Preliminary Results for Benchmark Exercise # 2 using CFAST and JASMINE

Stewart Miles, Fire and Risk Engineering Centre, BRE, UK

Part I of Benchmark Exercise # 2 is based on a series of fire experiments, performed in the VTT test hall in Finland between 1998 and 1999 as part of the ECSC Steel Research Programme. Each test involved a heptane pool fire one meter above the floor, lasting approximately six minutes. The instrumentation included thermocouple readings at three vertical columns, extending from the floor to the ceiling, and at various locations within the fire plume. These readings provide the main measurements against which numerical predictions are being compared for the current benchmark exercise. The measured temperatures have been processed to give estimates of upper layer temperature and layer height, where it is here assumed that a two-layer representation holds, and these are being used in the comparison against zone model predictions.

The benchmark specification document [1] contains full details of the test hall and the three cases being modelled. This was released in conjunction with a summary of the measurement data against which to compare predictions.

For case 1 and 2 there was no mechanical exhaust and the doorway openings to the hall were closed. However, the building is not airtight, and so the effect of air infiltration must be modelled somehow. The suggested approach [1] is to include four small openings, each of area 0.5 m^2, two at ground level and two at a height of 12 m. For case 3 there was mechanical extraction at 11 $m^3 s^{-1}$ through a duct 12 m above the floor, and for this case the two doors were each opened to an area of 3.2 m^2. An additional complication is provided by the sloping cross-sectional shape of the ceiling, providing a further challenge to zone models in particular.

This extended summary describes briefly some simulations undertaken by the author and the findings drawn from them, and accompanies the presentation slides. Simulations of all three cases have been performed with a zone model (CFAST/FAST version 3.1.6) and a CFD model (JASMINE version 3.1.2). A sensitivity analysis has been undertaken for a number of parameters, including the thermal properties of the walls and ceiling, the size and location of the restricted ventilation openings (cases 1 & 2) and the 'equivalent ceiling height' in the CFAST simulations. A CFD mesh sensitivity analysis has been conducted also.

All CFAST simulations have been performed with a single compartment with one or two horizontal flow vents to the outside, and for case 3 an additional vertical HVAC vent to the outside. The ceiling has been approximated as being flat, and for the majority of simulations was located at a height of 15.84 m, which gives the same enclosure volume as inside the actual test hall. The sensitivity to the choice of ceiling height has been investigated by performing simulations with the ceiling at 13 m and 18 m. The fire source for each case has been defined in terms of the specified time-dependent pyrolysis rate and a heat of combustion of 44.6×10^6 J kg^{-1}. Furthermore, the radiative fraction was set to 0.2. For the 'baseline' simulations the walls and ceiling were defined as conducting boundaries consisting of sheet steel on top of mineral wool, with thermal properties and thicknesses as specified in the problem definition. The sensitivity to the choice of thermal boundary condition at the walls and ceiling has been investigated by using sheet metal only, mineral wool only and non-conducting (adiabatic) boundaries.

A further parameter that has been investigated in the CFAST simulations for cases 1 and 2 is the size and location of the restricted ventilation wall openings for the 'infiltration' process. Here the four original 0.5 m^2 openings have been replaced by four 0.01 m^2 openings in one simulation and by two large openings of 16 m^2 (at floor level only) in another. The effect of increasing and decreasing the height above ground of the upper openings in the original specification has been investigated also. Note that in the CFAST simulations, where there are two vents at the same distance from the floor they are combined into a single opening (with an area equal to the sum of that for the individual openings).

JASMINE simulations of all three cases have been performed. The geometry of the test hall was modelled as accurately as possible with a Cartesian mesh, with the result that the sloping sections of the ceiling were approximated by a staggered (staircase) boundary. This gives the correct volume within the ceiling space, but will have some influence on the heat and momentum transfer at these sections of the ceiling. JASMINE models the Reynolds Averaged Navier Stokes (RANS) equations of fluid motion, and employs a κ-ε turbulence model to represent the effect of the turbulent motions on the flow field. Time-dependent simulations were performed using a one-second time-step and the fuel pyrolysis rate given in benchmark specification. An eddy break-up combustion model was employed, using a single step reaction mechanism for heptane and an effective heat of combustion of $0.8 \times 44.6 \times 10^{6}$ J kg^{-1}. Radiation transfer was calculated using a six-flux model, combined with an emissive power model to calculate the radiation exchange from CO_2 and H_2O combustion products.

