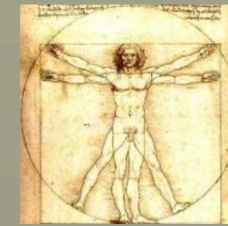

FIRE DYNAMICS - COMPARATIVE ANALYSIS OF CFD SIMULATION TOOLS AND THEIR UTILIZATION

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CFD and Evacuation in Built Environment

Tel-Aviv, December 2015

Content

Introduction

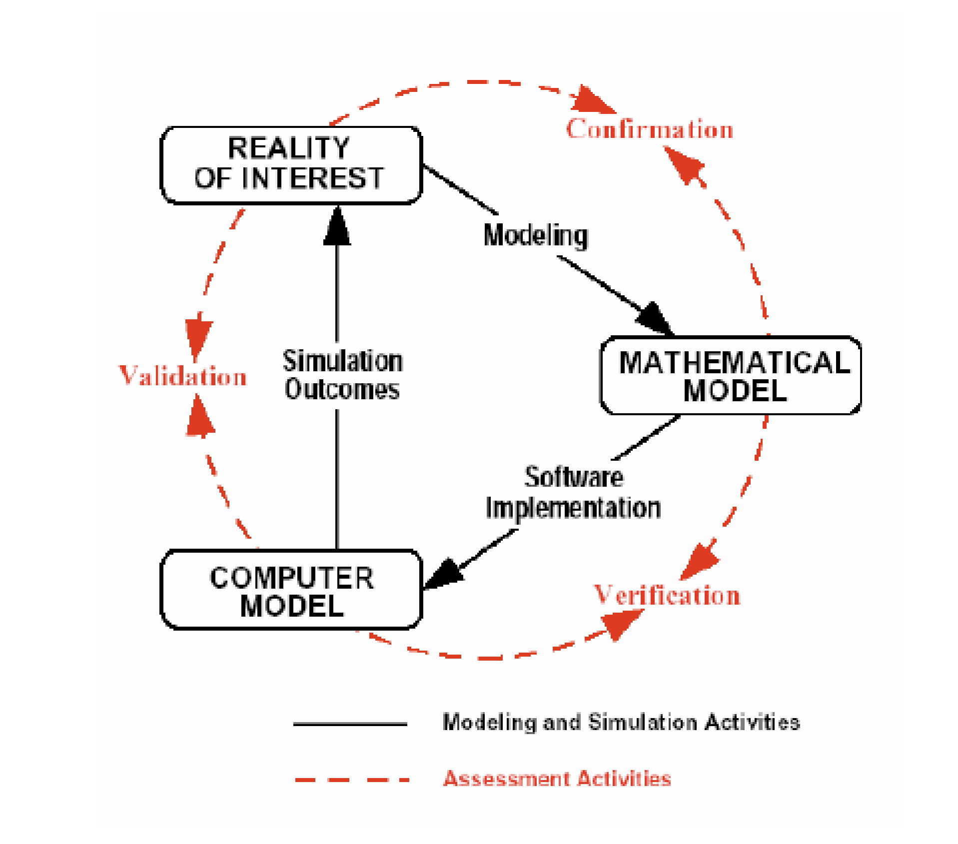
What is CFD ? → Computational Fluid Dynamics

Simulation design process and its benefits

- greater flexibility in managing ‘testing’ environment
- faster turn-around time
- more comprehensive post-processing options
- lower costs

Introduction

Simulation process is fundamentally different from physical experimentation and testing !



Concept relations in modelling analysis [1]

Fire dynamics and modelling principles

Fire is a complex process

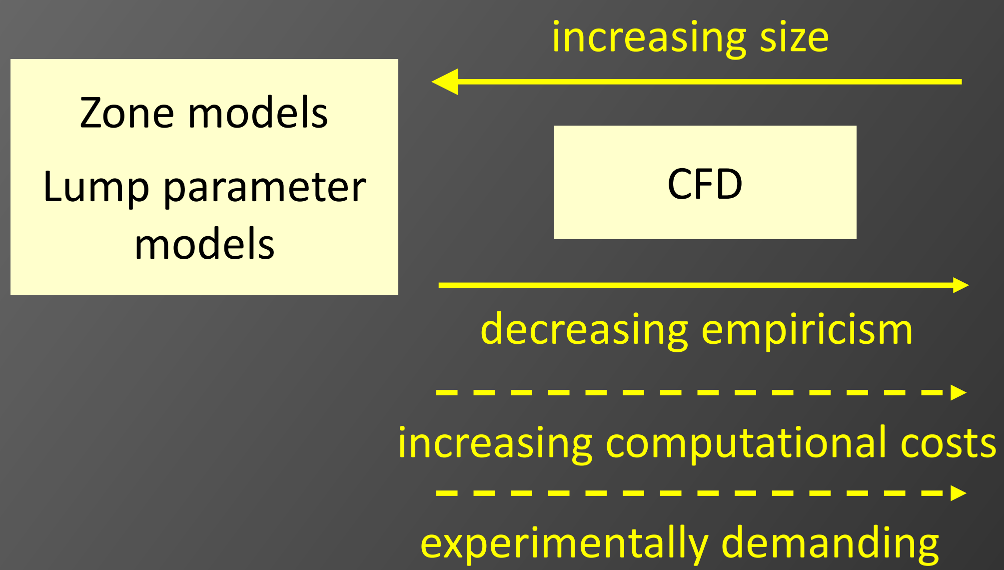
- chemical reactions
- release of heat
- external factors

Analytical tools are of limited applicability !

Fire dynamics and modelling principles

The solution is in space discretisation !

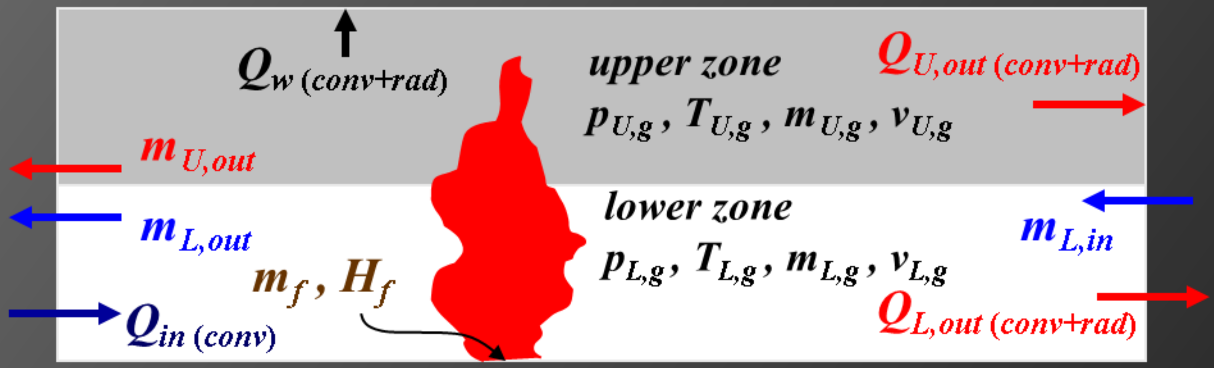
- Thermodynamic conditions
- Exchange of mass and energy → model complexity and level of empiricism



Fire dynamics and modelling principles

Zone models are the simplest modelling representation of fire.

- Conservation of mass and energy in a space separated onto zones
- Heat due to combustion of flammable materials, buoyant flows as a consequence of fire, mass flow, smoke dynamics and gas temperature
- One- and two-zone models



Typical two-zone model arrangement [2]

Fire dynamics and modelling principles

Further domain discretisation leads to so-called 'field' or CFD models

and ....

more accurate results.

Computational Fluid Dynamics (CFD) - group of methods and algorithms to solve discretized fluid flow and heat transport equations

Validation and verification

As the complexity of models increase, how do we know that the models give correct and accurate results?

- Software capabilities
- Definition of simulated problem
- Understanding of analysis objectives
- Definition of performance parameters
- Agreement on quality acceptance criteria

Validation and verification

Control quality through validation and verification cases [3]:

- geometrically simple
- representative and predominant 'physics'
- experimental and/or theoretical data

Testing methodology, toolset (i.e. software), and practitioner

Generic and project focused validation and verification activities

Validation and verification

Typical performance parameters in fire modelling

Conservation of mass, momentum and energy although case dependent:

- Adiabatic temperature of combustion
- Released energy
- Flame speed
- Composition change
- Far field heat flux
- Atmospheric dispersion and heat transfer correlations
- Supersonic flow speeds

CFD analysis codes

Fire dynamics is fluid flow and heat transfer problem

General CFD simulation packages: ANSYS-CFX, Fluent, Star-CD, Numeca, Comsol, OpenFoam etc.

