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Evaluation of a multi-zone modelling concept for large volume buildings and tunnels

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ABSTRACT

The multi-zone modelling concept could be a good alternative to two-zone modelling and CFD modelling for some situations when performing fire safety designs. However, few such models exist, and the evaluation of the concept is scarce. This paper is dedicated to study the multi-zone modelling concept and its usefulness in fire safety engineering by benchmarking it against experimental data and simulations with FDS. Two different areas are studied in the paper: large volume buildings and tunnel fires.

The simulations of the large volume buildings results in reasonable estimates of gas temperatures and it is also concluded that the multi-zone concept can be a complement to more advanced numerical modelling tools like FDS. The results from the tunnel scenarios are promising but it is concluded that more benchmarking is needed.

INTRODUCTION

In a fire in small and medium-sized enclosures the fire and fire plume will cause turbulence and mixing of the hot gases, this results in that the hot gas layer will have a rather uniform temperature. This applies to both the stratified pre-flashover fire and the post-flashover fire. Models that include an assumption of a uniform hot gas layer, sometimes called “compartment fire framework”, also includes the concept of flashover. Flashover occurs when the heat from the stratified hot gas layer is so intense that all combustibles in the enclosure will ignite. A lot of effort has been conducted within this framework and there are several textbooks (Karlsson, 1999; Drysdale, 2011) that are dedicated to the compartment fire.

The situation becomes more complex in large or non-uniform spaces (like atria or tunnels) where the described type of mixing will not take place; thus, the hot gas layer will not be uniform. In such a case the concepts of flashover, and pre- and post-flashover fires becomes obsolete, and the non-uniform hot gas layer calls for other modelling methods. The International Standards Organization (ISO, 2013) have published guidance for use of two-zone models, which gives indications of the possible limits of the compartment fire framework. These limits state that when the enclosure aspect ratio (compartment length divided compartment width, or compartment height divided by compartment width) is above 5, caution should be applied.

Bong (2012) studied which type numerical model to use for different enclosures sizes. A two-zone model was seen to give very good predictions of the hot gas layer temperature and layer height, compared to data from FDS, in enclosures up to 600 m² and relatively good predictions up to 1200 m². However, for larger enclosures the FDS demonstrated a clear non-uniform temperature

distribution in both the horizontal and vertical direction, which of course was not captured with the two-zone model.

Two-zone models are not sufficient when modelling the conditions in large areas. CFD models can capture the temperature distribution in a large volume; however, they require an extensive number of control volumes and often a long computation time. A third option is so-called multi-zone (MZ) model. In a multi-zone model the enclosure is divided into several (typically 100-500) zones. The benefit of this is that it is possible to resolve the temperature distribution in an enclosure to some degree; consequently, the model can be applied outside the compartment fire framework.

The accuracy and possible benefits of the multi-zone concept is rather unknown. So, the scope of this paper is to evaluate the multi-zone concept and its usefulness in fire safety engineering.

METHOD

The evaluation of the multi-zone concept is performed by comparing data from a model called the MZ Fire model to previously published experimental data and data from simulations with FDS. The comparisons between the models and between models and experimental data are performed qualitatively, with graphs. Parts of the evaluation of the MZ Fire model have been performed in a previous publication (Johansson, 2021). However, the MZ Fire model have been improved further and more data have been included in this paper. The overall concept of a multi-zone model is presented in the following sub-section, this general description is based on previous presentation of the concept (Suzuki et al., 2004).

Concept of multi-zone modelling

In a multi-zone model the enclosure is divided into several regions (horizontal) and zones (vertical) as illustrated in Figure 1. This means that the entire enclosure is made up of several smaller computational volumes. The conservation mass and energy are applied for each volume.