Convection and radiation heat transfer to the solid boundaries was included. Conduction into the boundaries was calculated approximately using the concept of a time-dependent conduction depth into a semi-infinite material. Furthermore, the steel sheet was ignored in these calculations, so that the conduction losses will in general have been under-estimated. However, the conductivity of the solid was increased for some simulations to investigate the effect of increased conduction losses on the gas temperatures and smoke layer height.

The ventilation openings have been modelled exactly as specified. However, additional simulations have been performed for case 1 with narrow slot openings instead of the square ones (but with the area of each maintained at 0.5 m^2), and with partially porous east and west walls, where the porosity was set to give an equivalent flow area as the vents.

A numerical mesh containing approximately 130,000 elements was used in most of the simulations. A mesh refinement study was performed for two simulations, where the first 60 seconds was repeated using a mesh containing eight times as many elements, i.e. the resolution was increased by a factor of two in each direction.

The preliminary results from the CFAST and JASMINE simulations are reasonably encouraging and informative. Comparison plots of predicted and measured temperatures and layer depths are shown in the presentation slides. The effect of varying conduction losses, ventilation opening sizes etc are illustrated too.

Probably the most important finding, demonstrated by both the zone and CFD models, is the sensitivity of the gas temperatures to the conduction losses to the walls and ceiling. In the CFAST simulations the closest agreement with measurement was obtained by using either a sheet metal and mineral wool two-layer material or by using the sheet metal alone. In the JASMINE simulations the effect of ignoring the steel was apparent, with closer agreement with measurement obtained when the conduction losses were then increased. The results so far seem to indicate that the conduction into the steel is important. The smoke layer height, however, seems to be less sensitive to the boundary conduction loss calculation.

An important issue in the use of the zone model is the choice of 'equivalent ceiling height'. The sensitivity analysis performed so far indicates that while the upper layer temperature is sensitive to the choice of ceiling height, the layer height is sensitive only during the initial stage of the fire.

Both the zone model and CFD simulations indicate that the exact choice of openings in cases 1 & 2, to represent the infiltration process, is not critical. The only exception to this finding was in the CFD simulation with porous walls, which indicated a break down of stratification after about three minutes. However, the physical significance of implementing slightly porous walls in a CFD simulation is somewhat uncertain and this result should be treated with caution at this stage. The CFAST simulation with the very small openings produced high pressures inside the enclosure, at a level that would have been greater than anything achieved in the experiments. This supports the assumption that the building is not particularly airtight.

Reasonable agreement has been shown between measured plume temperatures and those predicted in the JASMINE simulations. The mesh refinement study has indicated some sensitivity to this parameter, with the finer mesh producing results closer to those measured. Further JASMINE simulations are currently being performed to investigate the mesh resolution and boundary conduction issues in more depth.

CFAST and JASMINE simulations will be performed for Part II of Benchmark Exercise # 2. This is a 'hypothetical' example for which there are no experimental measurements. However, the dimensions of the building are greater than in Part I, and have been selected to more closely represent a turbine hall. Full details of the geometry and cases to be modelled are provided in the specification document [1]. The fire source is representative of a large hydrocarbon pool fire. 'Target' cables and beams are included, for which the likelihood of thermal damage is to be estimated. Although the building geometry is rectangular, in some of scenario cases there is the added complexity of an internal ceiling, effectively dividing the space into two connected compartments.

1. Specification for Benchmark Exercise # 2 - Fire in a Large Hall, February 2002.

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#1

Benchmark Analysis # 2

Fire in a Large Hall

Preliminary CFAST and JASMINE Simulations for Part I

Stewart Miles
Fire and Risk Engineering Centre, BRE, UK
Tel: +44 (0)1923 664924
Fax: +44 (0)1923 664910
E-mail: miless@bre.co.uk

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#2

Summary of Simulations

- Cases 1, 2 and 3 investigated
- CFAST/FAST version 3.1.6
  - predictions of upper layer temperature and layer height
  - investigation into implementation of geometry (complex roof)
  - investigation into boundary (conduction) heat losses
  - investigation into restricted ventilation openings (cases 1 & 2)
- JASMINE (CFD) version 3.2.1
  - comparison with temperature profiles at thermocouple trees 1,2 & 3
  - investigation into boundary (conduction) heat losses
  - investigation into restricted ventilation openings (cases 1 & 2)
  - grid refinement study

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CFAST Simulations - Cases 1&2