Specialized CFD simulation tools : FDS, Flacs, KFX, Sophie, SmartFire etc.

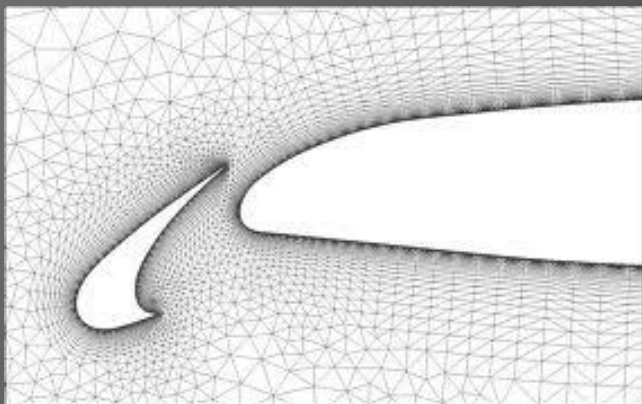
Significant differences in simulation approach, physics and chemistry models, user friendliness, support and business model

All these matters in selecting the right tool!

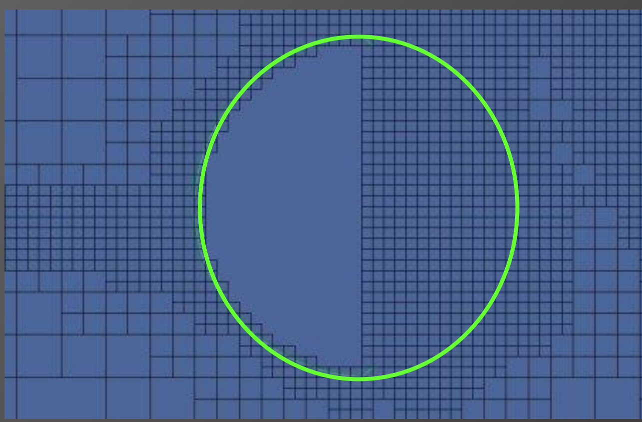
CFD analysis codes

Areas of differentiation:

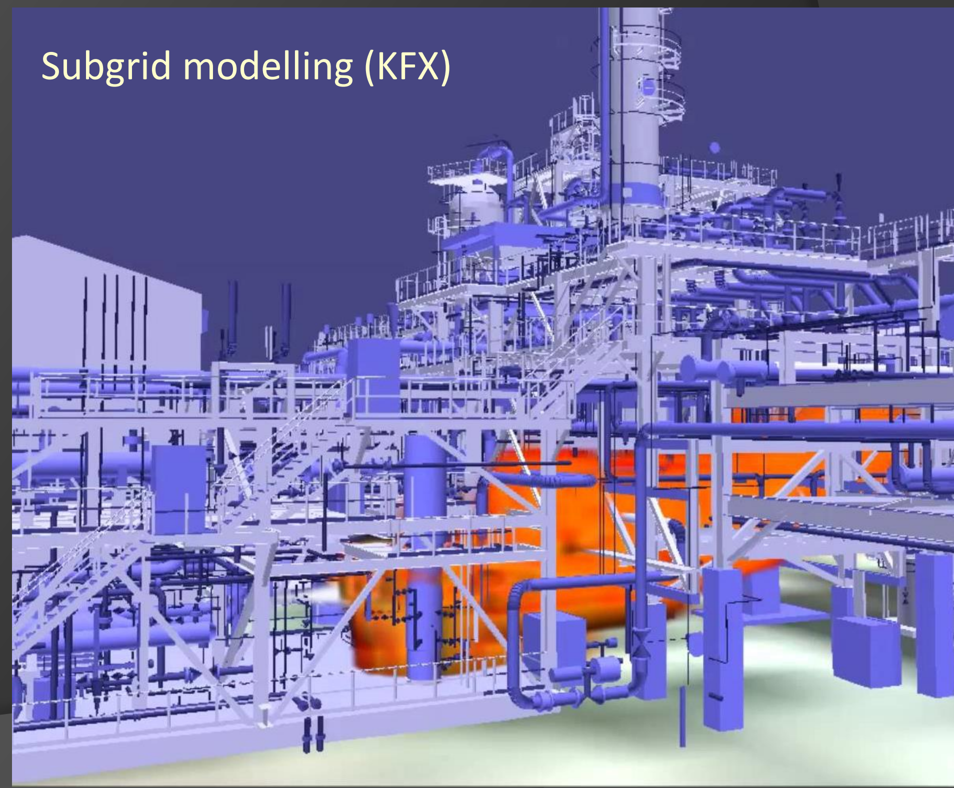
- Geometry resolution : fully resolved geometry OR immerse solids



Fully resolved geometry (ANSYS CFX)



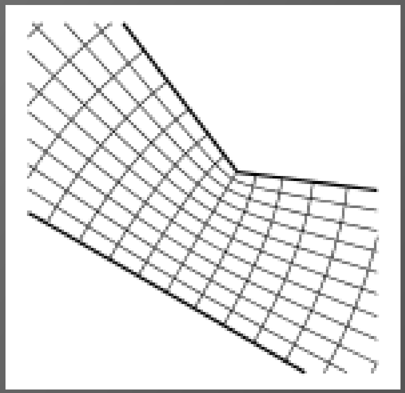
Immerse solid



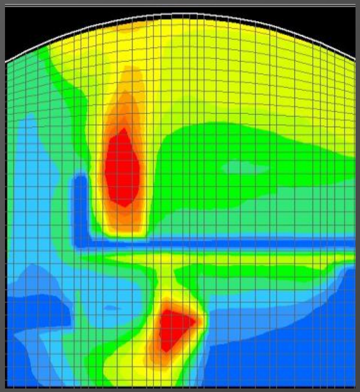
Subgrid modelling (KFX)

CFD analysis codes

- Grid type and generation method: body fitted, structured, unstructured (tetrahedral, hexahedral or polyhedral elements), nested meshes etc.

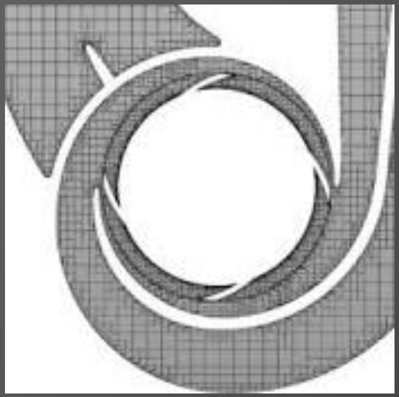


Body-fitted grid

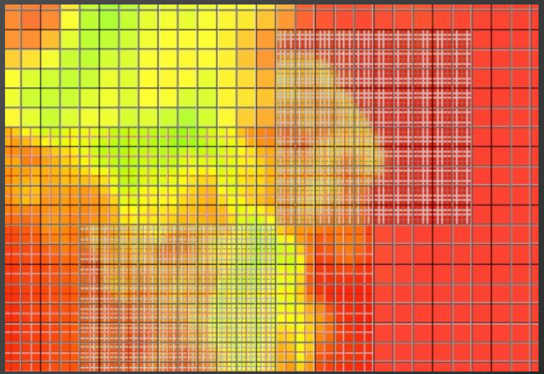


Structured grid (SmartFire)

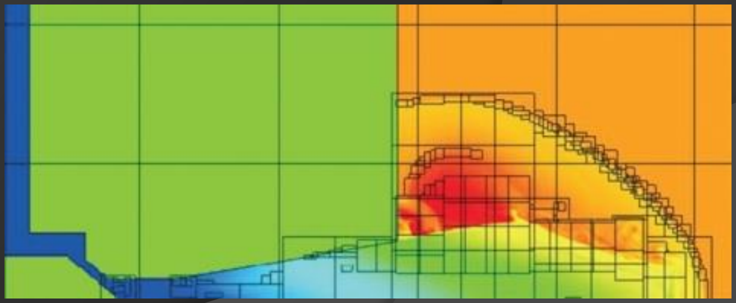
Unstructured polyhedral grid (Star-CD)