The fire is specified as a heat release rate and the heat and hot gases rises upwards from the fire in a plume that enters the highest located zone in the fire region, *i*. The fire plume flow rises until it hits the ceiling. Air and hot gases are entrained in the plume from the zones that it passes through. Mass is transported horizontally to zones in adjacent regions due to hydrostatic pressure differences. The vertical flow of mass between zones is calculated based on the conservation of mass. The calculated properties (like temperature or soot concentration) are uniform in each zone. The model extends into a three-dimensional volume.

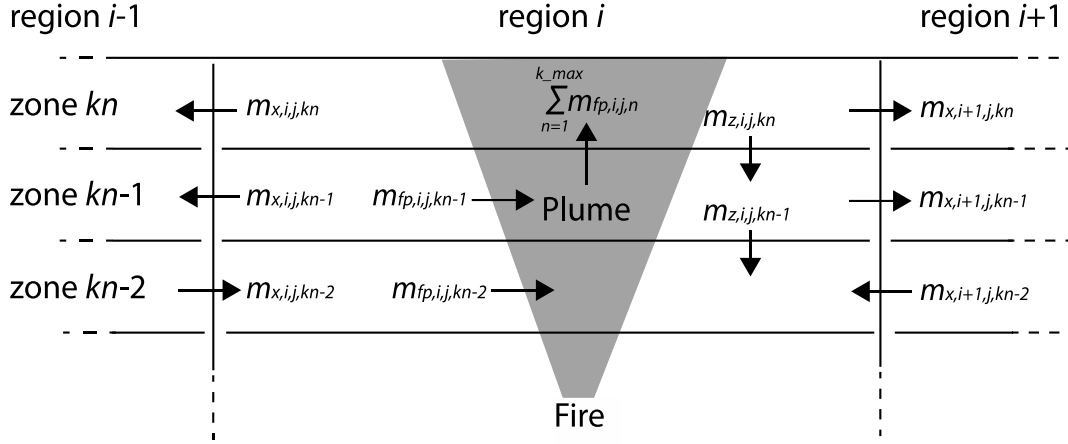


Figure 1: Principles of the multi-zone concept, re-drawn from Suzuki et al (2004).

The user specifies the heat release rate in the input file, and it is not affected by the surrounding conditions (e.g., radiant heat feedback or oxygen concentration). This means that the user needs to account for relevant surrounding conditions when specifying the heat release rate. Heat is transferred to solid obstructions through convection and radiation, and through 1D conduction in obstructions. Heat is transferred between zones through the flow of hot gases and radiation.

The driving mechanism behind the transport of smoke in the MZ Fire model is temperature differences between the different zones. An overview of the most important principles in the model is given below.

The general equation for the conservation of mass in each zone is calculated as in equation 1.

$$\frac{d}{dt}(\rho_{i,j,k} V_{i,j,k}) = -\dot{m}_{fp,i,j,k} + \dot{m}_{x,i-1,j,k} - \dot{m}_{x,i,j,k} + \dot{m}_{y,i,j-1,k} - \dot{m}_{y,i,j,k} + \dot{m}_{z,i,j,k+1} - \dot{m}_{z,i,j,k} \quad [1]$$

where $\rho_{i,j,k}$, [kg/m³] and $V_{i,j,k}$, [m³] are the density and the volume of the k -th zone in the region with x -coordinate i and y -coordinate j , and $\dot{m}_{fp,i,j,k}$ [kg/s] is the mass flow rate entrained into the fire plume in that zone. The horizontal mass flow rate from the $(i-1)$ -th and $(j-1)$ -th region to the i -th and j -th region is represented by $\dot{m}_{x,i-1,j,k}$ and $\dot{m}_{y,i,j-1,k}$ respectively. The horizontal mass flow rate from the k -th zone down to the $(k-1)$ -th zone is $\dot{m}_{z,i,j,k}$. The plume mass flow enters the top layer in each fire region. In the original model the plume mass flow is calculated with Heskestad's plume model (Heskestad, 1983). The horizontal mass flow in the x -direction, $m_{x,i,j,k}$, [kg/s] is calculated as:

$$m_{x,i,j,k} = C_d A_x \sqrt{2\rho_{i,j,k}(\Delta P_{i,j,k} - \Delta P_{i+1,j,k})} \quad (\Delta P_{i,j,k} - \Delta P_{i+1,j,k} \geq 0) \quad [2a]$$

$$m_{x,i,j,k} = C_d A_x \sqrt{2\rho_{i,j,k}(\Delta P_{i+1,j,k} - \Delta P_{i,j,k})} \quad (\Delta P_{i,j,k} - \Delta P_{i+1,j,k} < 0) \quad [2b]$$

The horizontal mass flow in the y -direction, $m_{y,i,j,k}$, [kg/s] is calculate similar as in the x -direction. $\Delta P_{i,j,k}$ is the pressure difference between the zone and the ambient. The vertical mass flow, $m_{z,i,j,k}$, is solved from the conservation of mass equation.

The conservation equation for energy is calculated as in equation 3.

$$\frac{d}{dt} (c_p T_{i,j,k} \rho_{i,j,k} V_{i,j,k}) = -c_p \dot{m}_{fp,i,j,k} T_{i,j,k} + h_{x,i-1,j,k} - h_{x,i,j,k} + h_{y,i,j-1,k} - h_{y,i,j,k} + h_{z,i,j,k+1} - h_{z,i,j,k} - \dot{Q}_{w,i,j,k} + \dot{Q}_{r,i,j,k} \quad [3]$$

where c_p [J/kgK] and $T_{i,j,k}$, [K] is the specific heat and temperature of k -th layer in the region with x -coordinate i and y -coordinate j . $\dot{Q}_{w,i,j,k}$ [W] is the convection heat loss to wall boundaries in contact with the zone and $\dot{Q}_{r,i,j,k}$ [W] is the net radiation heat to the zone. The energy flow, h , [W] depends on the direction of the mass flow over the zone boundaries.

The conservation of energy for the top layer is calculated as:

$$\frac{d}{dt} (c_p T_{i,j,k_{max}} \rho_{i,j,k_{max}} V_{i,j,k_{max}}) = \sum_{k=1}^{k_{max}-1} c_p \dot{m}_{fp,i,j,k} T_{i,j,k} + \dot{Q}_{c,i,j} + h_{x,i-1,j,k_{max}} - h_{x,i,j,k_{max}} + h_{y,i,j-1,k_{max}} - h_{y,i,j,k_{max}} - h_{z,i,j,k_{max}} - \dot{Q}_{w,i,j,k_{max}} + \dot{Q}_{r,i,j,k_{max}} \quad [4]$$

where, $\dot{Q}_{c,i,j}$ [W] is the convective heat released by the combustion transported to the top layer through the fire plume in the fire region. $\dot{Q}_{c,i,j}$ is zero in non-fire regions.

To get an expression for the temperature increase in each zone Equation 3 is rewritten as:

$$\frac{d}{dt} (c_p T_{i,j,k} \rho_{i,j,k} V_{i,j,k}) = c_p \rho_{i,j,k} V_{i,j,k} \frac{dT_{i,j,k}}{dt} + c_p T_{i,j,k} \frac{d}{dt} (\rho_{i,j,k} V_{i,j,k}) \quad [5]$$

Then Eq. 1 and 3 is substituted into Eq. 5 and after rearranging the general equation for calculating temperature is as follows:

$$\frac{dT_{i,j,k}}{dt} = \frac{1}{c_p \rho_{i,j,k} V_{i,j,k}} [h_{x,i-1,j,k} - h_{x,i,j,k} + h_{y,i,j-1,k} - h_{y,i,j,k} + h_{z,i,j,k+1} - h_{z,i,j,k} - \dot{Q}_{w,i,j,k} + \dot{Q}_{r,i,j,k} - c_p T_{i,j,k} (\dot{m}_{x,i-1,j,k} - \dot{m}_{x,i,j,k} + \dot{m}_{y,i,j-1,k} - \dot{m}_{y,i,j,k} + \dot{m}_{z,i,j,k+1} - \dot{m}_{z,i,j,k})] \quad [6]$$