- Baseline simulations (following problem specification)
  - 2 horizontal flow vents (1.414 x 0.707 m) at floor level and 12 m
  - 'equivalent flat ceiling' height = 15.84 m
  - heptane fire source
    - ΔH_c=44.6x10^6 J kg^{-1}
    - pyrolysis rate as specified
    - radiative fraction = 0.2
    - hydrogen to carbon ratio = 0.19
  - two-layer solid material at walls and ceiling (steel and mineral wool)
- Variant simulations
  - steel only and mineral wool only solid material at walls and ceiling
  - adiabatic boundaries
  - single horizontal flow vent (8 x 4 m) at floor level (e.g. two 4 x 4 m doors)
  - 2 horizontal flow vents (0.2 x 0.1 m) at floor level and 12 m
  - 'equivalent flat ceiling' height = 13 m and 18 m
  - upper vent at 6 m and 14 m

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#4

CFAST Simulations - Case 3

- Baseline simulations (following problem specification)
  - 1 horizontal flow vent (1.6 x 4 m) at floor level (two 0.8 x 4 m openings)
  - 'equivalent flat ceiling' height = 15.84 m
  - heptane fire source
    - ΔH_c=44.6x10^6 J kg^{-1}
    - pyrolysis rate as specified
    - radiative fraction = 0.2
    - hydrogen to carbon ratio = 0.19
  - two-layer solid material at walls and ceiling (steel and mineral wool)
  - 11 m^3 s^{-1} extraction flow rate through HVAC vent at 10 m height
- Variant simulations
  - 'equivalent flat ceiling' height = 13 m and 18 m
  - HVAC vent at 8 m height

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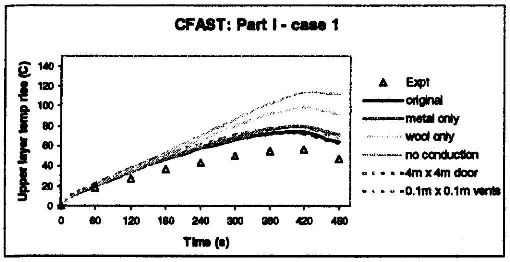
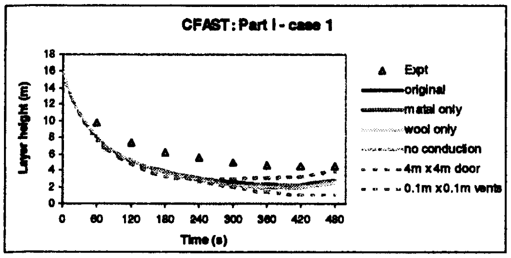
CFAST Analysis - Case 1





Findings:

upper layer temperature sensitive to conduction heat loss mechanism (but only after 2 minutes)

upper layer temperature not sensitive to size of 'restricted ventilation openings'

layer height not sensitive to conduction heat loss mechanism

layer height sensitive to size of 'restricted ventilation openings' (but only after 4 minutes)

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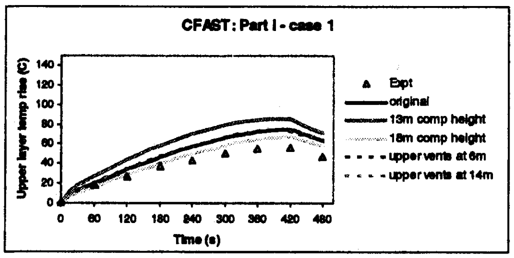
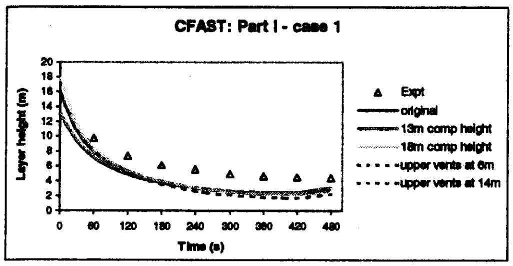
CFAST Analysis - Case 1





Findings:

location (height) of upper 'restricted ventilation openings' not significant

upper layer temperature sensitive to height of 'equivalent flat ceiling'

layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

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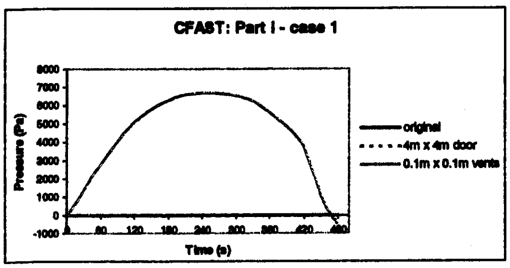
CFAST Analysis - Case 1



