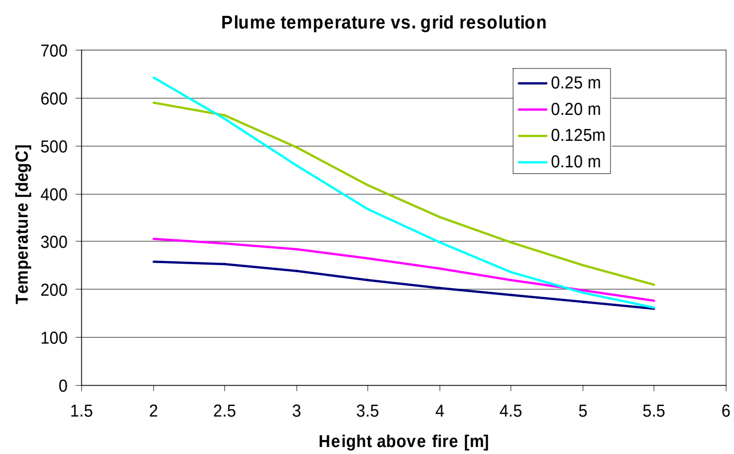
For a CFD simulation to be reliable we need:

- Proper assumptions / input data for
  - Fire (HRR, Smoke yields)
  - Ventilation (natural / powered)
- Proper selection of sub-models
- Reasonable grid resolution / cell aspect ratios
- Realistic boundary conditions
- “Internal check” of critical parameters
  - Flame temperature
  - Mass balance

GRID RESOLUTION

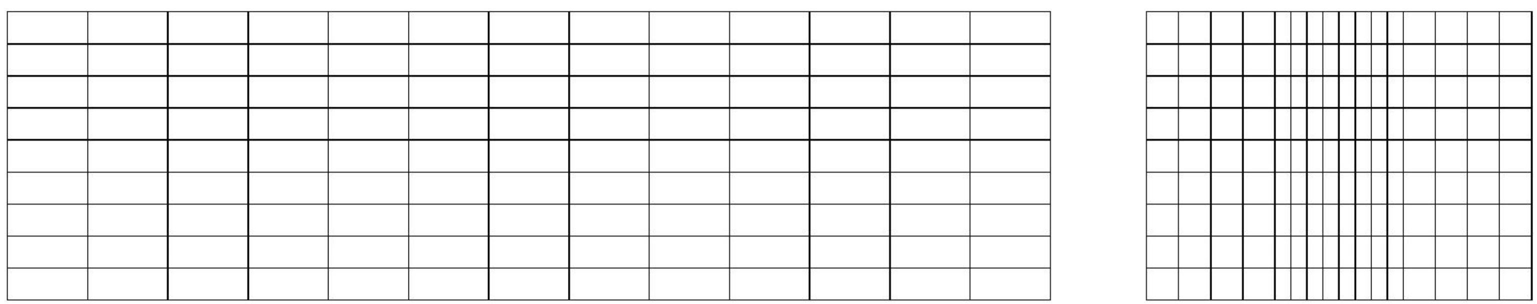
- Grid resolution can have significant impact on the accuracy of CFD predictions, particularly for LES models.
- Grids can be “stretched” in the areas of particular interest
- Domain size is typically limited to 3M cells for FDS simulations carried out on a single computer but can be larger for parallel simulations
- Proper resolution of fire area is also vital (for FDS: $D/\Delta x>10$, $z^*/\Delta x>20$)





