MODELING STRATEGIES IN FIELD SIMULATIONS OF A SINGLE SIDE WELL-VENTILATED FIRE IN A SMALL COMPARTMENT

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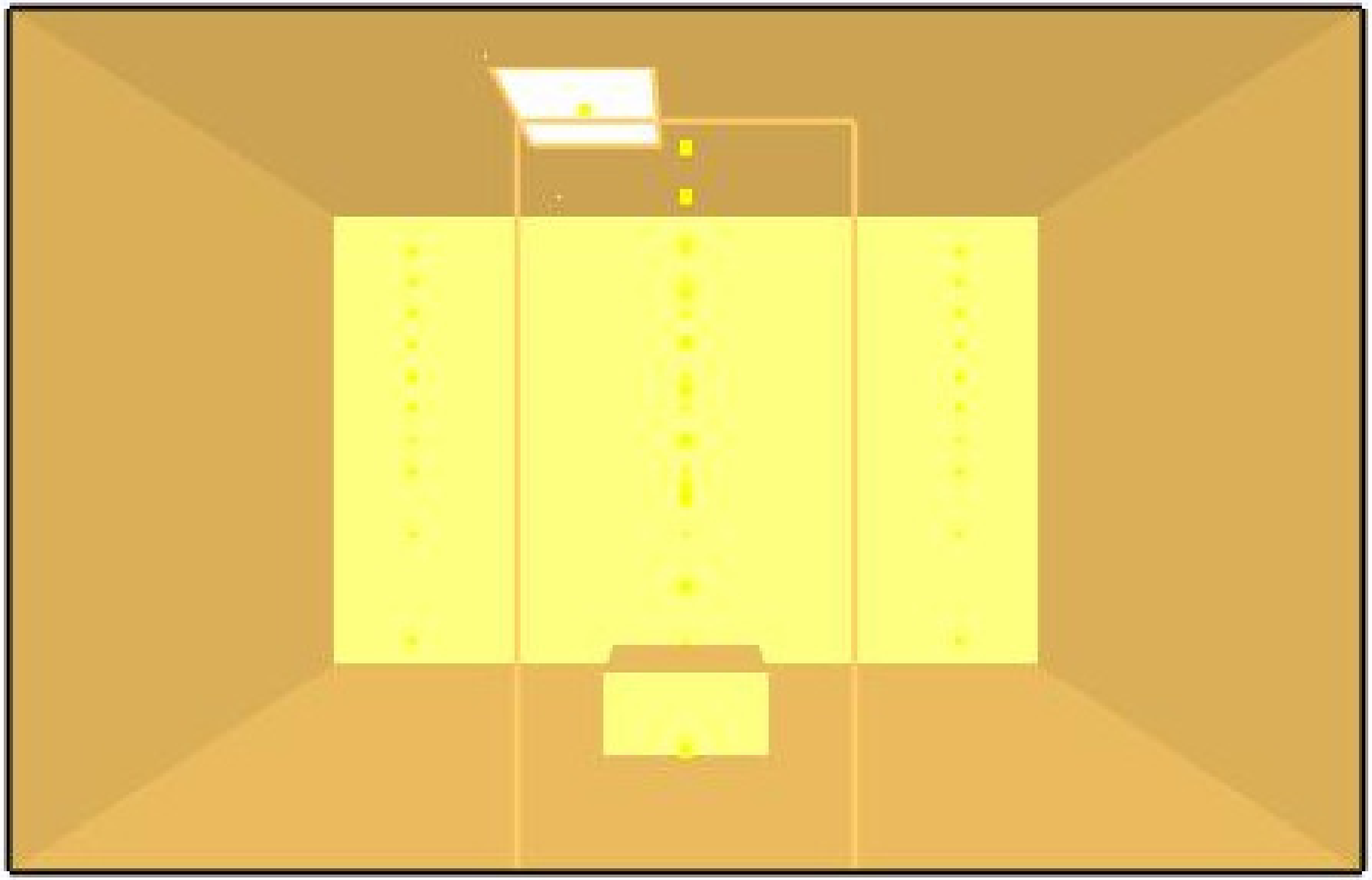
Introduction

- Smoke and heat exhaust ventilation system (SHEVS)
- Full scale experiments of a well-defined, fuel controlled fire in a small compartment
- Openings in the roof serve as natural SHEVS
- Specific features:
  - The fire source size is relatively large, compared to the door opening, roof openings and compartment dimensions;
  - The heat release rate of the fire source per unit area is relatively high;
  - There is asymmetry in the roof openings' positions.

Introduction



Introduction

- Compartment:
  - Width: 3.6m (x-direction),
  - Depth: 3.0m (y-direction),
  - Height: 2.3m (z-direction).
- Front wall: door opening (0.9m x 2.0m).
- Two roof openings (0.75m x 1m each), closer to the front wall.
- The fire heat release rate has been imposed by mass flow rate control.
- The fuel is hexane, with ΔHc = 44MJ/kg.