significant over-pressure with the very small openings

pressure ~ ambient for other opening sizes

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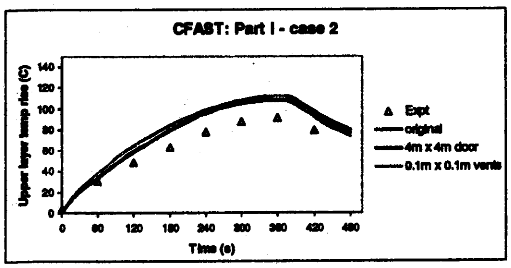
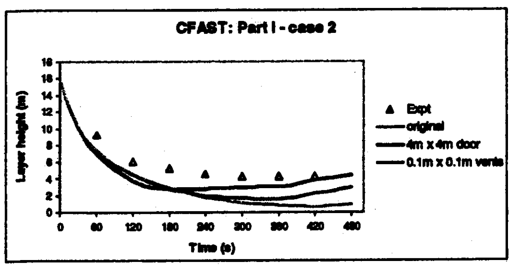
#8

CFAST Analysis - Case 2





Findings:

upper layer temperature not sensitive to size of 'restricted ventilation openings'

layer height sensitive to size of 'restricted ventilation openings' (but only after 3 minutes)

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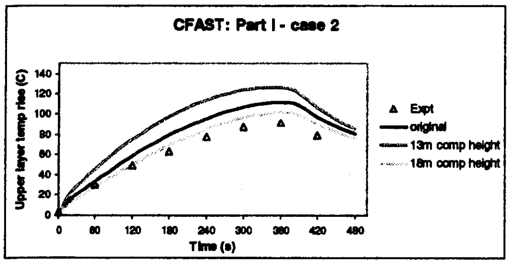
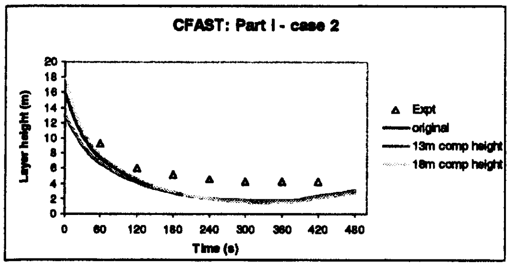
CFAST Analysis - Case 2





Findings:

upper layer temperature sensitive to height of 'equivalent flat ceiling'

layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

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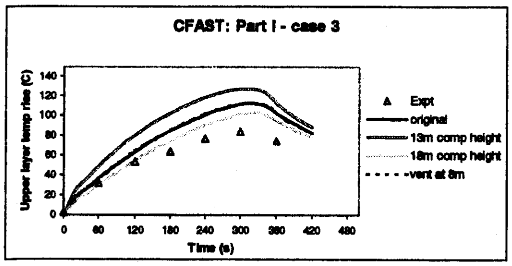
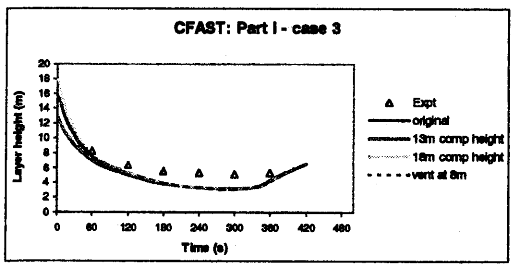
CFAST Analysis - Case 3





Findings:

location (height) of HVAC vent not significant (within range investigated)

upper layer temperature sensitive to height of 'equivalent flat ceiling'

layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

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CFAST Analysis - Case 3

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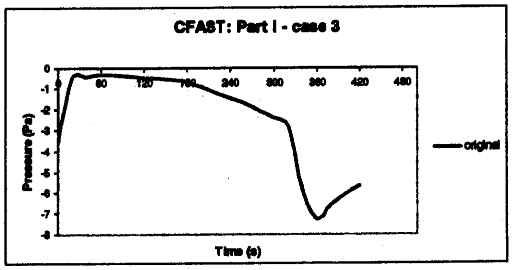

JASMINE Simulations - Cases 1&2

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RANS with standard κ-ε turbulence model

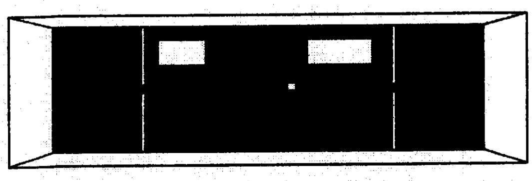
Numerical time-step = 1s

Eddy break-up combustion model with heptane (ΔH_c=0.8 x 44.6x10^6 J kg^{-1})

