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Optimizing the Grid Size Used in CFD Simulations to Evaluate Fire Safety in Houses

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Abstract

In the event of a fire in a house, the occupants may be harmed by untenable conditions developed during the fire. The time to untenable conditions can be estimated using experimental studies or numerical simulations. Experimental studies usually provide realistic information but are expensive and time consuming. Numerical simulations, using validated models, can therefore be used to overcome these drawbacks and may also be used to help in the design of experimental setups.

As part of a research project to evaluate life safety in houses, the Fire Risk Management Program at IRC/NRC has carried out numerical simulations to study fire performance of Canadian houses. The numerical simulations were conducted using the Fire Dynamics Simulator (FDS) [1], a CFD model developed by NIST. As a first step, the effect of the grid sizes on the simulation results of the fire in a house was investigated in order to determine an optimum grid size that will be adopted for future simulation. Several fire sizes have been investigated and the optimum grid resolution has been found. The chosen grid resolution was then used to determine the time when conditions would become untenable, based on criteria found in the literature.

This paper presents the details of the grid optimization study as well as the evaluation of life safety in houses.

Keywords: Fire safety; Fire dynamics; Flame height; Large eddy simulation

1 Introduction

To evaluate life safety in houses, the Fire Risk Management program at IRC/NRC, has carried out numerical simulations to study fires in houses. The numerical simulations were conducted using FDS. The effect of the grid sizes on the simulation results of a fire in a house was investigated in order to determine an optimum grid size that will be adopted for future simulation.

This paper presents the details of the grid sensitivity analysis that was performed. Three different basement fire sizes were modelled.

2 CFD Fire Model

FDS is a CFD fire model that employs the large eddy simulation (LES) techniques [1] to compute the gas density, velocity, temperature, pressure and species concentrations in each control volume. FDS has been demonstrated to predict thermal conditions resulting from a fire in an enclosure [1, 2]. A complete description of the FDS model is given in reference [1].

2.1 Model setup and boundary conditions

FDS requires as inputs the geometry of the facility being modelled, the computational cell size, the location of the ignition source, the fuel type, the heat release rate, the material thermal properties of walls, the vents and boundary conditions.

Geometry

The full-scale test facility is a three-storey building. Figure 1 shows a perspective view of the facility. The three levels of the facility are enclosed within a 10.77 m x 9.24 m x 8.22 m tall rectangular volume.

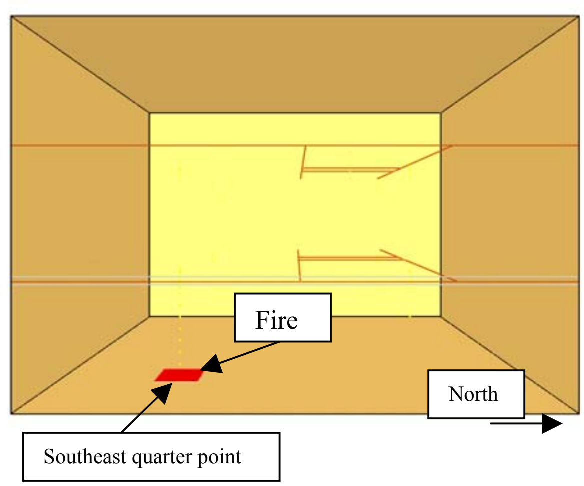

Figure 1: Perspective view of the Facility

Vents

This simulation considered the following openings:

- Opening to the outside of the structure located in the main floor of the facility and is approximately 0.9 m wide x 2.4 m high.
- First stairway opening from the basement to the main floor and is approximately 3 m x 0.9 m at a height of 2.7 m.
- Second stairway opening from the main floor to the second floor is approximately 3 m x 0.9 m at a height of 5.5 m.

These vents were assumed open during the entire simulation.

Material properties

The ceilings and floors of the facility are composed of steel. The walls are composed of gypsum board. The input data are given below and are taken from the database provided by FDS.

Steel:

Specific heat x density x thickness: 20 (KJ/K.m^2)
Thickness: 0.005 (m)

Gypsum board:

Conductivity: 0.48 (W/m K)
Diffusivity: 4.1 10^{-7} (m^2/s)
Thickness: 0.013 (m)

Boundary conditions

The floors and ceiling are considered thermally-thin walls; i.e, the temperature is assumed to be the same throughout the width.