Introduction

- Present study: numerical CFD simulation results.
- LES results with NIST's Fire Dynamics Simulator (FDS) [3], in comparison to steady RANS results, obtained with Fluent 6.2.
- Discussion of mesh quality requirements for LES simulations, based on the steady RANS results.
- Discussion of entrainment of fresh air.
- Importance of the buoyancy model in the steady RANS simulations.

Numerical simulation set-up: LES

- LES simulations with FDS
- Grid (in)sensitivity of the results has been verified.
- Standard Smagorinsky SGS model, with Cs = 0.20.
- Relatively large fire source in relatively small compartment -> LES can be accurate, because a sufficient amount of grid cells can be used.
- Cubic cells with size 5cm -> 72 x 60 x 46 = 198720 cells. The mesh quality is discussed in more detail below.

Numerical simulation set-up: LES

- Default FDS settings have been used:
  - default boundary conditions for velocity and temperature (or heat flux). The influence of the latter boundary condition is relatively small.
  - Radiation: finite volume method (Discrete Ordinates Method).
  - Combustion: mixture fraction approach with flame sheet model.

Numerical simulation set-up: RANS

- Steady RANS with Fluent, version 6.2.
- Same mesh as for the LES results.
- Turbulence model:
  - 'realizable' k-ε turbulence model
  - buoyancy source terms based on a 'generalized gradient diffusion hypothesis' (GGDH)
  - transport equations:

$$\frac{\partial}{\partial x_j}\left(\bar{\rho} k \tilde{v}_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P - \bar{\rho}\varepsilon + G$$

$$\frac{\partial}{\partial x_j}\left(\bar{\rho} \varepsilon \tilde{v}_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \bar{\rho} C_1 S \varepsilon - \bar{\rho} C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + S_{\varepsilon B}$$

Numerical simulation set-up: RANS

$$S_{\varepsilon B} = C_{1\varepsilon}\left(1 - C_{3\varepsilon}\right)\frac{\varepsilon}{k}G$$

$C3\varepsilon = 0.8$, $C1\varepsilon = 1.44$

$$G = g\frac{3}{2}\frac{\mu_t}{\bar{\rho}k\sigma_t}\left(\overline{u'w'}\frac{\partial\bar{\rho}}{\partial x} + \overline{v'w'}\frac{\partial\bar{\rho}}{\partial y} + k\frac{\partial\bar{\rho}}{\partial z}\right)$$