Cartesian cut-cell grid (Mentor Graphics)



Nested grid (FDS)



Dynamic nested grid

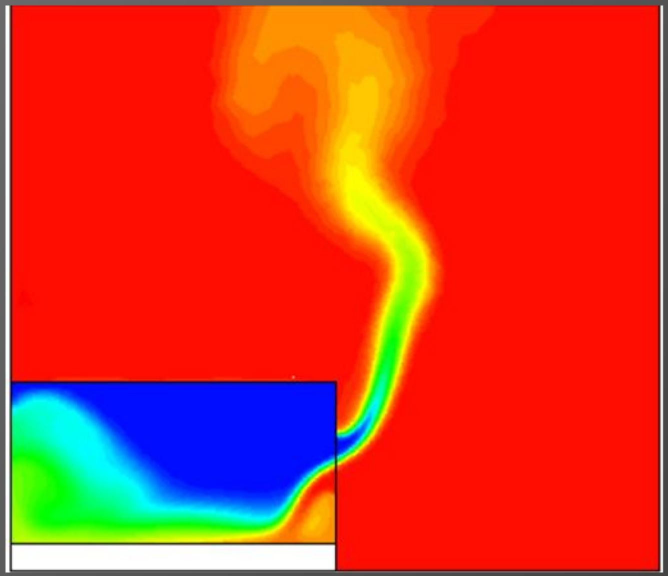
CFD analysis codes

Numerical grid is the critical component

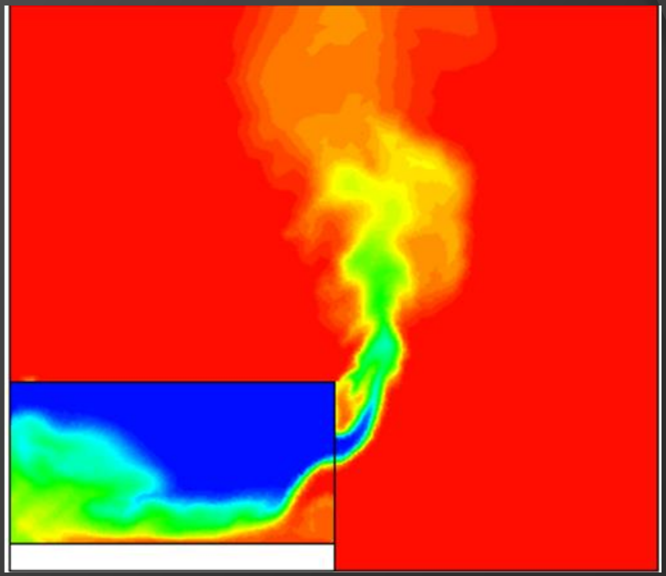
- quality of numerical results
- foundation for any software development

CFD analysis codes

- Turbulence modelling: algebraic turbulence mixing models, two-equation turbulence models, Reynolds stress modelling, Large-Eddy Simulation models



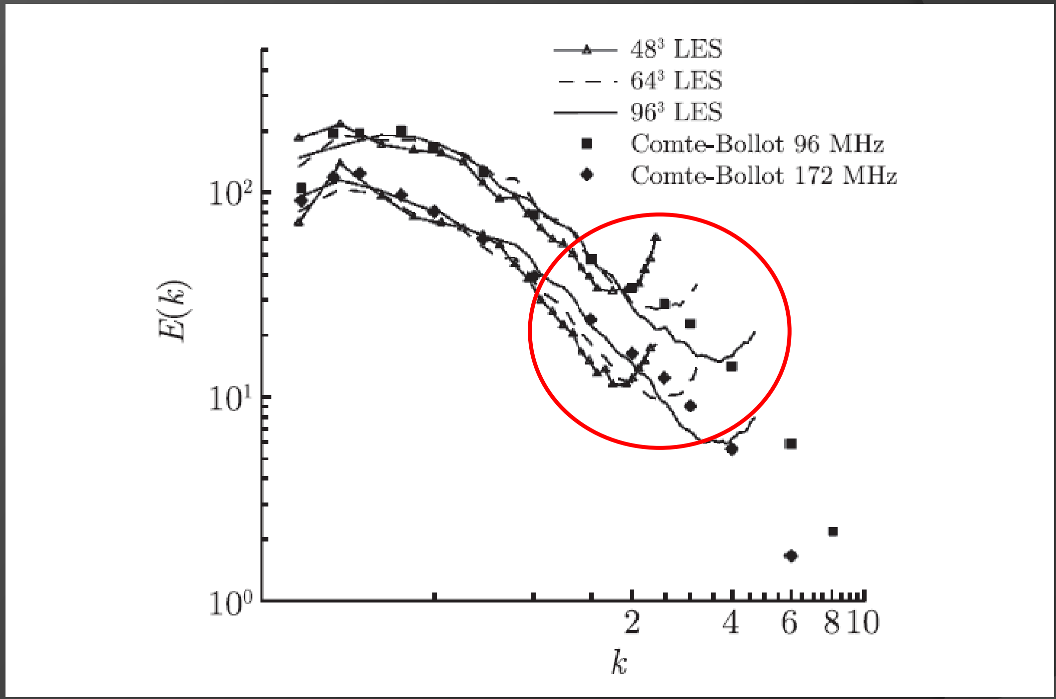
Backdraft - RANS turbulence model [4]



Backdraft - LES turbulence model [4]

CFD analysis codes

Sensitivity of LES results to the numerical grid density especially if the combustion rate depends on the level of turbulence!



Turbulence energy cascade - underresolved LES [5]

Robustness of Reynolds Average Navier-Stokes (RANS) models

CFD analysis codes

- Fire modelling: via heat sources

  - lost information on chemical composition

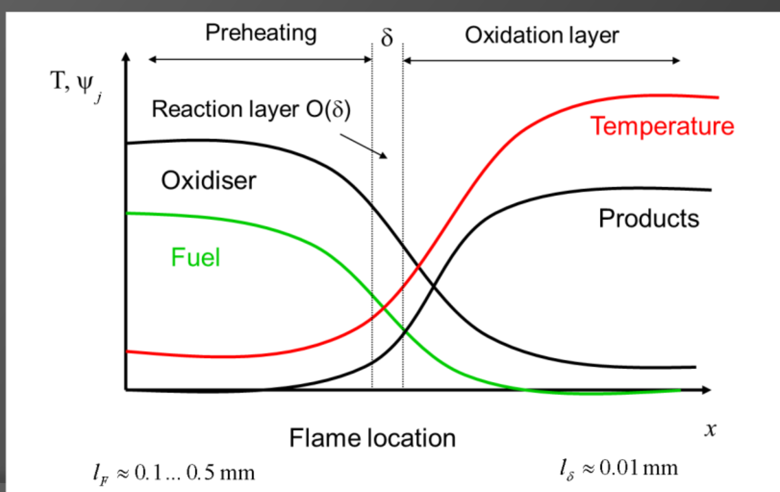
  - thermal loading under-estimated

  or with reaction modelling

  - composition transport equations

  - chemical balance equation

  - reaction rate model (eddy dissipation model, flamelet model, finite chemistry, burning velocity, mixed-is-burnt)