Six-flux radiation model (& Truelove's emissive power model)

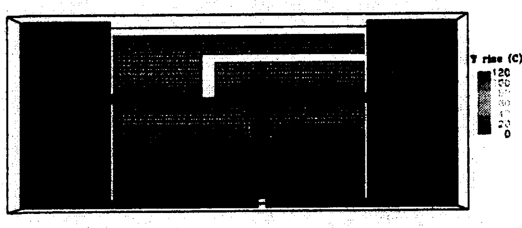
Convection (h_c=10 J s^{-1} m^{-2} K^{-1}) and radiation heat losses to solid boundaries

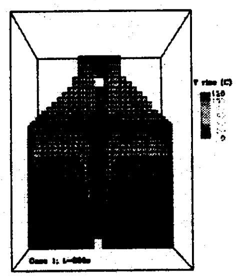
Semi-infinite approximation for conduction at boundaries (time-dependent conduction depth) - steel ignored



Ventilation options investigated:
- 0.5 m^2 squares
- 0.072 x 6.9 m slots
- slightly porous east & west walls

Boundary heat losses investigated:
- conductivity modified





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#13

JASMINE Simulations - Case 3

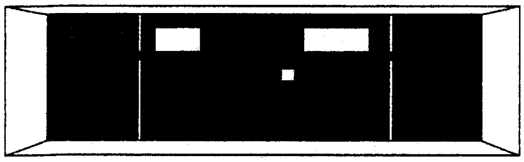
RANS with standard κ-ε turbulence model — Numerical time-step = 1s

Eddy break-up combustion model with heptane (ΔH_c=0.8 x 44.6x10^6 J kg^{-1})

Six-flux radiation model (& Truelove's emissive power model)

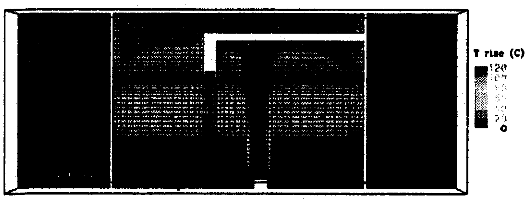
Convection (h_c=10 J s^{-1} m^{-2} K^{-1}) and radiation heat losses to solid boundaries

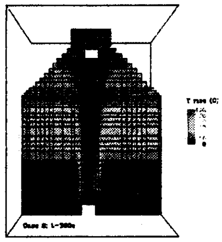
Semi-infinite approximation for conduction at boundaries (time-dependent conduction depth) - steel ignored



Boundary heat losses investigated:
conductivity modified

Mesh refinement investigated





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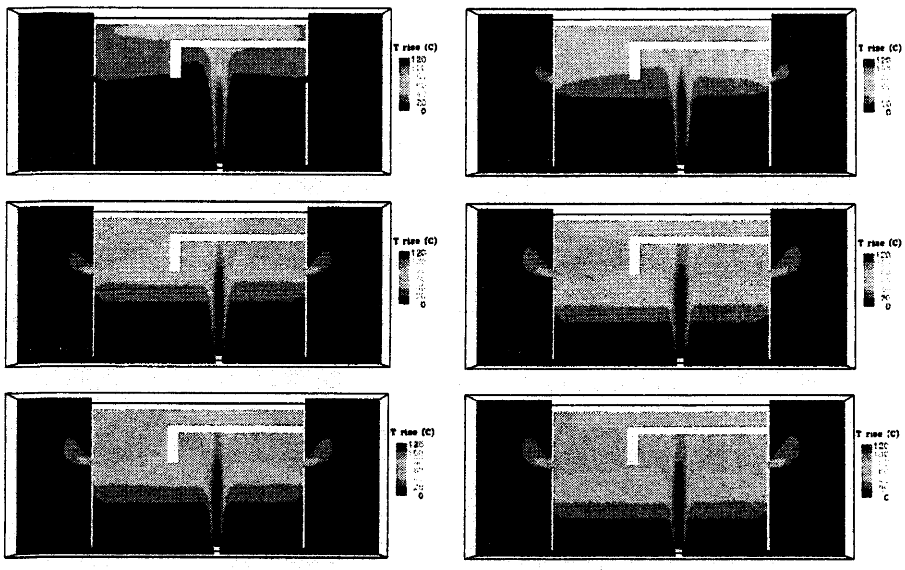
JASMINE Temperatures for Case 1