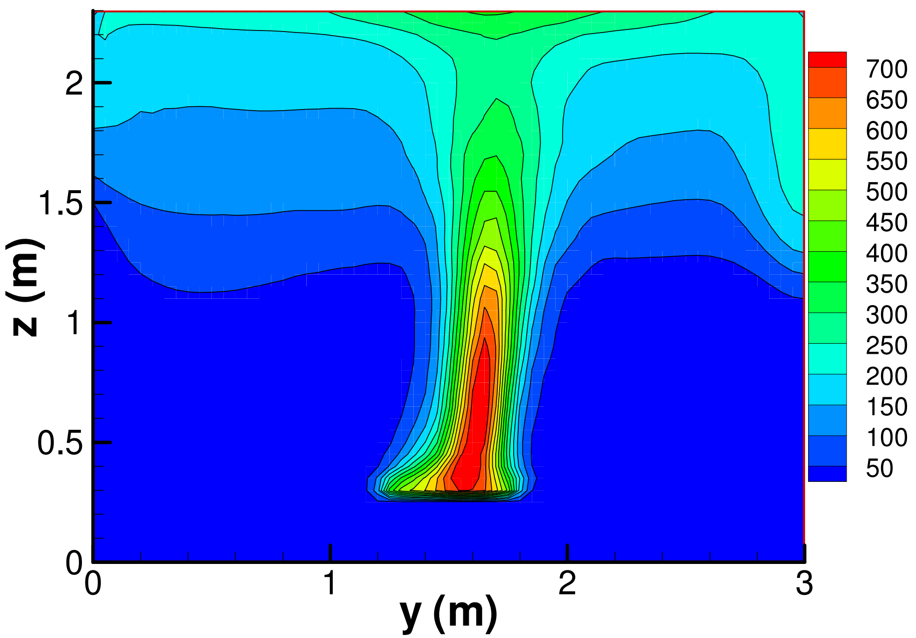
$\sigma_t = 0.85$

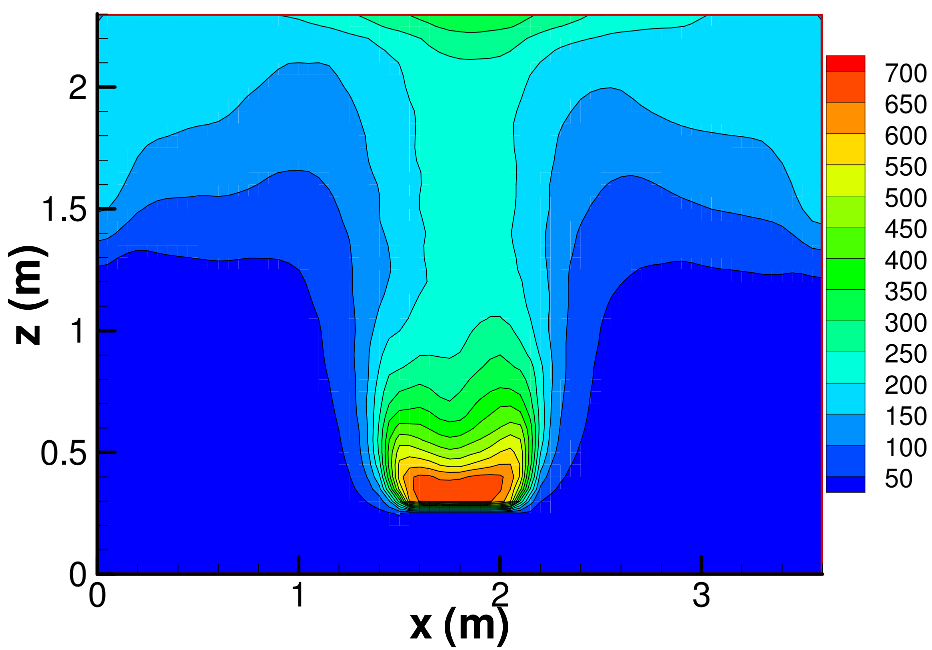
Numerical simulation set-up: RANS

- Combustion: mixture fraction with flame sheet model: very similar to LES results.
- Radiation: prescribed local heat loss of 30% in the functional dependence of temperature on mixture.
- Atmospheric pressure is imposed in the door opening and the roof openings.
- No-slip wall boundary conditions are applied.
- Standard wall functions for the turbulence quantities.
- Convection is allowed at the walls, but this heat loss is small, compared to the heat flux through the roof openings.