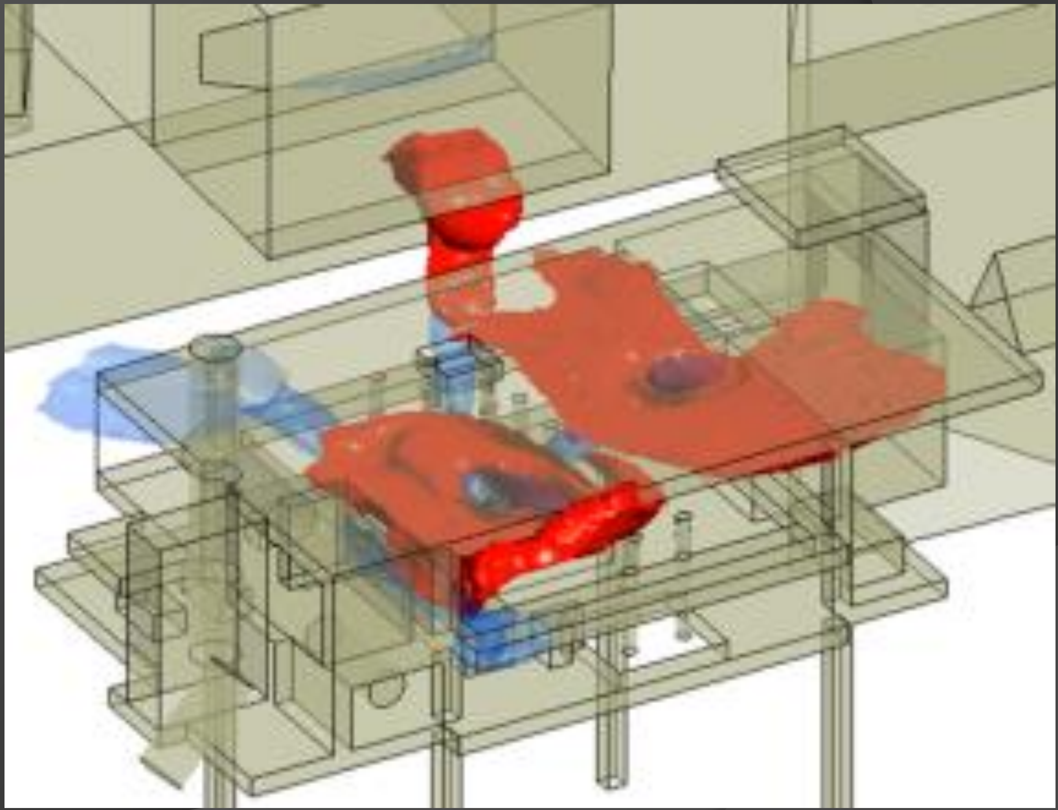


Premixed combustion [2]

CFD analysis codes

Modelling approach and the number of additional transport equations required

Extinction criteria (i.e. shear, temperature, local energy density, time of preheating etc)



Premixed combustion developing into jet fire

CFD analysis codes

- Thermal radiation: In fire simulations, it should not be neglected

Reduction of fire heat release rate (35% in FDS)

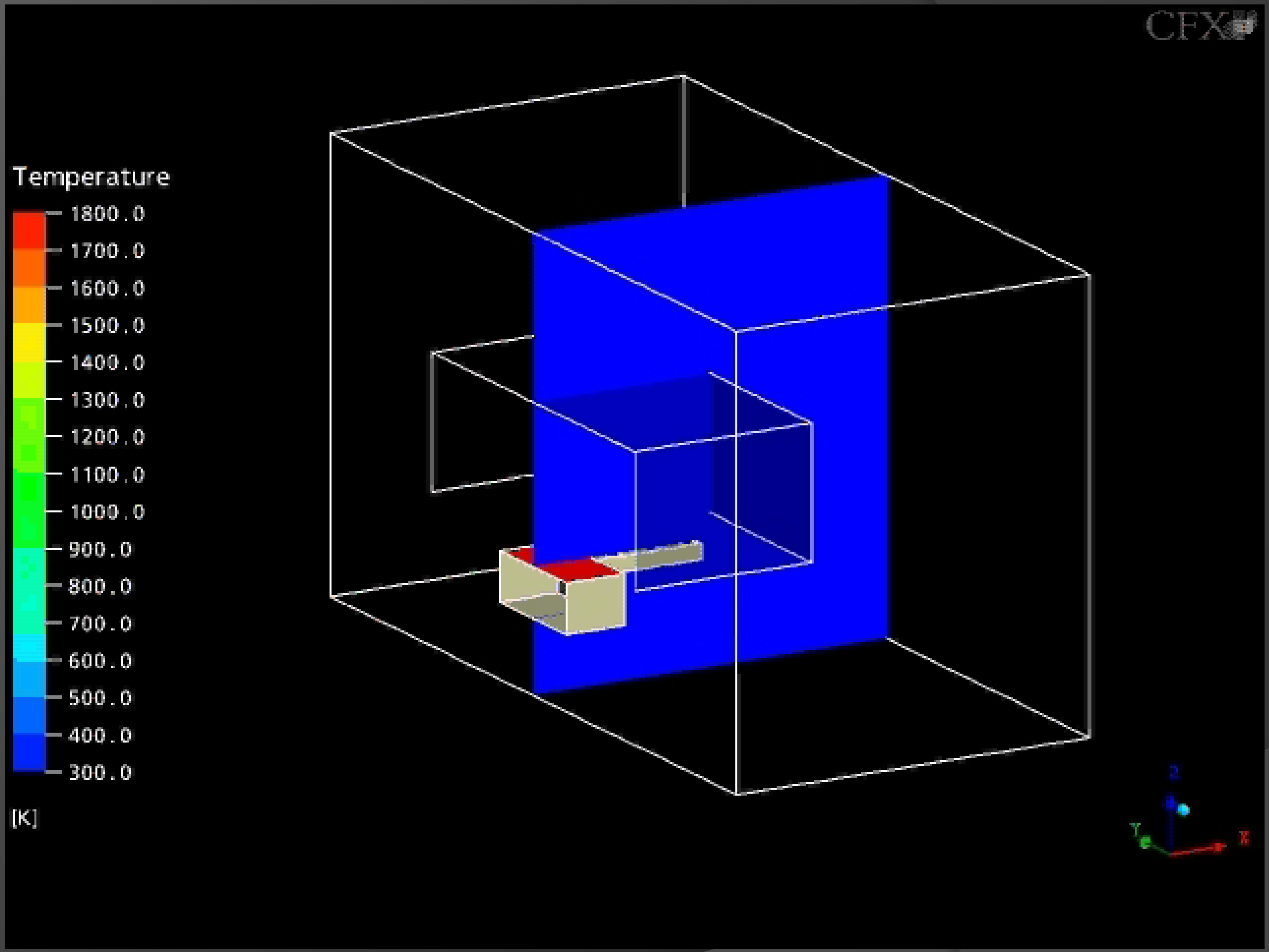
Modelling of thermal radiation - solving transport equation for radiation intensity

$$\frac{dI_\nu(\Omega)}{ds} = -(K_{a\nu} + K_{s\nu}) I_\nu(\Omega) + K_{a\nu} I_{e\nu} + \frac{K_{s\nu}}{4\pi} \int_{4\pi} I_{s\nu}(\Omega') P_\nu(\Omega' \rightarrow \Omega) d\Omega'$$

change of intensity | absorption and scattering | emission | in-scattering

Probably the weakest feature in many CFD packages

CFD analysis codes



CFD simulation of flashover experiment [6]

CFD analysis codes

- User support: Essential for utilisation of the software full capabilities
- Business model:
  - open source code
  - one-off or annual license fee
  - funding through governmental agency

Short development cycles of engineering software (6 to 12 months)

Constant improvements and maintenance

Comparative analysis

A comparative analysis of Fire Dynamics Simulator (FDS) and ANSYS simulation tools [7, 8]

Three different fire scenarios:

- fire in an enclosure (Ulster experiments)
- fire in a tunnel under natural ventilation (Memorial tunnel)
- fire in a underground train station (Kings' Cross accident)

Transient behaviour of selected cases, importance of convective vs radiative heat transfer, heat transfer across the walls or in the last case, complex geometry