Exterior walls are considered thermally thick walls. The model performs a one-dimensional heat transfer calculation across its thickness.

Fire specification

Three fire sizes are considered for this study with peaks ranging from 1500 to 3000 kW (see Table 1). These fires start at t=0 of the simulation and grow according to a fast t-squared curve (α = 0.0469 (kW/s^2)) to a constant peak value. A T-squared fire is modelled in FDS by specifying the time to reach the peak heat release rate. The fire source was approximated as a rectangular object representing a propane burner with a specified heat release rate. The fire area of the propane burner is 1 m wide by 1 long located on the floor of the basement. The time to peak values of the three fires are summarized in the Table 1.

Q_{peak} (kW)	t_{peak} (s)
1500	179
2500	231
3000	253

Table 1: Time to peak values for simulated fires

Position of the thermocouple

In the model the thermocouple trees as well as the measurement of CO, CO_2 and extinction coefficient, are placed at different points of the basement to record the predicted quantities. Table 2 and Table 3 show the positions of the measurements that will be presented.

TC - N^o	Position (m)			Description
	x	y	z	
2	2.69	6.93	2.63	SWQP
12	8.07	6.93	2.63	NWQP
17	8.07	2.31	2.63	NEQP

Table 2: Thermocouple position

SWQP: Southwest quarter point of the basement
NWQP: Northwest quarter point of the basement
NEQP: Northeast quarter point of the basement
EXT.: Extinction coefficient
TC: Thermocouple
M: Measurements of CO, CO_2 and extinction coefficient

The measurement of CO, CO_2 and extinction coefficient were taken at a height of 1.5 m. This height was chosen to indicate the effect on the occupants in the house.

M - N^o	Position (m)			Description
	x	y	z	
43,47,51	2.69	6.93	1.5	CO, CO_2 and Ext. at SWQP
45,49,53	8.07	6.93	1.5	CO, CO_2 and Ext. at NWQP
46,50,54	8.07	2.31	1.5	CO, CO_2 and Ext. at NEQP

Table 3: CO, CO2, Extinction coefficient measurement

3 Grid resolution analysis

CFD numerical simulations are computationally very expensive. One of the most significant factors influencing the computation time is the size of the computational grid specified by the user. Because it is possible to over-resolve or under-resolve a space by specifying grids that are too fine or too coarse, it is important to determine an appropriate grid size that would optimize the solution accuracy and time.

To study the effect of the grid size on the prediction of the temperature and the concentration of the CO_2, simulations were conducted for different grid and fire sizes. The facility geometric domain is partitioned in two domains. The first domain represents the basement and the second represents the remaining storeys. In the model, the fire occurred in the southeast quarter point of the basement (Figure 1). Table 4 presents the grid sizes used for the basement. For the main and second storeys the domain was idealized using (0.20x0.20x0.20 m) grid distribution.

Cases	Grid sizes (m)
Case 1	0.20x0.20x0.20
Case 2	0.14x0.14x0.14
Case 3	0.10x0.10x0.10
Case 4	0.08x0.08x0.08

Table 4: Grid sizes for the basement domain

The basement domain, being the place of fire origin, was the main focus. The parameters of interest were the temperature, visibility, CO and CO_2 concentrations. Those parameters were recorded in different quarter points of the basement.

In the following sections, the results of the simulations for the three fire sizes are presented.

3.1 Resolution Criteria

The quality of the resolution depends on both the size of the fire and the size of the grid cells [2]. The characteristic fire diameter D^* represents the combined effect of the effective diameter of the fire and the size, defined as follows:

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

where:

D^* : characteristic fire diameter, m;

D : effective diameter, m;

$\dot{Q}$: total heat release rate, kW;

ρ_∞ : density at ambient temperature, kg/m^3;

c_p : specific heat of gas, kJ/kg.K;

T_∞ : ambient temperature, K;

g : acceleration of gravity, m/s^2.

The ratio $D^* / \max(\delta x, \delta y, \delta z)$ is an indication of the number of cells in the fire region.

Where: $\delta x, \delta y, \delta z$: grid sizes, m.

The higher the ratio, the better the numerical model predictions. The fire resolution index is the fraction of the ideal stoichiometric value of the mixture fraction that is being used in the calculation. It indicates how well resolved the calculations are. When the fire resolution index is equal to 1, the calculation is well resolved.