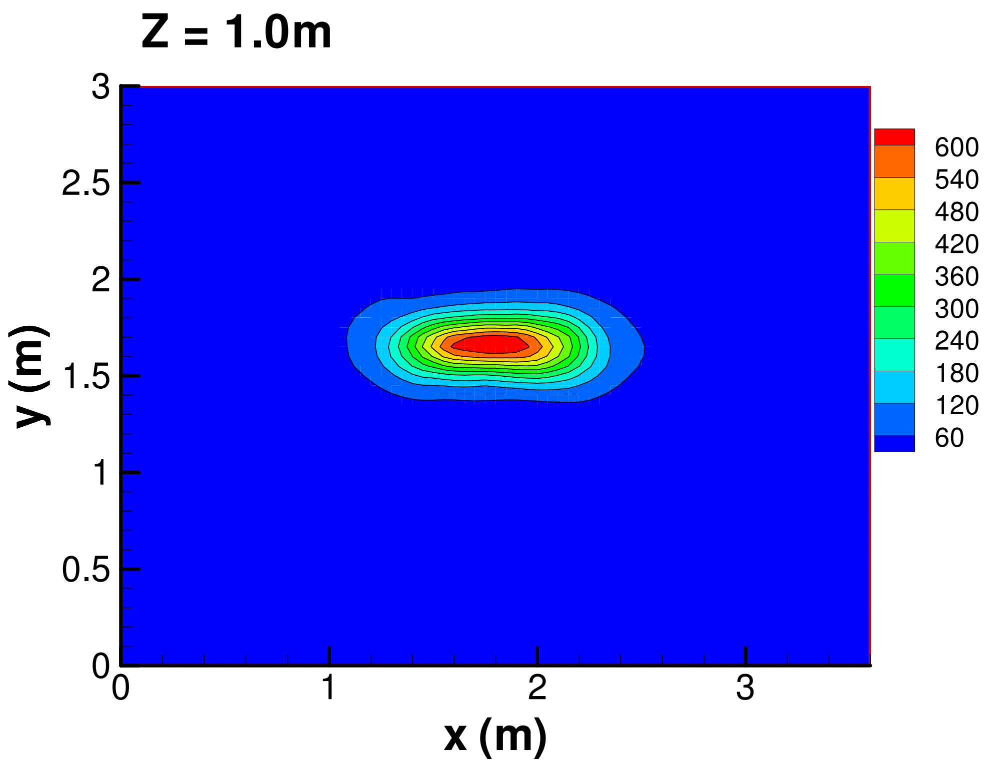
Results: general discussion

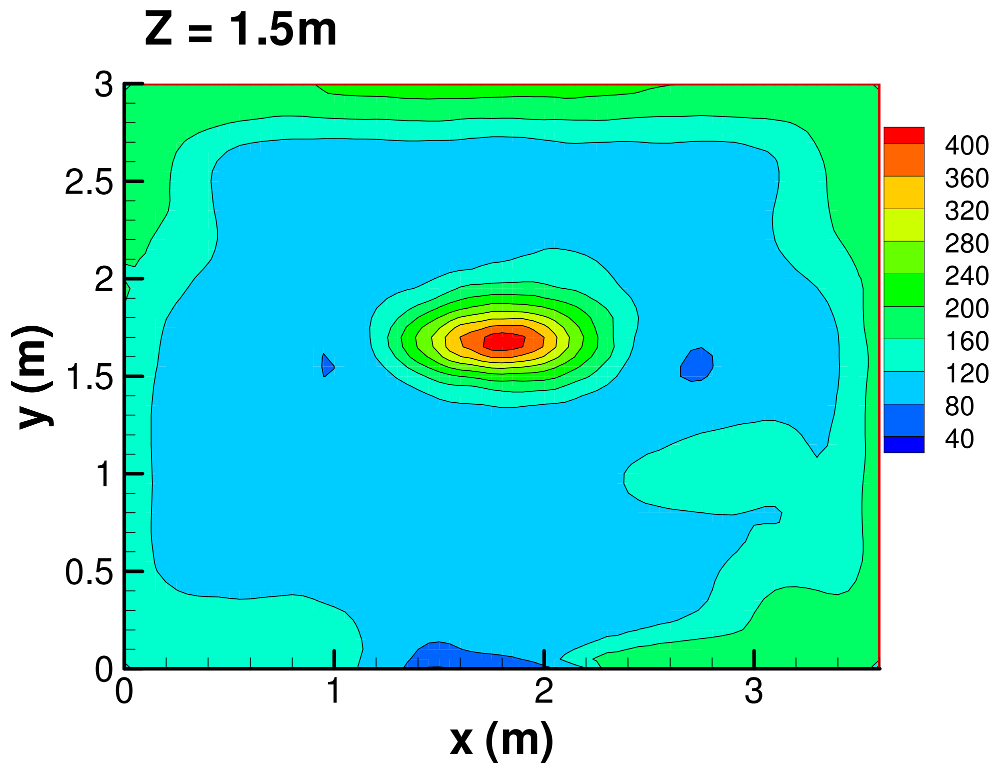
- Af = 0.6m x 0.6m, Q = 440kW and $Aroof$ = 0.75m x 1m
- X = 1.8m, y = 1.5m, z = 1.0m, z = 1.5m
- LES results