Comparative analysis

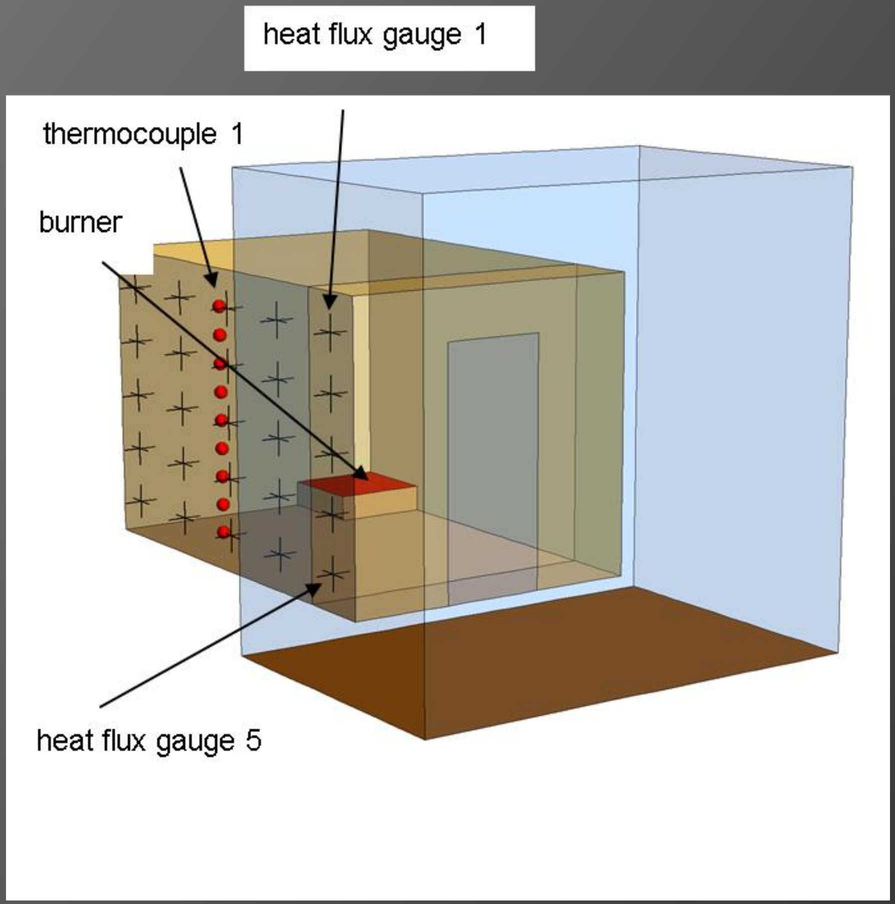
- Fire Dynamics Simulator (FDS) - computational fluid dynamics (CFD) model
- Smokeview (SMV) - visualization programme
- PyroSim - commercial graphical pre-processor

FDS and Smokeview applications - National Institute of Standards and Technology (NIST) in the US and VTT Technical Research Centre in Finland

Form of Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires

Comparative analysis

- Fire in an enclosure (Ulster experiments)



CFD simulation domain for the Ulster experiments [10]

Experiments performed by University of Ulster [9]

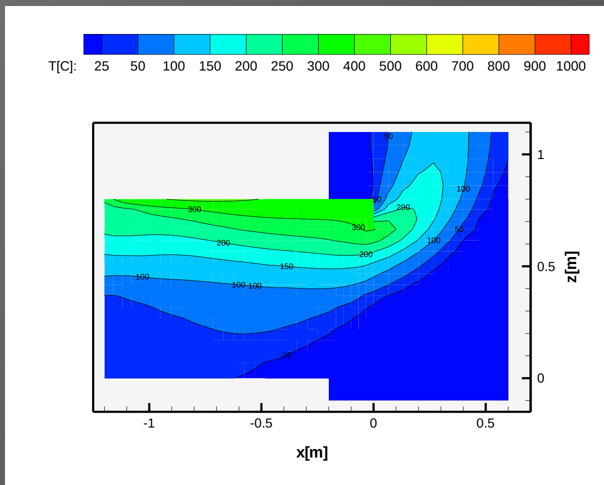
Transient fire (approx. 650 s) in a corner of an enclosure (80 cm long, 80 cm high, 120 cm wide):

- fuel (methanol) mass flow prescribed
- full combustion model
- radiation heat transfer
- heat transfer across the walls

Temperature and heat fluxes monitored at the wall

Comparative analysis

- Fire in an enclosure (Ulster experiments)



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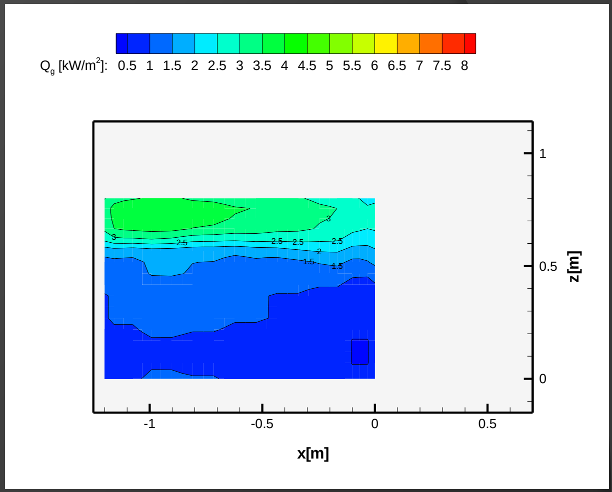

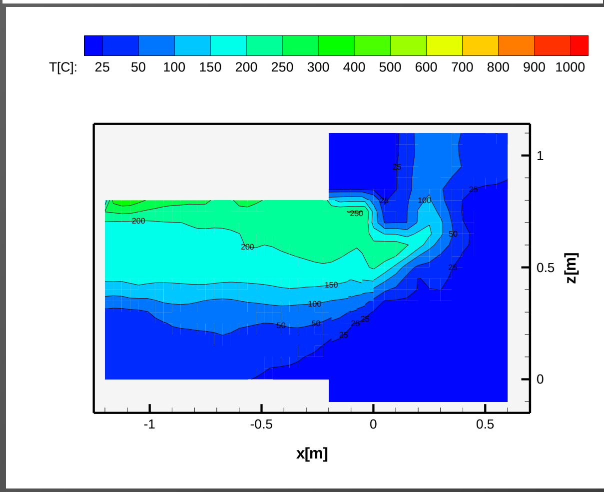

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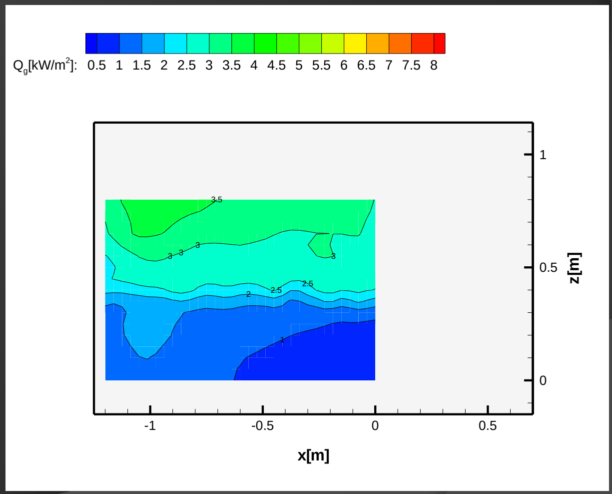
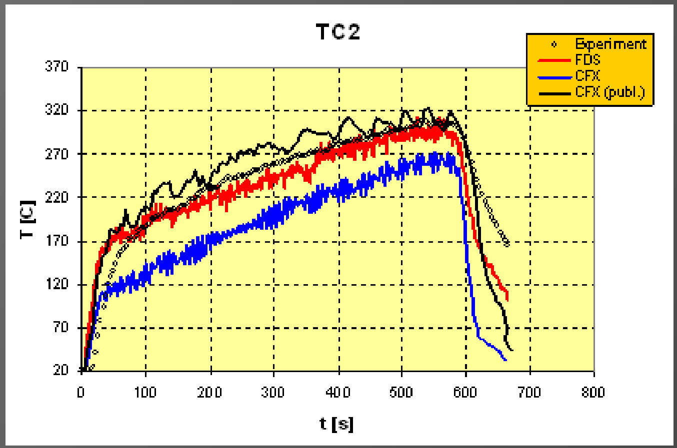


Temperature (left) and gauge heat flux (right) at 600.0 s and y = 0; **a)** CFX, **b)** FDS [8]

Comparative analysis

- Fire in an enclosure (Ulster experiments)



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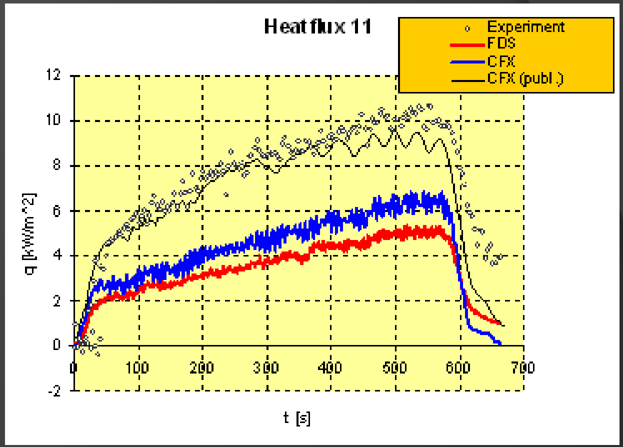