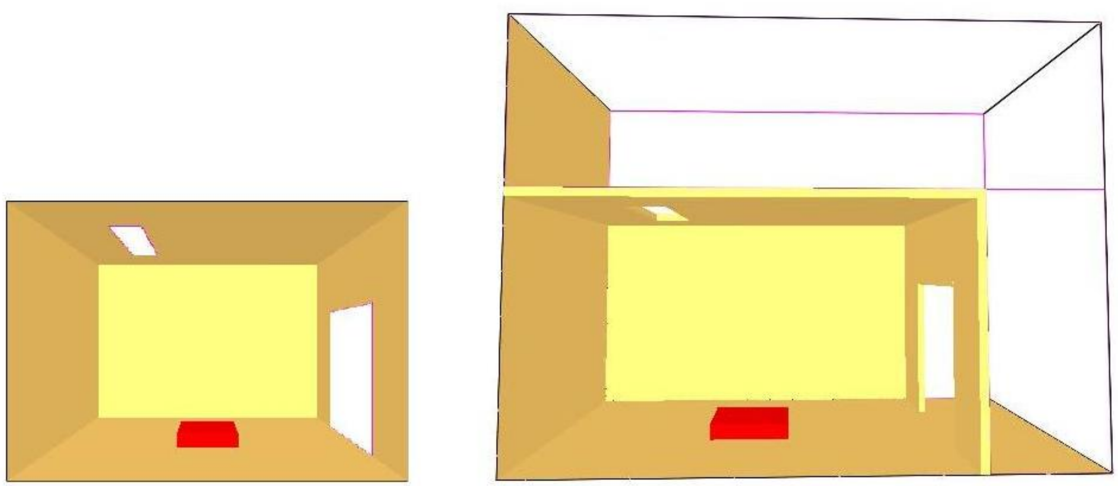
CELL ASPECT RATIO

- Cox and Kumar recommend 1 to 50 as the maximum aspect ratio (RANS models).
- Lower values close to fire (ideally, close to 1:1)
- For FDS much lower ratios are recommended (1:3 can be adopted as a reasonable limit)



BOUNDARY CONDITIONS

- Do not use symmetry condition
- Vents should ideally be modelled as opes in walls and not as a boundary condition (domain should be extended to include the outside of the building)
- Be careful with specifying mechanical ventilation



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TEMPERATURE PREDICTIONS

- Temperature should be monitored in “key” locations (e.g. within the fire compartment).
- Thermocouple readings should be used to create graphs (temperature slices may not capture all the detail of the temperature field)
- Flame temperature should not exceed 1300 ^{o}C, anything higher must be examined closely as it is likely to be caused by incorrect fire source specification

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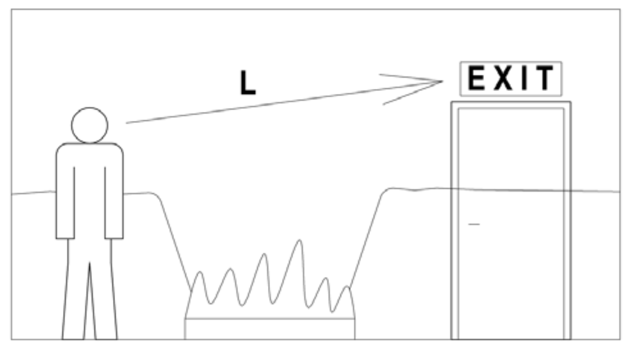
VISIBILITY PREDICTIONS (1)

- Light is attenuated when passing a distance L through smoke
- Light extinction coefficient K depends on the density of smoke
- Visibility through smoke depends on the type of object viewed:
  - C=3 for light-reflecting signs
  - C=8 for light emitting signs
- Density of smoke depends on the soot yield in fire [kg/kg]

$$I/I_0 = e^{-KL}$$

$$K = K_m \rho Y_s$$

$$S = C/K$$



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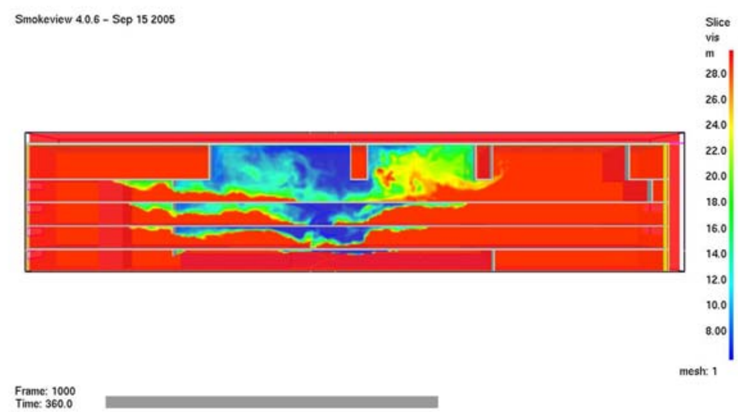
VISIBILITY PREDICTIONS (2)

- Specification of appropriate smoke yields is crucial for correct visibility predictions
- For flaming fires y_s range from 0.01 to 0.20
- Smoke yields increase in under-ventilated fires
- Visibility between two points: iso-surfaces of smoke concentration vs. line-of-sight integration of smoke concentrations