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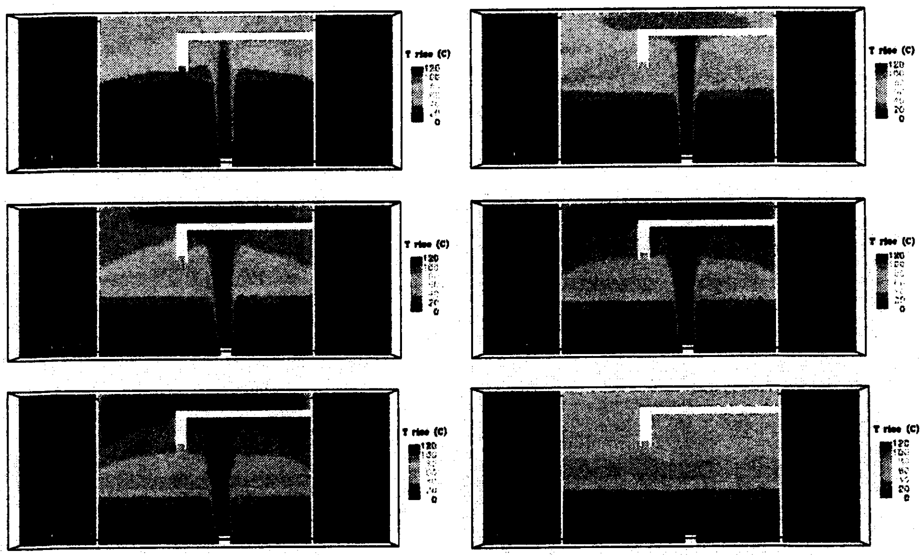
JASMINE Temperatures for Case 3



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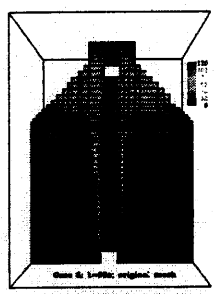
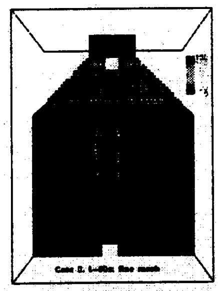
CFD Mesh Refinement

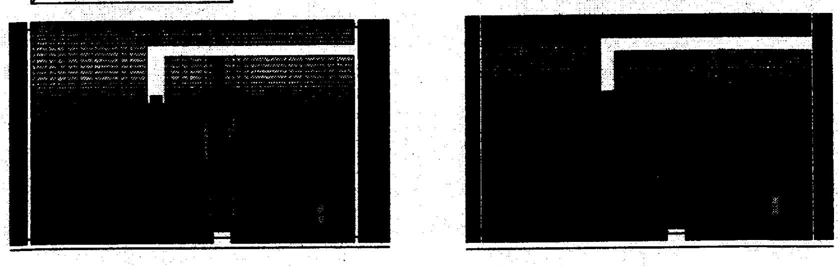
Predictions of temperature for case 3 at 60s



~ 136 500 elements



~ 1 100 000 elements
(x2 in each direction)



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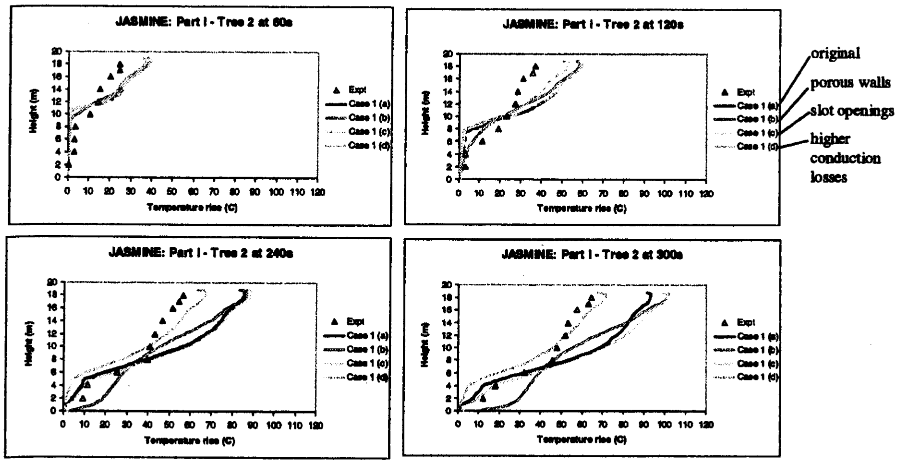
JASMINE Analysis - Case 1



Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height is less so)