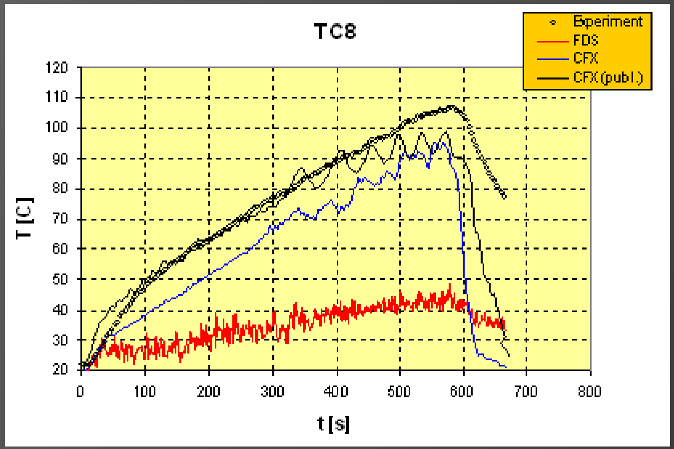

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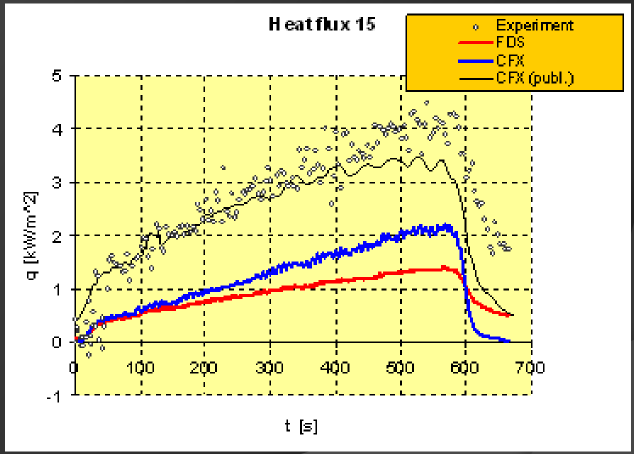
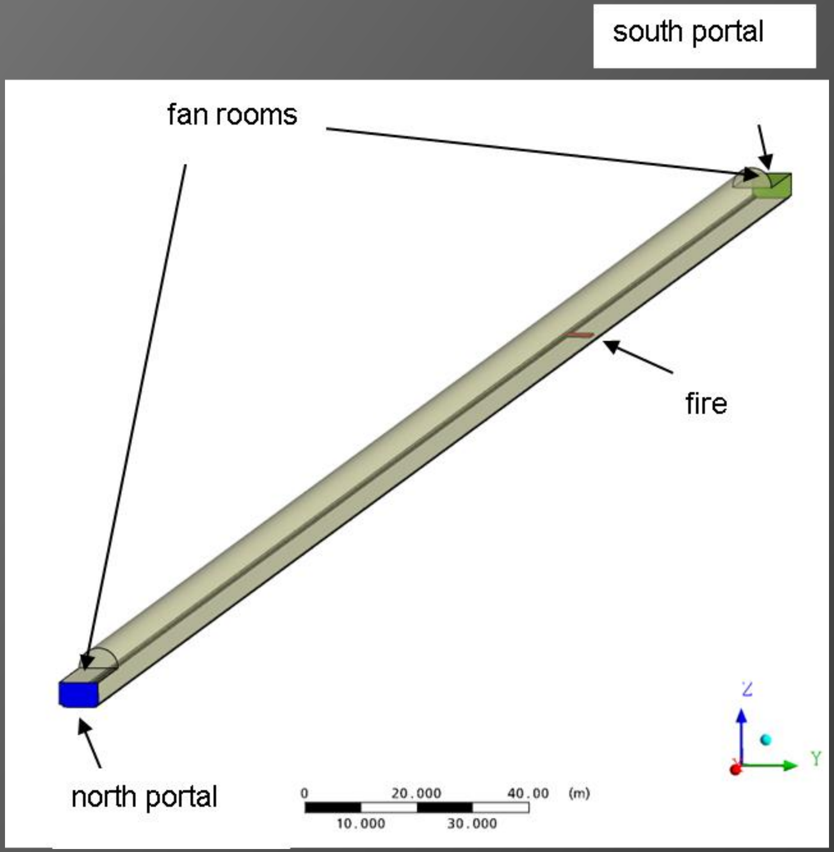


Temperature (left) and gauge heat flux (right) time variations; **a)** hot layer, **b)** cold layer [8]

Comparative analysis

- Fire in a tunnel under natural ventilation (Memorial tunnel)



CFD simulation domain for the Memorial tunnel experiment [7]

Full scale fire in a tunnel (Memorial Tunnel experiment, USA, 1995)

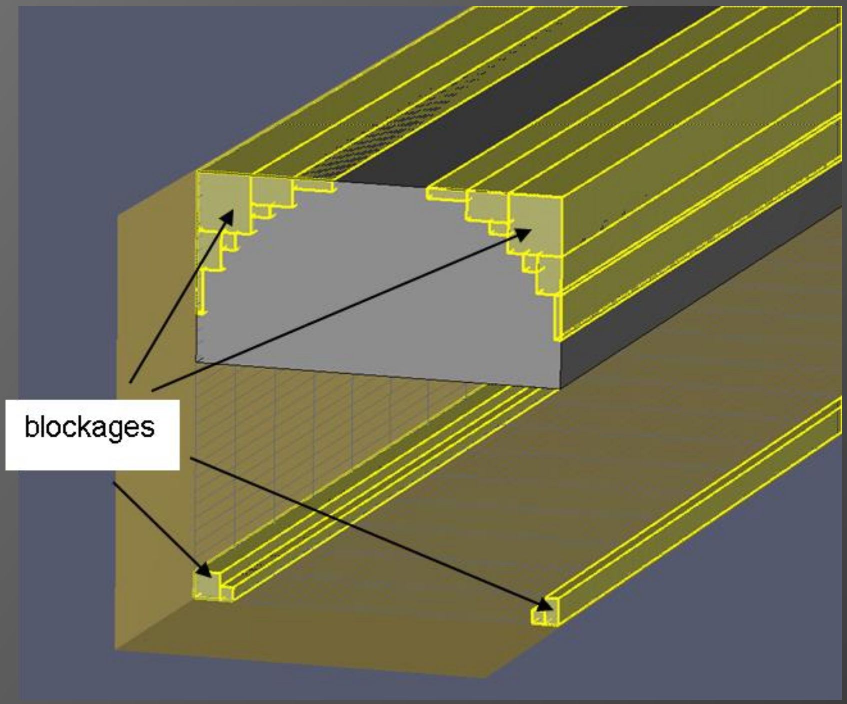
50 MW fire in a 853 m long road tunnel with 3.2% inclination from South to North:

- propane as a fuel
- full combustion model
- radiation heat transfer
- prescribed wall heat transfer coefficient

Temperature comparison between the CFX and the FDS results, and comparison of velocity profiles with the experiment

Comparative analysis

- Fire in a tunnel under natural ventilation (Memorial tunnel)



Geometry representation in FDS

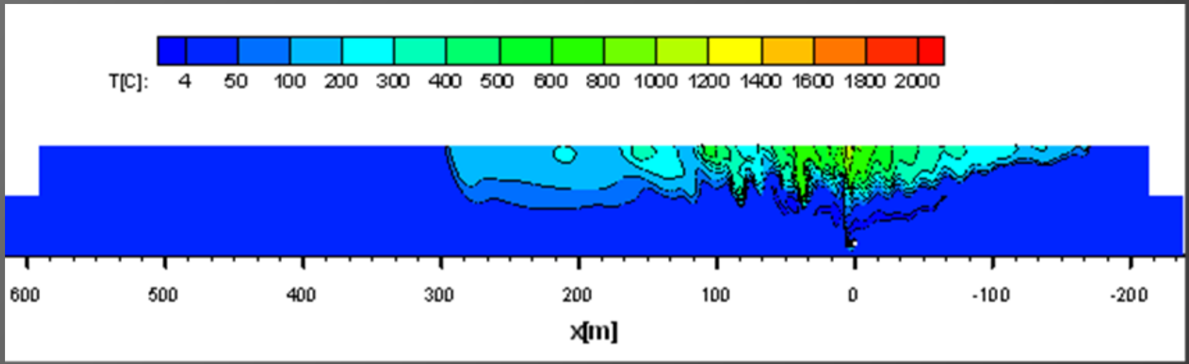
FDS uses structured grid

- defined as a simple rectangular volume
- non-rectangular (e.g. cylindrical) shapes carved from the initial rectangular volume
- curved walls are not smooth and a boundary layer is not approximated