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CFD MODELLING REPORT

When CFD is used as a tool in FSE design a detailed report should be produced containing the following information (as a minimum):

- Name and version of the CFD model used
- For less known codes - information about the developers and validation for fire applications
- Type of the sub-models selected for turbulence (RANS/LES), radiation, combustion etc.
- Type and resolution of the computational grid, total no. of cells (for FDS also the no. of meshes) and maximum aspect ratio
- Assumptions made in relation to the design fire, smoke yields, material properties of enclosure, wind conditions etc.
- Print-out of sample input files
- Summary of results (full results should also be attached on CD)

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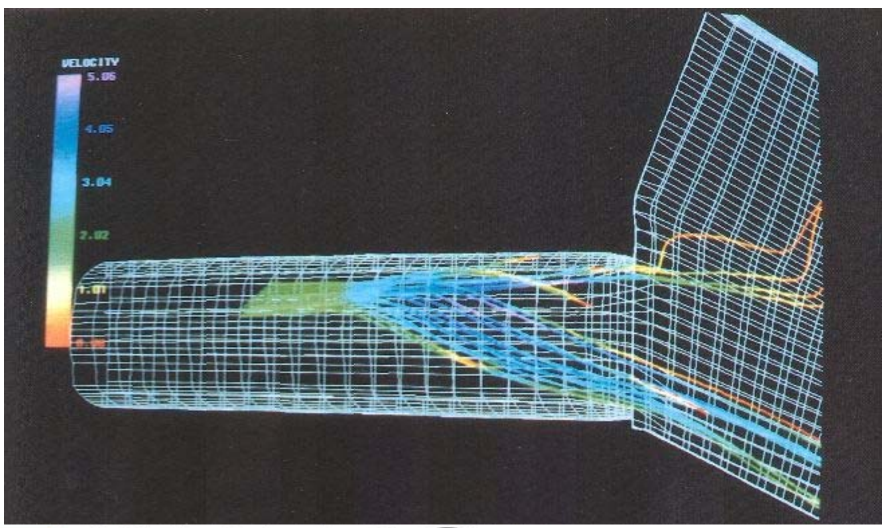
EXAMPLE 1 – KING'S CROSS FIRE

CFD analysis used as part of the official enquiry into fire (1987) in King's Cross underground station.

Unexpected behaviour of fire predicted by the CFD analysis.



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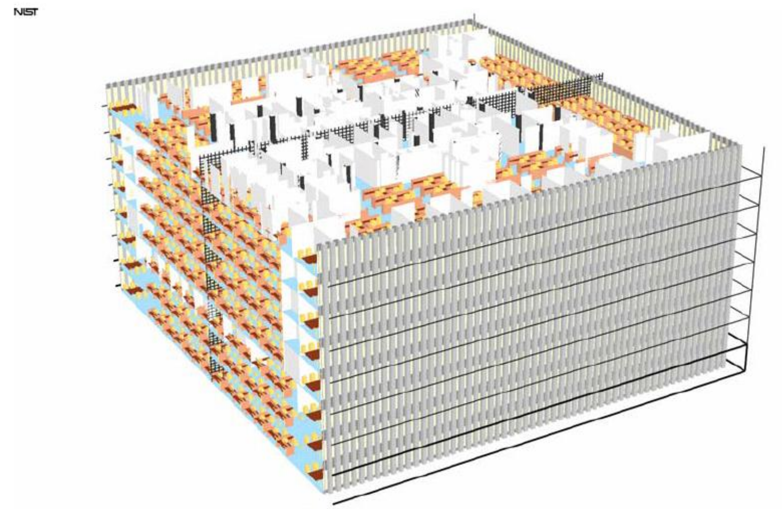
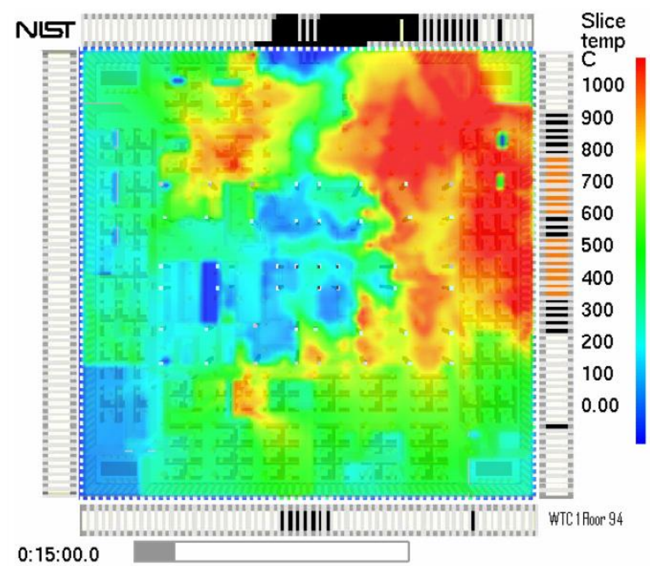
EXAMPLE 2 - WTC INVESTIGATION