Narrow slot openings give same results as square openings

Porous walls 'restricted ventilation' reduces stratification

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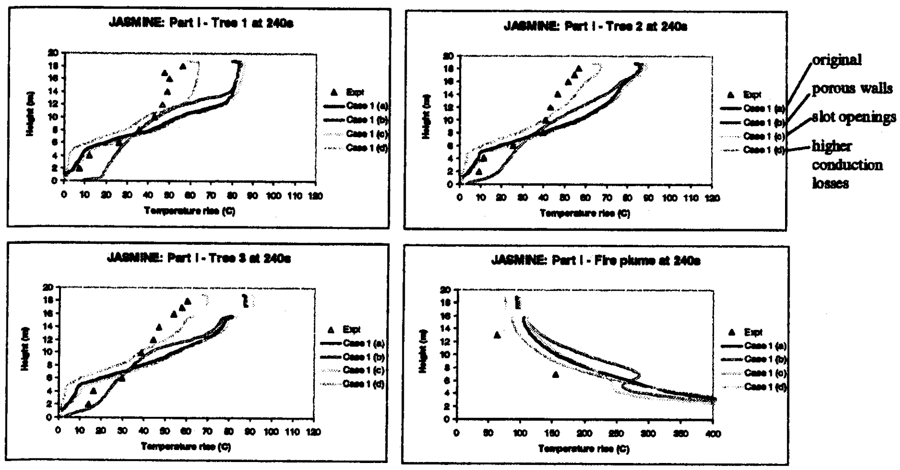
JASMINE Analysis - Case 1



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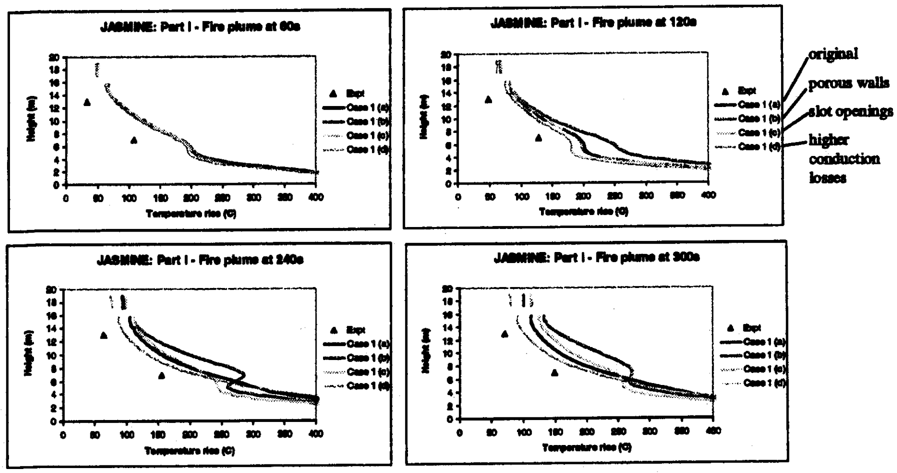
JASMINE Analysis - Case 1



Conduction heat loss mechanism has less pronounced influence on plume temperature

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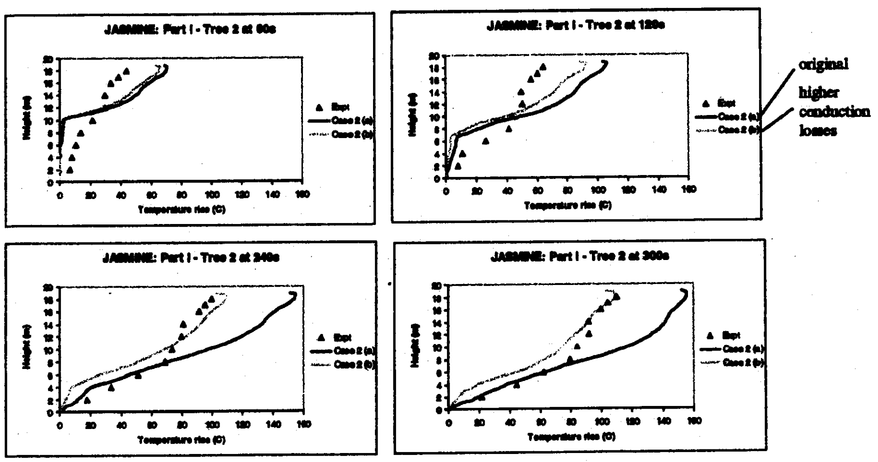
JASMINE Analysis - Case 2



Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height less so)