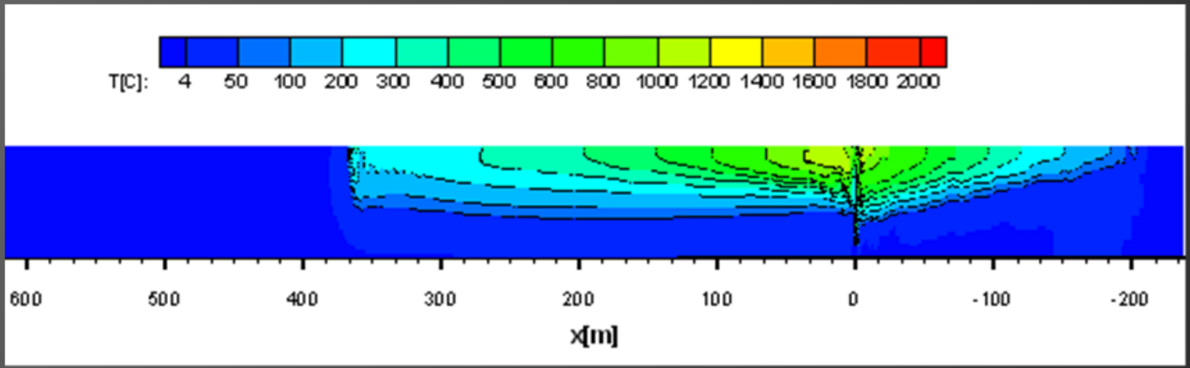
Automatisation with **PyroSim** !

Comparative analysis

- Fire in a tunnel under natural ventilation (Memorial tunnel)



a)

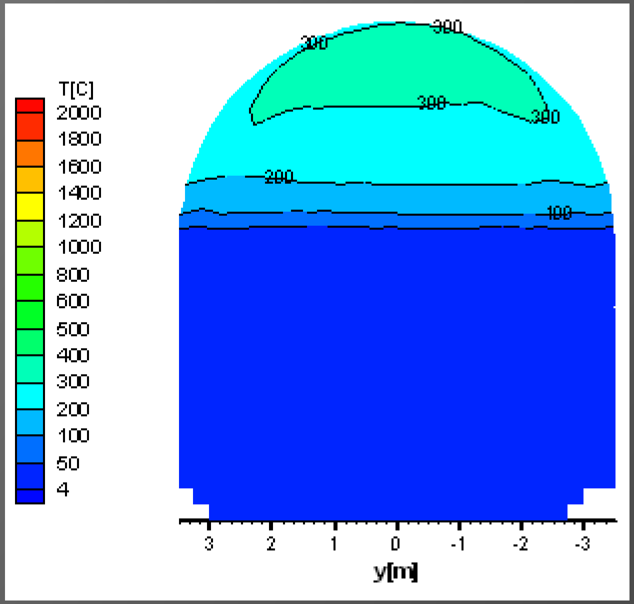


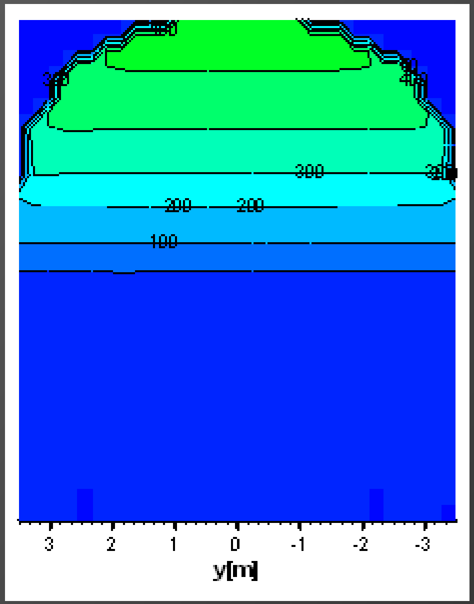
b)

Temperature at 120.0 s and y = 0; **a)** CFX, **b)** FDS

Comparative analysis

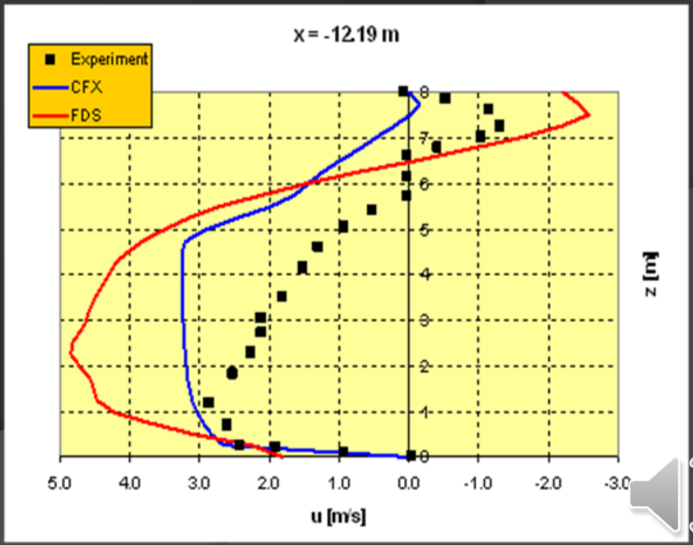
- Fire in a tunnel under natural ventilation (Memorial tunnel)





a) b)

- Influence of turbulence models on the hot layer thickness

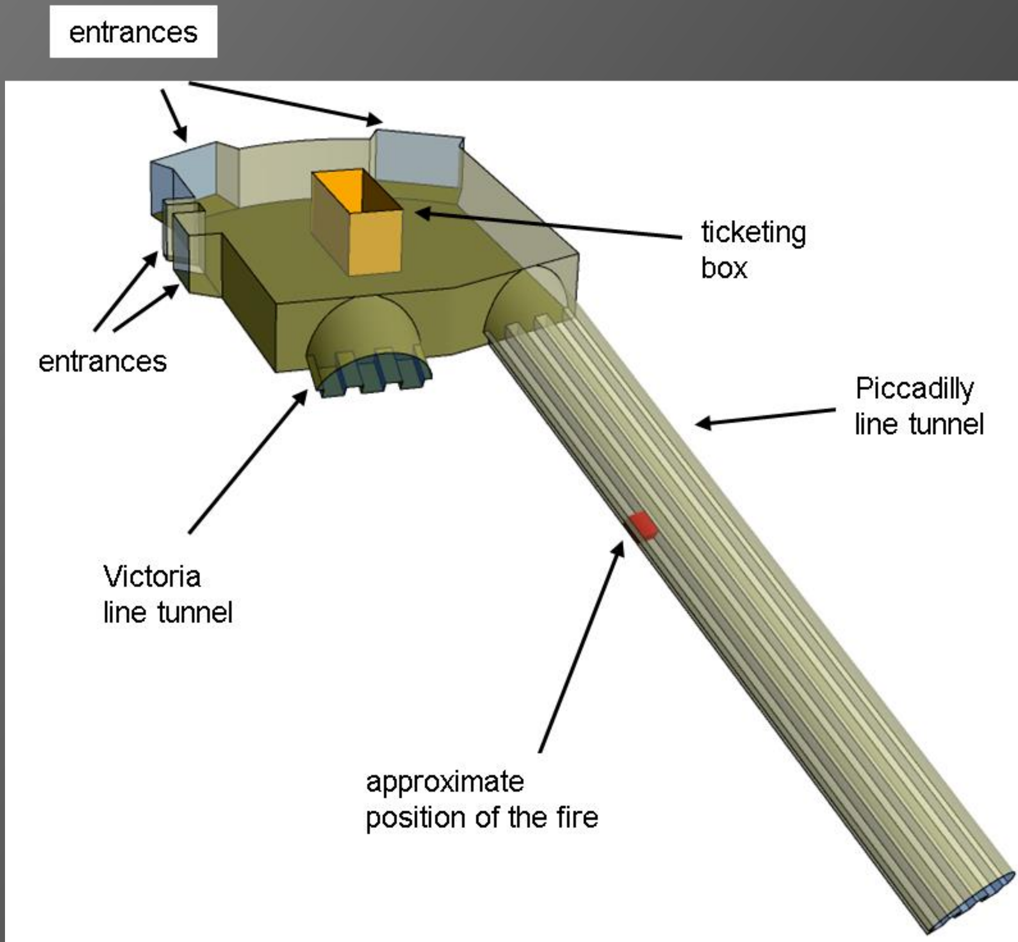


Temperature (above) at 180.0 s and x = -12.19 m;
a) CFX, **b)** FDS [8]