As part of the investigation into the WTC collapse FDS was used by NIST to estimate thermal conditions on the fire-affected floors.



The results were used as input data for further structural analysis.

Large scale experiments to Validate FDS for this application

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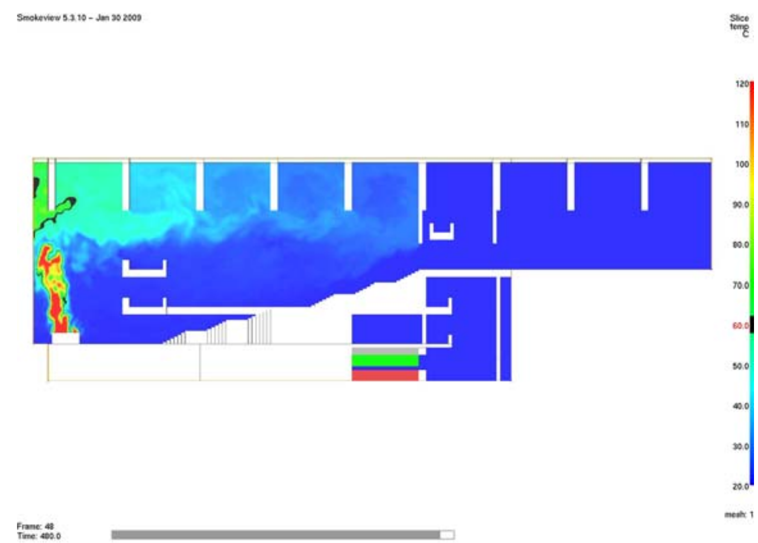
CFD CASE STUDY - LARGE ATRIUM

INBEPO used CFD modelling to predict smoke spread in the main atrium of the new university library in Wroclaw (Poland).

- Simulations carried out using FDS ver. 5
- 4 different fire locations modelled
- Multiple meshes used
- 1.8M-2.4M grid cells in total
- Results: visibility / temp