Modifications in the MZ Fire model for tunnel fire scenarios

Tunnel fire dynamics can be very different from that in normal enclosures. When simulating tunnels some specific features have been added to the MZ Fire model, these are not included in the original model. The following features have been included in the specific tunnel version of the model:

- Longitudinal ventilation. Longitudinal ventilation exists in tunnels, and it is important to control then movement of smoke in case of fire. Therefore, the possibility to account for the longitudinal ventilation is included.
- Tunnel gradient. The inclination and length of the tunnel both have a large effect on the pressure difference and the flow of smoke. A possibility to account for the gradient is included in the model.
- Fire plume. The fire plume in tunnels can be greatly affected by the ventilation flow. The applied plume is therefore adjusted in the tunnel version of the MZ Fire model.

DESCRIPTION OF EXPERIMENTAL DATA

There are data from fire experiments in large enclosures and tunnels available in the literature; however, in many cases the description of the experimental conditions is insufficient to use the data to benchmark models. Still, there are some experimental data that are considered useful for the purpose of this study. In this paper data from five different experimental setups are used, four of these are large enclosures experiments (Hamins et al., 2005; McGrattan et al., 2018; Chow et al., 2001 and Gutiérrez-Montes et al., 2009) and the fifth is a tunnel (Lemaire & Kenyon 2006).

The experiments are presented in the sub-sections below, and a summary of the experiments based on five non-dimensional variables are presented in Table 1. The non-dimensional variables characterize important aspects of each experiment, and they are included to give the reader a better understanding of type of scenario that they represent.

Table 1: Dimensionless parameters values in the four compartment fire tests.

Parameter	Tests in large volume enclosures				Tunnel test
	BE3	NIST corner	PolyU	Murcia	BeNeLux
Dimensionless heat release rate	0.31	1.72 ¹ /3.44 ²	0.20	1.56	0.21 ³ /0.36 ⁴
Enclosure aspect ratio (L/W)	3.10	1.57	2.04	1.00	85.71
Enclosure aspect ratio (H/W)	0.54	0.54	2.45	0.97	0.53
Flame length ratio	0.59	0.54 ¹ /0.70 ²	0.08	0.21	0.70 ³ /1.53 ⁴
Equivalence ratio	0.13	0.02 ¹ /0.04 ²	1.50	0.02	0.03 ³ /0.02 ⁴
Radial distance ratio	3.76	15.02	4.45	6.87	2.09-59.01 ⁵

The *dimensionless heat release rate*, \dot{Q}^* , gives an indication if the fire is buoyancy-driven (natural fire), or momentum-driven (jet fire). In most natural fires \dot{Q}^* is less than 10. The *enclosure aspect ratio* is the enclosure length (L) divide by the enclosure height (H) or the enclosure height (H) divided by the enclosure width (W). If any of these are large (>5) the enclosure will have characteristics of a corridor or shaft, and it is hard to argue that the smoke layer properties will be uniform throughout the layer. The *flame length ratio* is the flame height relative to the ceiling height, when the flame height is greater than the ceiling, flames will extend radially under the ceiling. Traditional plume and flame height correlations does not account for this type of behaviour. The *equivalence ratio*, ϕ , is the rate of the fire's oxygen consumption divided by the oxygen supply rate to the enclosure. When $\phi < 1$ the conditions are well-ventilated and when $\phi > 1$ the fire is under-ventilated. The *radial distance ratio* is the distance between the fire and the target of interest divided by the diameter of the fire. Low radial distance ratios will require accurate modelling of thermal radiation.