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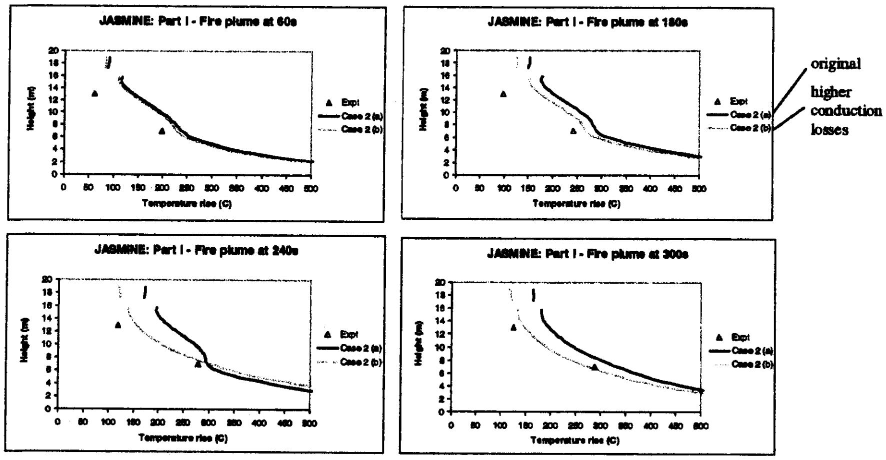
JASMINE Analysis - Case 2



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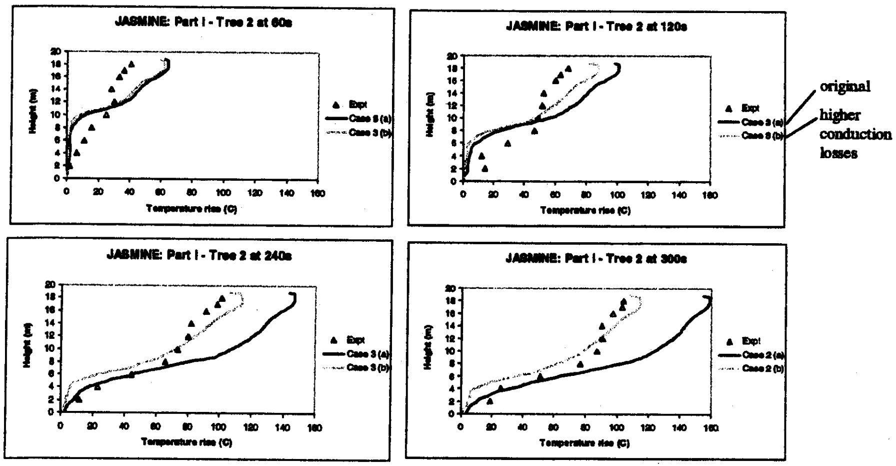
JASMINE Analysis - Case 3



Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height less so)

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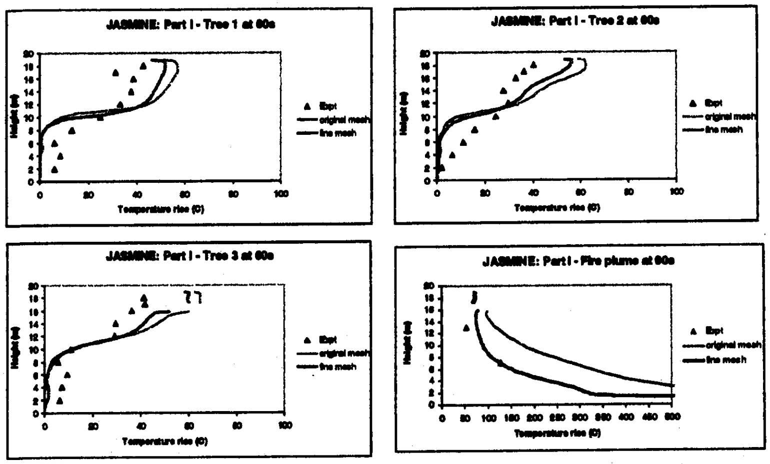
JASMINE Analysis - Case 3



Mesh resolution also an important consideration

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Closing Remarks

- Important general findings:
  - conduction losses into walls/ceiling needs care
    - sheet metal influences layer temp
  - specification of restricted ventilation openings:
    - has only small influence on layer temperature
    - has a more important influence on layer height (mainly during later stages)
- Important findings for CFAST:
  - choice of 'equivalent' ceiling height:
    - influences upper layer temperature
    - but influences layer height only at early stages
- Important findings for JASMINE:
  - mesh resolution needs consideration
  - sloping ceiling approximation ?