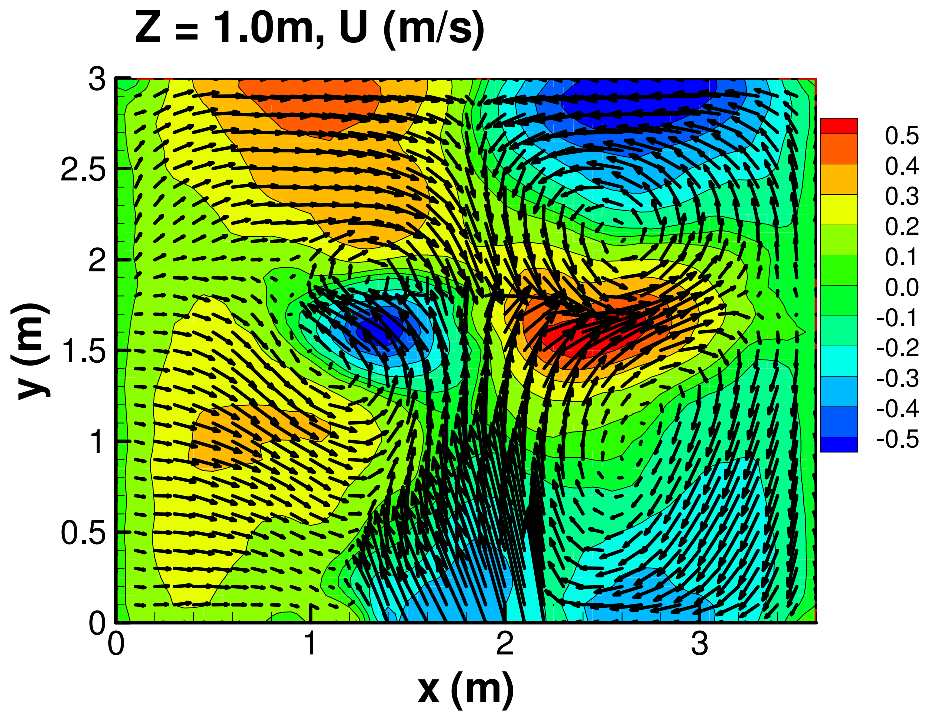
Results: general discussion

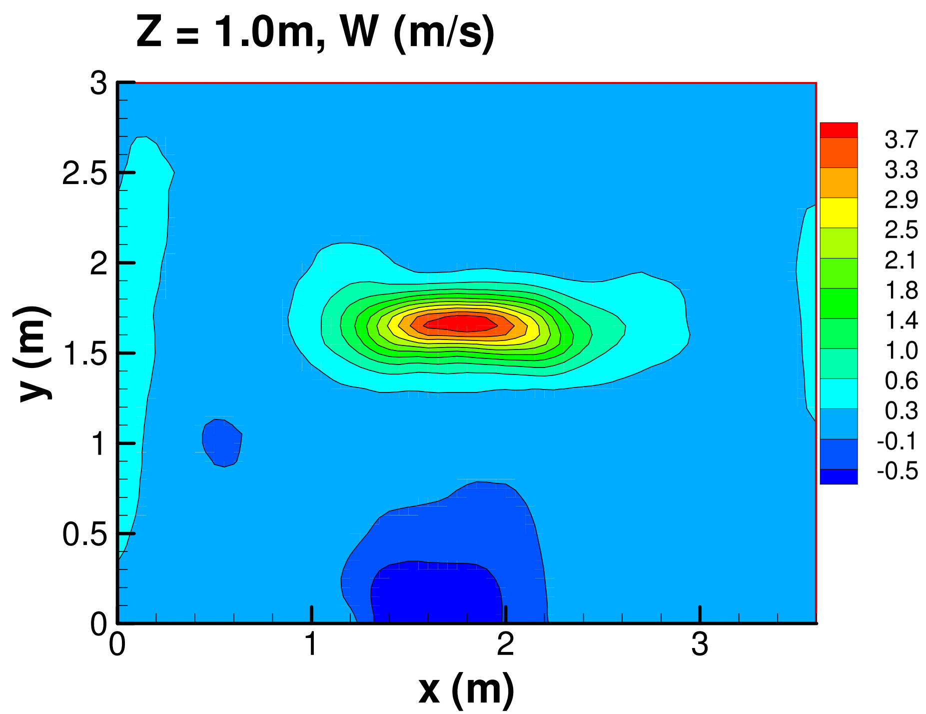




Results: general discussion