The resolution of the fire plume simulation was defined as a dimensionless parameter [4]:

$$R^* = \frac{\max(\delta x, \delta y, \delta z)}{D^*}.$$

3.2 Tenability criteria

To evaluate life safety in a house, tenability criteria are needed. The Fire Engineering Design Guide [5] in New Zealand adopted the criteria shown in Table 5.

Tenability type	Tenability limit
Toxicity	CO $\leq$ 1400 ppm CO2 $\leq$ 0.05 mol/mol
Smoke obscuration	Visibility in the relevant layer should not fall below 2 m. This value corresponds to optical density of 0.5 m^{-1}

Table 5: Tenability criteria

3.3 Fire 1- 1500 kW

This fire source was approximated as a rectangular object representing a propane burner with a specified heat release rate. The fire area of the propane burner was 0.1 m wide and 0.1 long located in the southeast quarter point of the basement. The heat release rate of the fire was assumed to follow a fast T-squared growth, reaching a peak of approximately 1500 kW in 179 s.

Table 6 shows the different cases along with the grid number, grid size, dimensionless parameter R*, Fire resolution index (FRI), and computation time. The FRI was found to be equal to 1 for a resolution index of 0.07.

Cases	Grid number	Grid size (m)	R*	FRI	Run time (h)
1	54x54x40	0.20	0.17	0.5	2.7
2	75x65x20	0.14	0.12	0.7	8.9
3	108x90x27	0.10	0.08	0.8	30.6
4	135x120x36	0.08	0.07	1	90.4

Table 6: Fire 1: $\dot{Q}$ = 1500kW and D* = 1.132 m

In the following section, the effect of the grid sizes on the predictions of temperatures, gas concentrations and the extinction coefficient is presented.

Temperature prediction

In the model the thermocouple trees are placed in different quarter points of the basement to record the predicted temperatures. The simulation results from thermocouple N° 2, located 0.1 m below the basement ceiling in SWQP is presented in this section to highlight the effect of the grid size on the estimated temperatures.

Figure 2 gives the time temperature profile predictions for thermocouple N° 2. The temperature is higher for the finer grid sizes. The temperature was lower when the grid size is coarse.

The computational time is quite high for finer grid sizes (Figure 3). It is important to find an optimum grid size that resolves the fire well. It is observed that the increase in temperature was limited for R* less than 0.08. For Case 4 the fire resolution index is equal to 1 and the R* equal to 0.07 (Table 6); thus, the fire is well resolved for Case 4. Therefore Case 4 will be adopted for this fire.

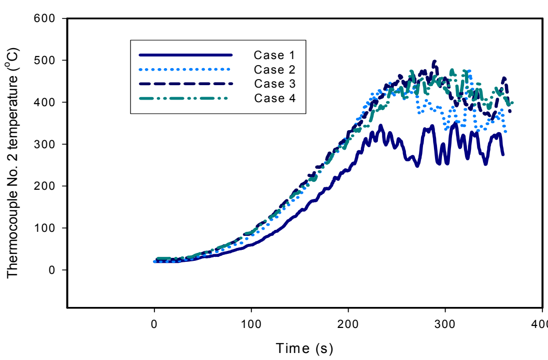

Figure 2: Time-temperature profiles 10 cm below basement ceiling –SWQP

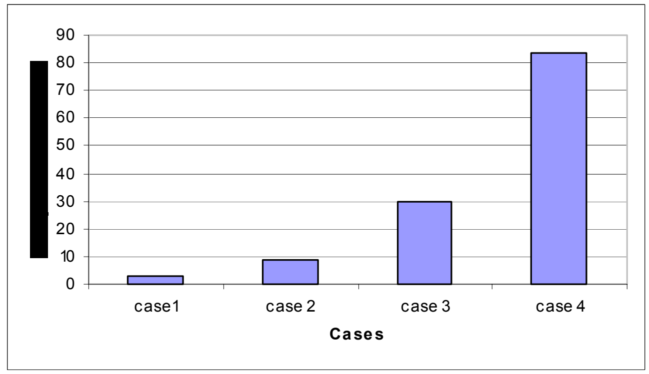

Figure 3: Computation time for all cases

CO prediction

Figure 4 gives the CO concentration vs. time for the measurement N° 43 located at 1.5 m from the floor in the SWQP. The figure shows that the effect of the grid is minimal on the prediction of the CO concentrations. The maximum CO concentration observed at this height is approximately 120 ppm which is below to the critical tenability limit criteria adopted by the Fire Engineering Design Guide [5] that leads to incapacitation.