Fire model benchmarking and validation exercise (BE3)

The International Fire Model Benchmarking and Validation Exercise (BE3) was conducted in an enclosure that measured 21.7×7×3.8 m³, see Figure 2. The fire was placed in the centre of the room and there was a door (2.0×2.0 m²) at one of the short ends. The walls and ceiling were made of

¹ Test with a 200 kW fire

² Test with a 400 kW fire

³ Test A

⁴ Test B

⁵ A range is given since targets at different locations were evaluated.

calcium silicate boards and the floor was made of gypsum. A full description of the enclosure, instrumentation and the test are given by Hamins et al. (2005).

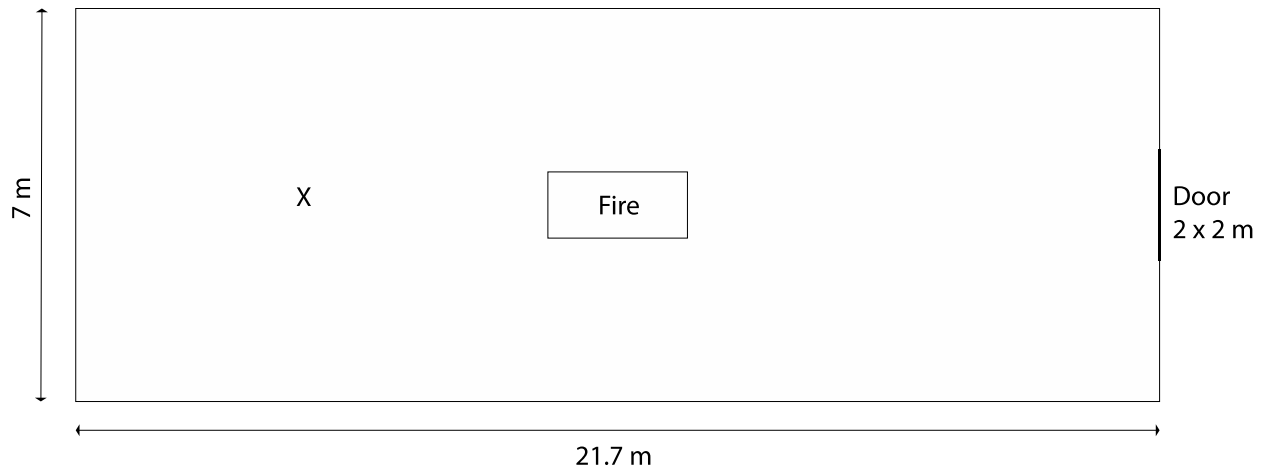


Figure 2: Enclosure used in BE3 tests; X marks the position of the thermocouple tree used in this benchmarking.

Test no. 3 in the experimental series is used in this paper. The fire consisted of a pan with heptane, corresponding to a maximum heat release rate of 1140 kW. Data from thermocouple Tree#7 (see Figure 2) is used in this study.

Wall and corner effects on plumes (NIST corner)

National Fire Research Laboratory (NIST) conducted a set of experiments for the U.S. Nuclear Regulatory Commission in 2017 (McGrattan et al., 2018). The objective of the experimental series was to provide measurement data with which to validate fire models used in industrial design applications.

The compartment was 11 m long, 7 m wide, and 3.8 m high (see Figure 3). A 1.8 m wide and 2.4 m high door was centred on one of the short walls. The compartment walls and ceiling were made of gypsum board, and the floor was made of plywood covered by gypsum board. The burner was constituted of four-square natural gas burners placed together with a total area of 0.61x0.61 m². The flow of gas was regulated with a mass flow controller and the heat release was kept at 200 and 400 kW in the tests studied in this paper. The compartment was well equipped with thermocouples and two thermocouple trees were located along the compartment centreline, at distances of one-third and two-thirds of the compartment length from the open door. A full description of the experimental setup is given by McGrattan et al. (2018).