- velocities

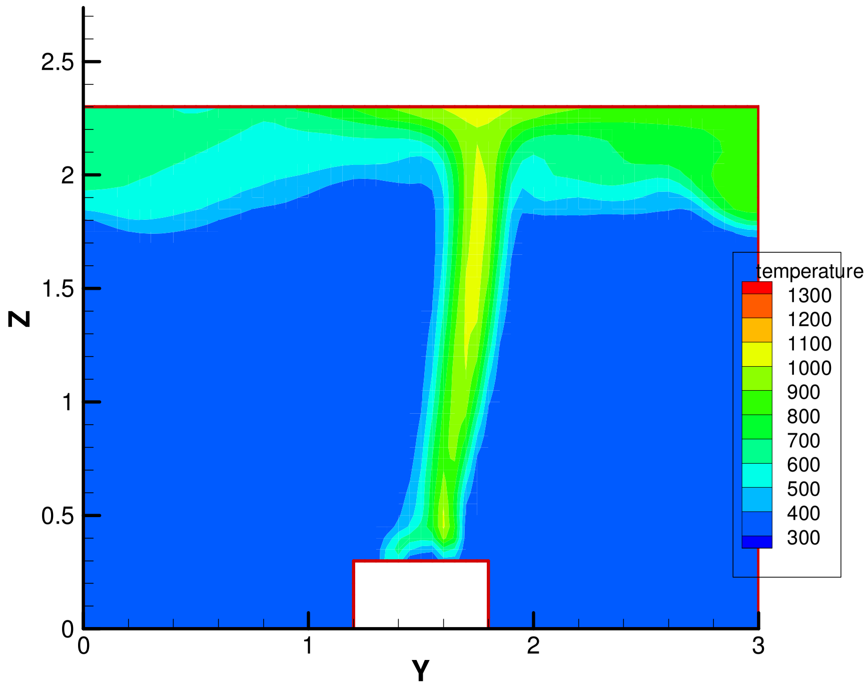




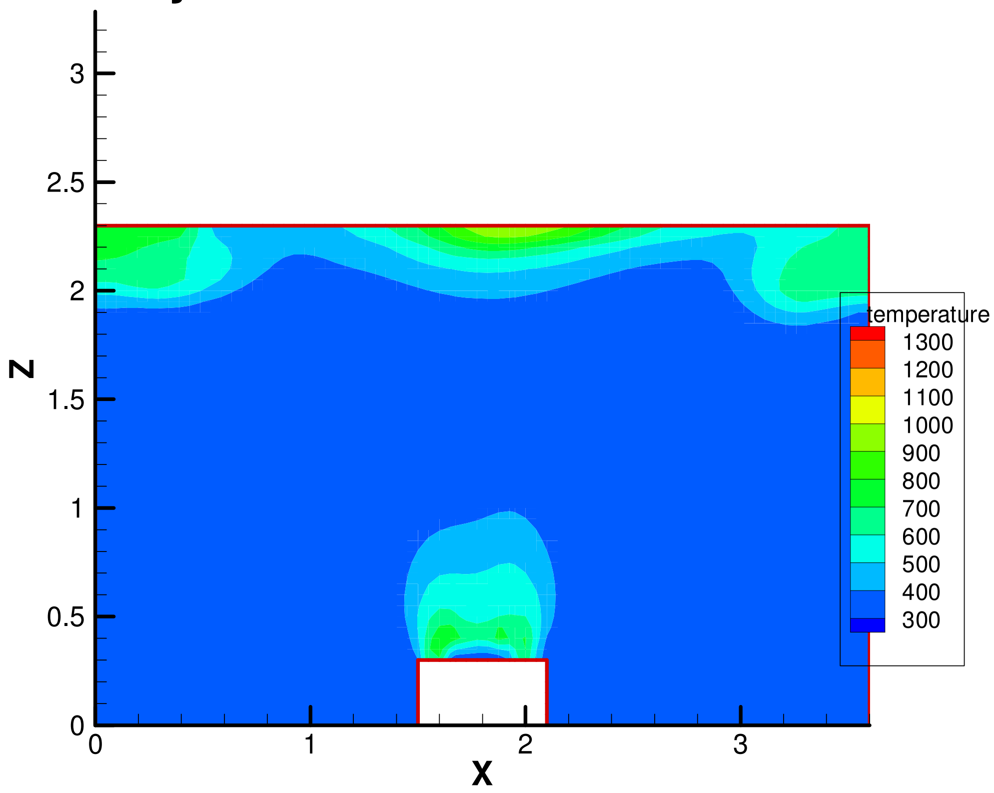
Results: mesh quality requirements

- RANS results:

x = 1.8m



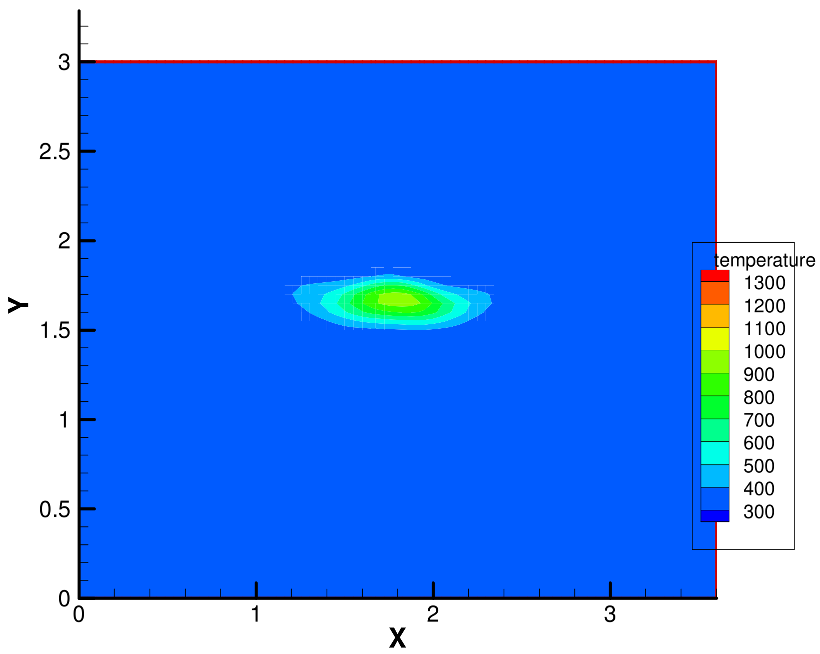
y = 1.5m



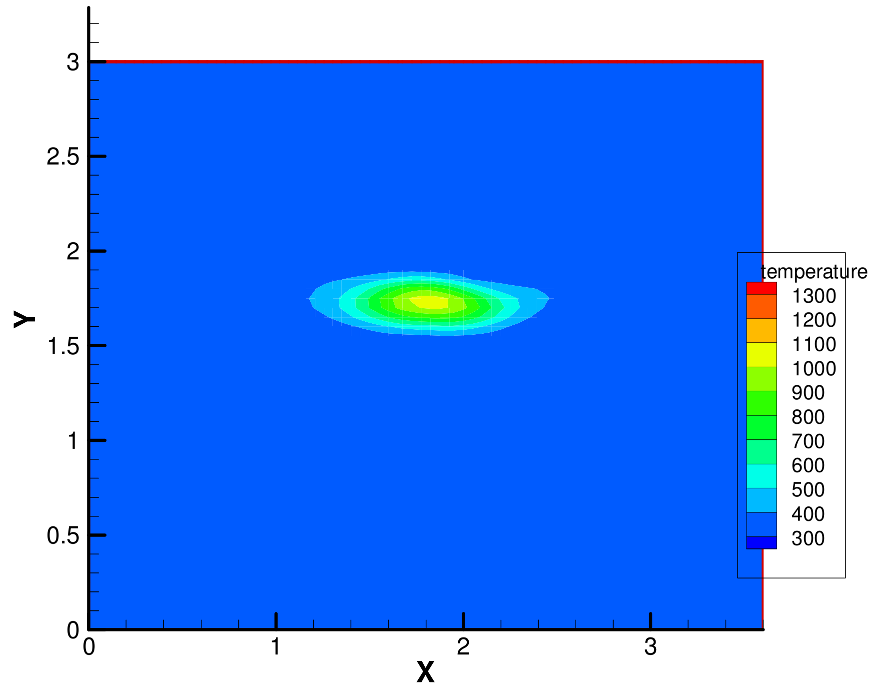
Results: mesh quality requirements

- RANS results:

z = 1.0m



z = 1.5m



Results: mesh quality requirements

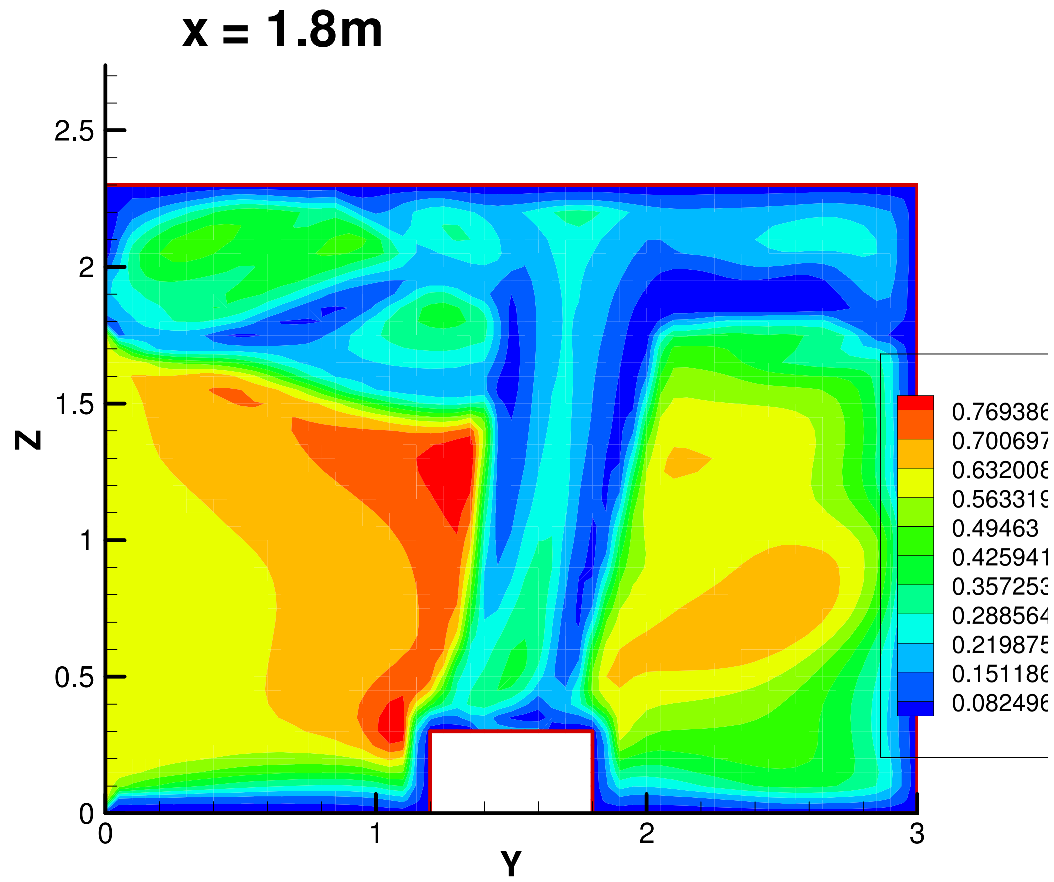
- Turbulent integral length scale from RANS results:

$$l_I = \frac{k^{1.5}}{\varepsilon}$$

- D* ranges from about 0.6m to about 0.75m for the fires under study, so that the cell size is smaller than 0.1D*