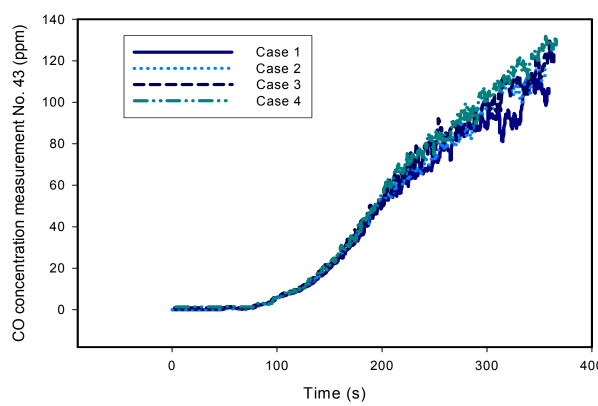

Figure 4: CO concentration at height 1.5 m - SWQP

CO_2 prediction

Figure 5 gives the CO_2 concentration vs. time for the measurement N° 47 located at 1.5 m from the floor in the SWQP The figures show that the effect of the grid is minimal on the prediction of the CO_2 concentration. The maximum CO_2 concentration observed at this height is 0.05 mol/mol. This value can lead to incapacitation based on the tenability limit criteria adopted by the Fire Engineering Design Guide [5] in New Zealand.

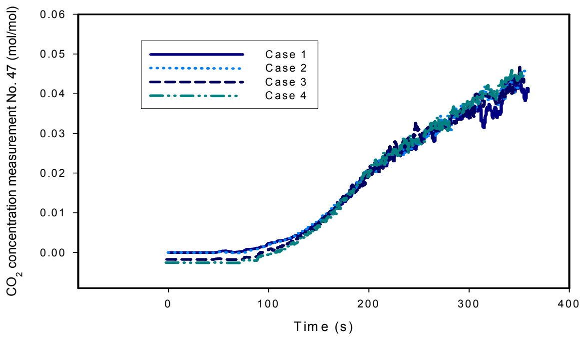

Figure 5: CO2 concentration at height 1.5 m – SWQP

Extinction coefficient prediction

Figure 6 gives the time extinction profile predictions for measurement N° 51 located at 1.5 m from the floor in the SWQP. The figures show that the effect of the grid is minimal on the prediction of the visibility. The maximum of the extinction coefficient observed at this height is approximately 1.6 (1/m) in SWQP. This extinction coefficient value is equal to the optical density as the coefficient relating them is equal to 1. This value should not be higher than 0.5 m^{-1} based on the tenability limit criteria [5]. The visibility becomes poor from 180 s.

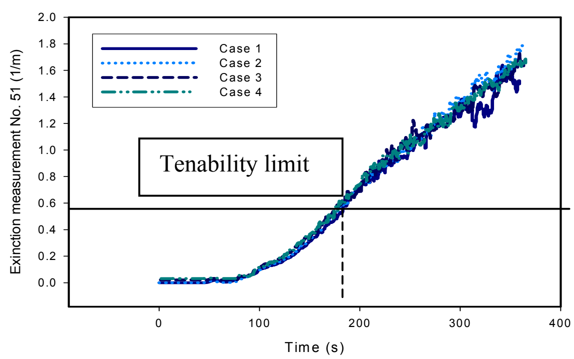

Figure 6: Extinction coefficient at height 1.5 m – SWQP

Centreline temperature of fire prediction

In the model a thermocouple tree is placed at the centerline of the fire to record the predicted temperatures of the plume centerline. The simulation results are presented in this section to highlight the effect of the grid size on the estimated temperatures of the centerline of the fire.

FIERASystem Simple Correlation sub-model [6] was used to calculate the plume centerline temperature and compare it to the CFD predictions. The sub-model uses the Heskestad's correlation [7] to determine the plume centerline temperature and is defined as:

$$T_{cp} = 9.1\left[\frac{T_\infty}{g.\,c_p^2.\,\rho_\infty}\right]^{1/3} Q_c^{2/3}\left(z - z_0\right)^{-5/3} + T_\infty$$

where:

T_{cp} : plume centerline temperature, K;

Q_c : convective heat release rate, kW;

z : height above top of the fire source, m;

z_0 : height of virtual origin relative to the base of fire source, m.