Streamwise velocity (right) at 180.0 s and x = -12.19 m, y = 0 m;
a) CFX, **b)** FDS [8]

Comparative analysis

- Fire in a underground train station (King's Cross accident)



CFD simulation domain for the King's Cross accident simulation [8]

The numerical simulation of a fire in an escalator tunnel of an underground station (Kings' Cross accident, UK, 1987)

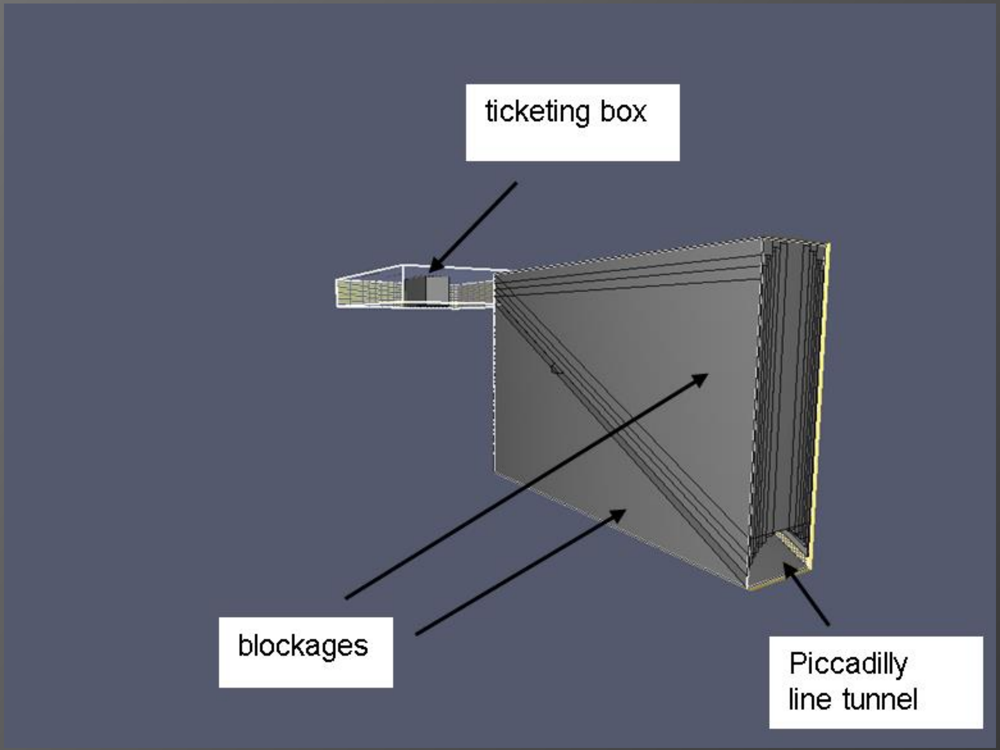
1.6 MW fire in a 50 m long Piccadilly line tunnel with inclination of almost 45º

- transient fire modelling
- inert fire model in CFX
- full combustion model with radiation in the FDS simulation

Qualitative comparison of temperature distribution

Comparative analysis

- Fire in a underground train station (King's Cross accident)

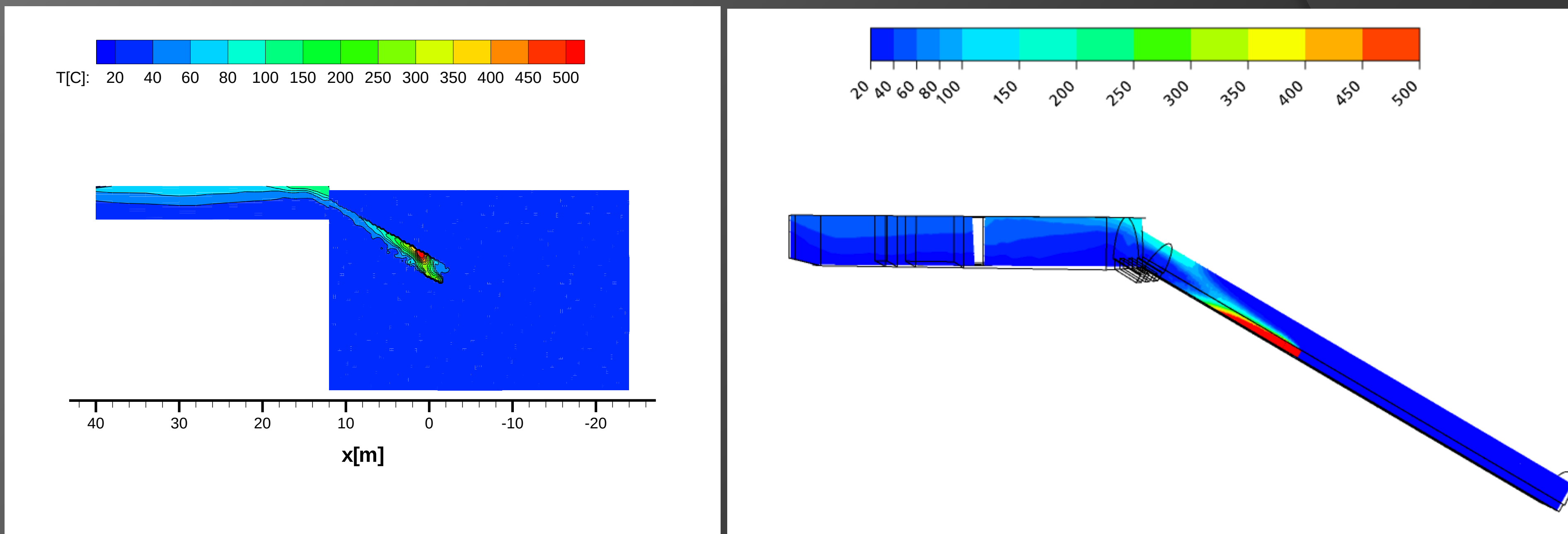


- Significantly simplified geometry
- For this case, approx. 1850 rectangular blocks were needed

FDS model of the King's Cross station [8]

Comparative analysis

- Fire in a underground train station (King's Cross accident)



a) b)

Temperature at 100.0 s: **a)** FDS, **b)** CFX [8]

Summary

- Fire Dynamics Simulator has an explicit solver for equidistant, structured numerical grids.
- FDS solver is at least 4 times faster than the CFX solver, but its parallel capabilities are limited (MPI parallel simulations possible).
- Interfaces between different structured grids - communication (interpolation) is performed only in one direction.

Summary

- FDS significantly under-predicts temperature where thermal radiation is a dominant heat transfer mechanism.
- Heat fluxes on the walls are in general under-predicted by the FDS.
- More serious accuracy limitations are related to numerical grids.

Summary

- The only available turbulence model is Large-Eddy Simulation (LES) - inappropriate for the grid resolution outside inertial subrange of turbulence.
- FDS offers the mixing fraction combustion model. Laminar flamelet model is also available.
- Solver parameters to control accuracy of the solution are not user accessible.
- Also tracking the progress of the numerical solution is only available in a command line mode.

Summary

- FDS uses rectangular blockages to suppress the numerical solution over a certain location.
- Representation of complex shapes with blockages is very time-consuming and often impossible.
- PyroSim preprocessing software automates the geometry preprocessing and solves the problem.
- Step-like surfaces cannot adequately capture boundary effects.
- Uniform grid resolution limits accuracy of numerical prediction (e.g. boundary layer, wall heat transfer, mixing, combustion)

Summary

The analysis software requires continues effort and funding.

The weakest point is the analyst.

Thank you !

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