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

Results: mesh quality requirements



Results: entrainment of fresh air

- lateral plume stretching, with more intense mixing at the back side of the plume, dominates the tilting of the plume towards the back wall
- instructive to discuss the value of the 'entrainment constant' Ce, appearing in the definition:

$$\dot{m}_s = C_e P Y^{3/2} \quad (Y \le 10 A_f^{1/2})$$

- 'Default' values: 0.19 or 0.34
- smoke-free height *Y* is defined as *Y* = 2.3m – *d*, where the hot smoke layer thickness is defined as:

$$d = \frac{\int_0^H (T - T_0)\, dh}{T_{av} - T_0}$$

Results: entrainment of fresh air

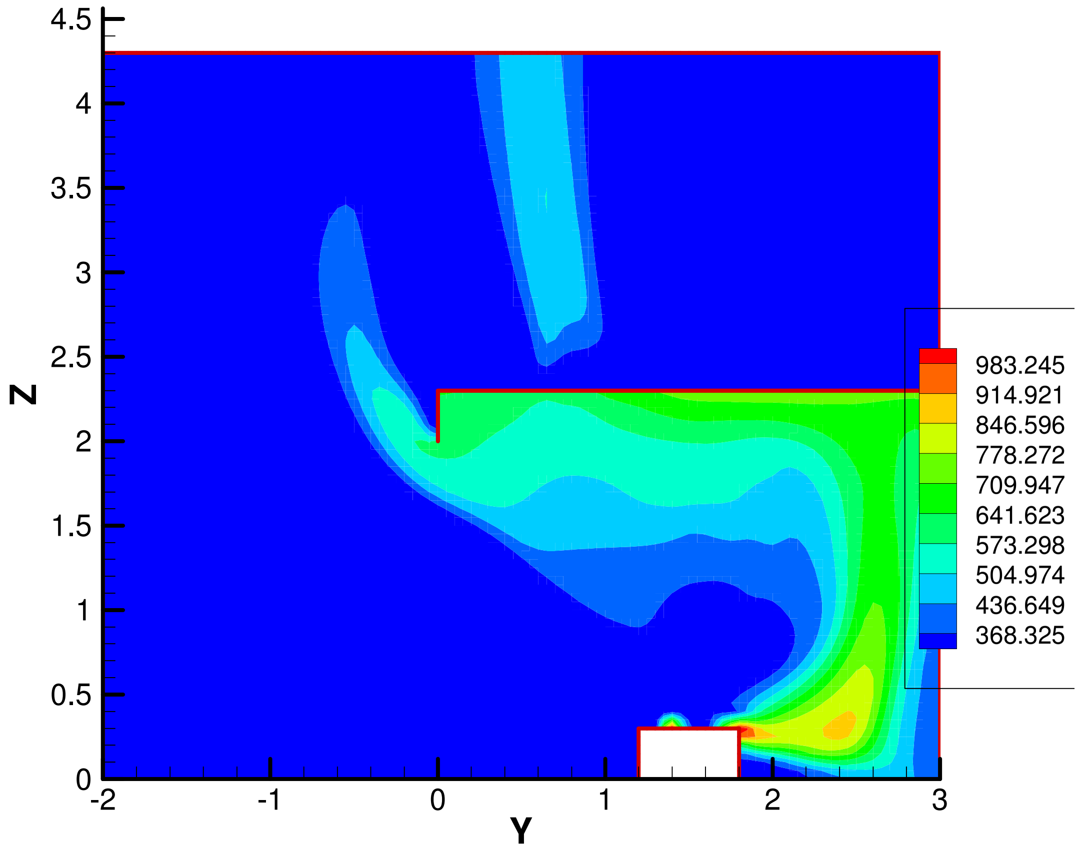
- Results:

$\dot{Q}_f$	330kW			440kW			550kW		
A_{roof} / A_f	$0.5m^2$	$0.75m^2$	$1.5m^2$	$0.5m^2$	$0.75m^2$	$1.5m^2$	$0.5m^2$	$0.75m^2$	$1.5m^2$
$9m^2$	0.49	0.63	0.87	0.48	0.50	0.92	0.49	0.66	1.09
$6m^2$	0.28	0.38	0.52	0.28	0.36	0.53	0.30	0.38	0.59

Results: buoyancy model in RANS

- Comparison to SGDH: $$G = g\frac{\mu_t}{\sigma_t}\frac{1}{\overline{\rho}}\frac{\partial\overline{\rho}}{\partial z}$$

x = 1.8m



Conclusions

- Numerical CFD simulation results have been presented for a fire in a small compartment, with natural ventilation from one side through a door opening, and through roof openings.
- The physical phenomena, governing the entrainment of fresh air into the plume, have been discussed. The lateral plume stretching by large scale vortices behind the plume, leading to enhanced turbulent mixing, has been highlighted.
- The quality of the LES results has been discussed, putting the mesh cell size into perspective with respect to the turbulent integral length scale. The latter is always an order of magnitude larger in the plume, as it should be.

Conclusions

- The entrainment 'constant' *Ce*, as applied in simplified calculation methods, has been discussed. It was illustrated that the classical default value (0.19) is too low for the configuration under study.
- It was shown that the buoyancy model is very important in the steady RANS simulations. When the SGDH approach is followed, no rising plume is recovered, due to excessive production of turbulent kinetic energy near the fire source, which in turn leads to lower mean temperatures, so that the buoyancy forces become too weak to generate a rising plume in the horizontal air flow from the door opening.