Heskestad estimation	FDS estimation			
	Case 1	Case 2	Case 3	Case 4
839 °C	479 °C	593 °C	962 °C	967 °C

Table 7: Plume centreline temperature comparisons

Table 7 shows the values of the temperatures obtained from the Heskestad's correlation and FDS prediction for a height 2.4 m above the fire. The Heskestad correlation provides an estimation that is closer to Case 3 and 4 of CFD prediction. The smaller grids provide a better predictions. This means that a better characterization of the combustion processes and flame behaviour (FRI close to 1, Table 6). The coarse grid (Case 1) gives the worse predictions when compared to Heskestad's correlation (FRI equals to 0.2, Table 6).

Figure 7 shows the temperature profile predictions for the fire plume at various heights. This figure shows a similar trend. The temperature is higher for the finer grid sizes. The fire plume temperature is lower when the grid size is coarse.

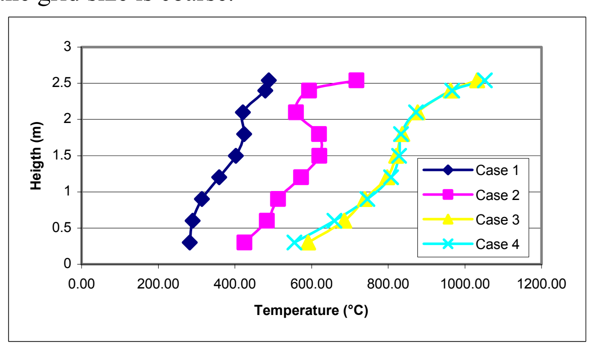

Figure 7: Temperature at various heights in the fire plume at 239 s

FIERASystem Simple Correlation sub-model [6] was used to calculate the ceiling jet temperature and compare it to the CFD predictions. The sub-model uses Alpert correlation to determine the ceiling jet temperature and is defined as:

$$T_{pl} = T_{\infty} + 6.81 \frac{\left(K \cdot Q/R\right)^{2/3}}{H}$$

where:

T_{pl} : plume gas temperature, °C;

K : configuration parameter;

1, when the fire is away from any walls;

2, when the fire is near a wall;

4, when the fire is in a corner;

H : vertical distance above fire, m;

R : radial distance from the centreline of the plume, m;

Q : heat release rate of the fire, kW.

Figure 8 shows the comparison of the predicted temperature at 0.3 m below the basement ceiling with the Alpert correlation. The Alpert's correlation [8] provides an estimation that is closer to Cases 2, 3 and 4 of CFD predictions. The smaller grids provide better predictions (FRI close to 1, Table 6).

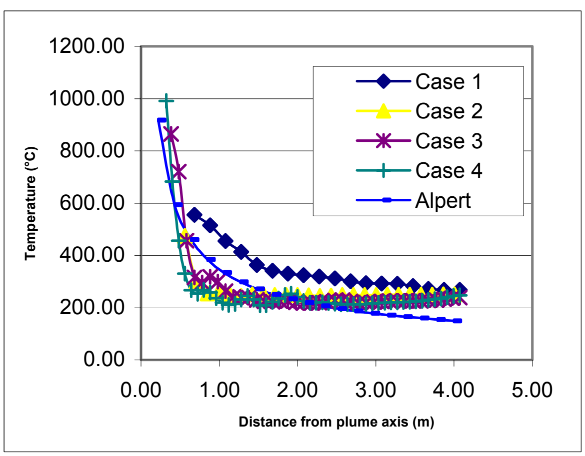

Figure 8: Comparison FDS prediction of the ceiling jet temperature with Alpert correlation

3.4 Fire 2- 2500 kW

The heat release rate of the fire was assumed to follow a fast T-squared fire, reaching a peak of approximately 2.5 MW in 231s.

Table 8 shows the different cases along with the grid number, grid size, dimensionless parameter R*, Fire resolution index, and computation time. The FRI was found to be equal to 1 from the resolution index of 0.07. Thus, the finer grid provides a better prediction.