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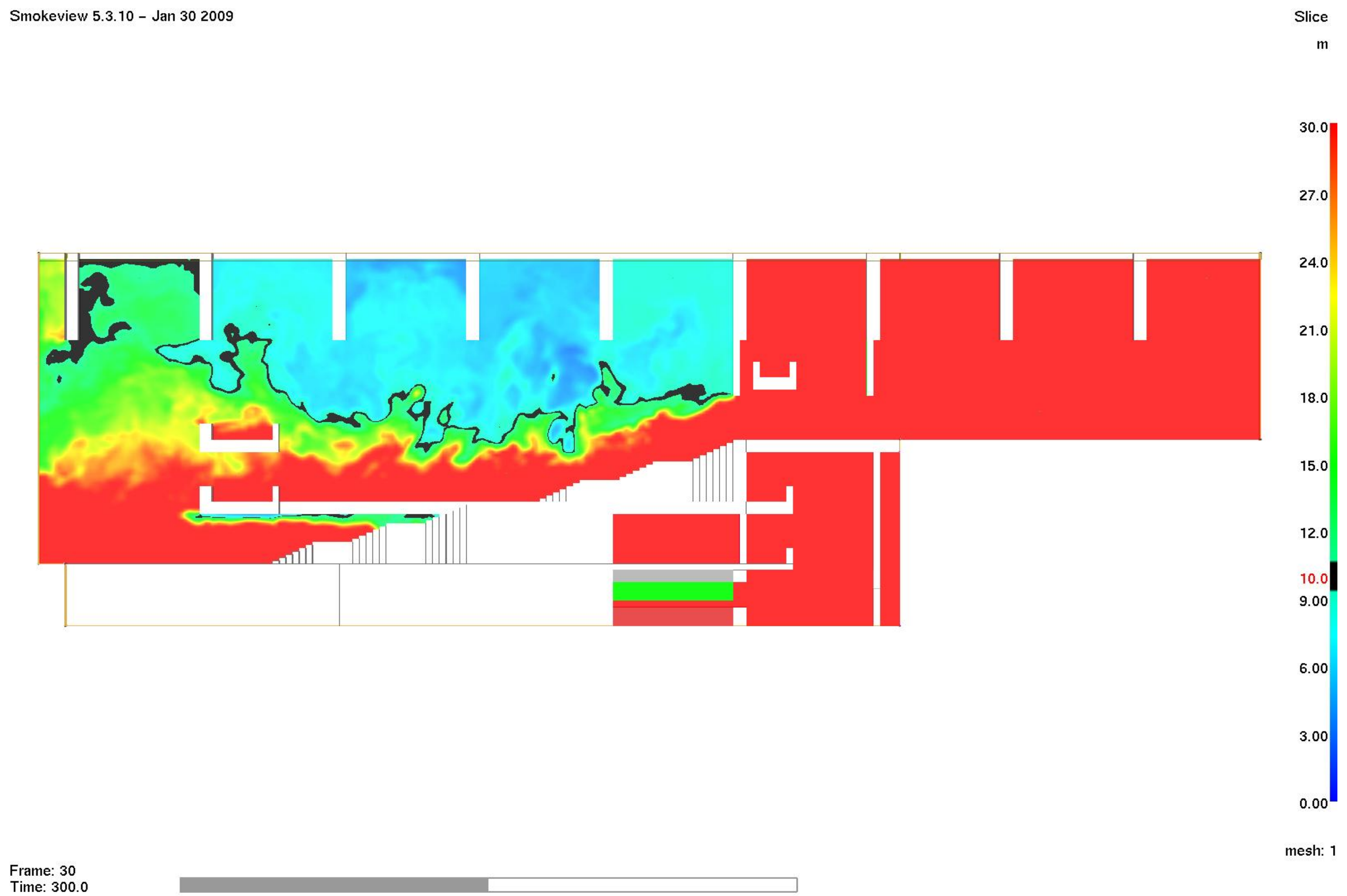
CFD CASE STUDY - LARGE ATRIUM



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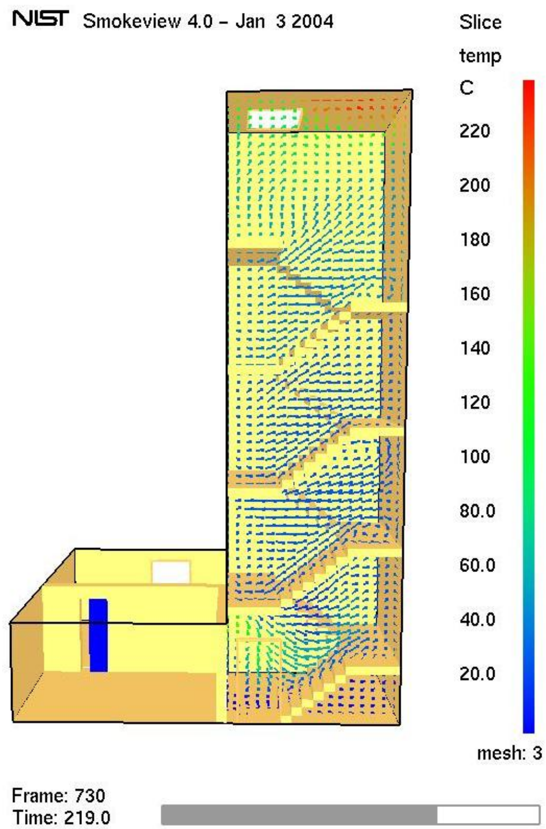
CFD MODELLING - SUMMARY

- It is a powerful tool for fire engineers (but only if used correctly!)
- Well validated for many FSE applications
- Good for smoke spread and temperature predictions (far-field), research is still on-going for more complicated phenomena such as flame spread, burning rate prediction & smoke production (near-field)
- Provides better picture than zone models but is much more time consuming
- Widely used worldwide to design complex buildings such as airports, underground stations, large atrium buildings etc.
- Right assumptions and selection of appropriate sub-models are critical for correct results
- Rubbish in = rubbish out (also true for zone models)
- Users need to be experienced fire engineers, competent in both fire science and numerical methods



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