Cases	Grid number	Grid size (m)	R*	FRI	Run time (h)
1	54x54x40	0.20	0.14	0.71	2.8
2	75x65x20	0.14	0.10	0.80	8.7
3	108x90x27	0.10	0.07	1	29.7
4	135x120x36	0.08	0.05	1	83.49

Table 8: Fire 2: $\dot{Q}$ = 2500kW and D* = 1.38 m

Figure 9 gives the time temperature profile predictions for thermocouple N^{o} 2. This figure illustrates that the increase of the temperature is not very significant when the fire is well resolved (R* =0.07). Therefore Case 3 will be adopted for this fire.

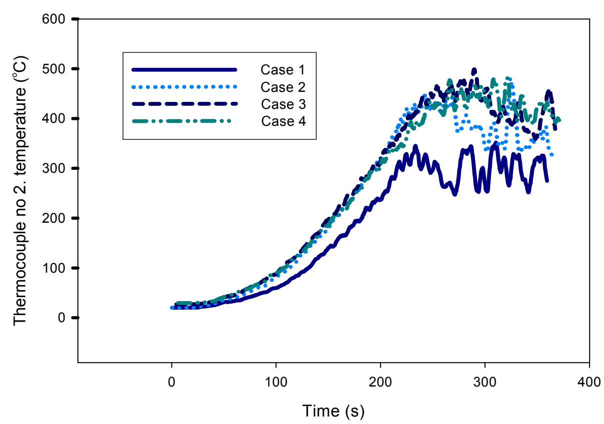

Figure 9: Time-temperature profiles 10 cm below basement ceiling –SWQP

Figure 10 shows the temperature profile predictions for three thermocouples placed 0.10 m below the ceiling in the tree quarter point. As can be noticed, the northwest quarter point, which is the further quarter, has a lower temperature.

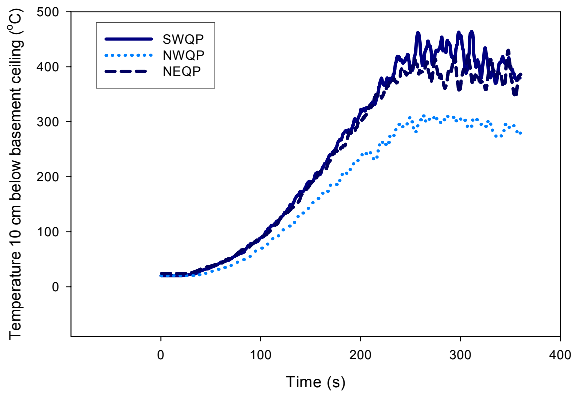

Figure 10: Time-temperature profile 10 cm below basement ceiling at three points

Figure 11 shows that the situation in the basement becomes hazardous at 280 s of the simulation. The CO_2 concentration reaches the tenability limit of 0.05 mol/mol.

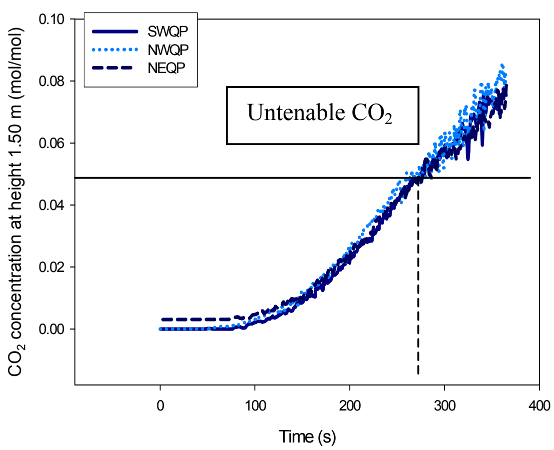

Figure 11: CO_2 concentration at three points of the basement at a height of 1.5 m

3.5 Fire 3- 3000 kW

The heat release rate of the fire was assumed to follow a fast T-squared fire, reaching a peak of approximately 3 MW in 253 s.

Table 9 summarizes some results from the simulations. The FRI was found to be equal to 1 from the resolution index of 0.07. Thus, the finer grid provides a better prediction. The Case 3 was chosen for this fire.

Cases	Grid number	Grid size (m)	R*	FRI	Run time (h)
1	54x54x40	0.20	0.13	0.84	2.89
2	75x65x20	0.14	0.09	0.98	8.78
3	108x90x27	0.10	0.07	1	28.69
4	135x120x36	0.08	0.05	1	82.31

Table 9: Fire 3: $\dot{Q}$ = 3000kW and D* = 1.49 m

Figure 12 gives the time temperature profile predictions for thermocouple N° 2. This figure illustrates that the increase of the temperature is not very significant when the fire is well resolved (R* =0.07). The fire dynamic is well simulated, with the finer grid which catches the most important phenomena. As shown in Figure 12, after the 280 s of the simulation the temperature starts to decrease due partly to the starvation of oxygen.

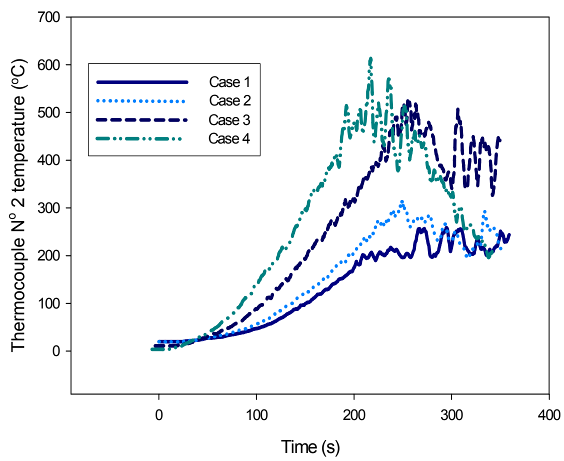

Figure 12: Time-temperature profiles 10 cm below basement ceiling –SWQP

Figure 13 and Figure 14 show that the situation in the basement becomes very hazardous after 280 s of the simulation. The CO_2 concentration reaches the tenability limit of 0.05 mol/mol.

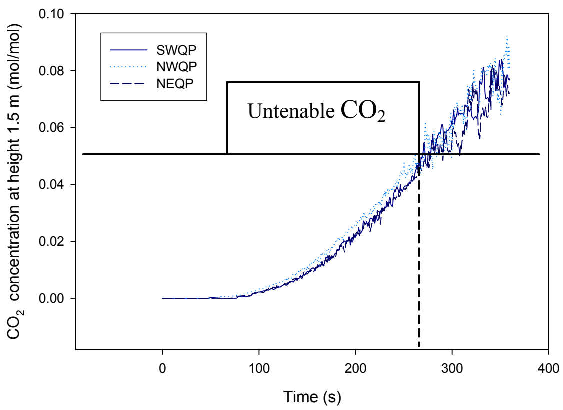

Figure 13: CO_2 concentration at three points of the basement at a height of 1.5 m

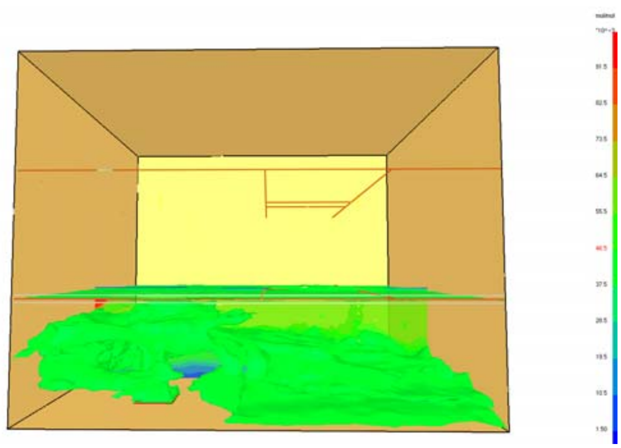

Figure 14:Iso-surface CO_2 concentration at 0.05 mol/mol

4 Conclusion

This paper presented details of the grid resolution sensitivity analysis, in order to determine an optimal grid size that can be used to evaluate fire safety in houses.

CFD simulations were conducted with three different fire sizes and four grid sizes. The numerical simulations showed that the computation times are significantly influenced by the grid sizes specified by the user. As well, the finer grid provides a better prediction of the temperature, visibility, CO and CO_2 concentrations. The coarse grid gave worse predictions when compared to well-established correlations. It was concluded that for the three fire sizes, the fire resolution index is equal to 1 when the resolution parameter is 0.07. Thus, this value will determine the optimum grid size for future simulations.

Based on the critical tenability limit criteria adopted by the Fire Engineering Design Guide [5], simulation results predicted that untenable conditions (for CO_2 criteria) were reached after 280 s for fire 2 and fire 3. The untenable conditions (for the visibility criteria) were reached after 180 s for fire 1.

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