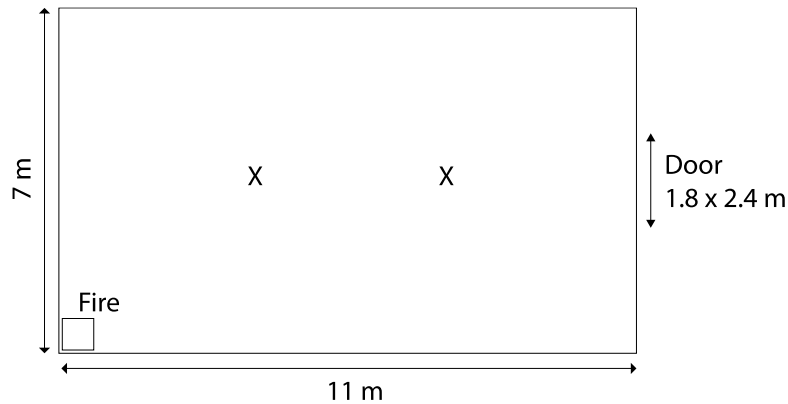


Figure 3: Overview of compartment used in the NIST corner tests; the X's marks the positions of the thermocouple trees used in this benchmarking.

PolyU atrium fire tests

The PolyU atrium was used to study smoke filling. Chow et al (2001) have published average data from five identical fire tests in the atrium (see Figure 4). The facility consisted of a single space ($22.4 \times 11.9 \times 27 \text{ m}^3$) made of concrete. A $2 \times 2 \text{ m}^2$ diesel pool fire was placed in the centre of the building. The only openings in the building were 0.2 m high gaps at floor level. The average heat release rate was estimated, based on the fuel mass loss rate during the five tests, to be 1660 kW. Thermocouple trees consisting of 20 thermocouples each was used to measure gas temperatures at different elevations in the room.

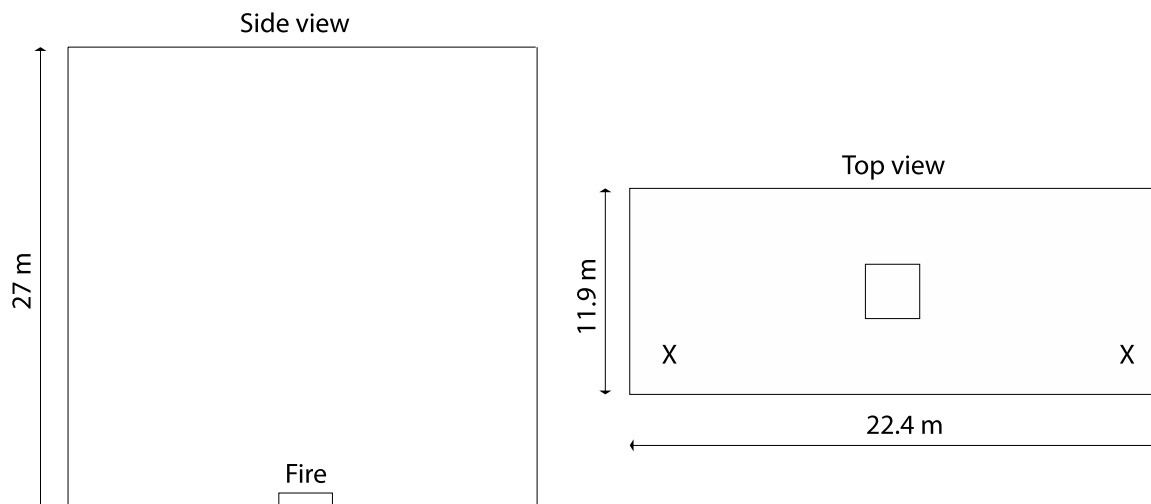


Figure 4: Overview of the enclosure used in the PolyU fire tests; the X's marks the positions of the thermocouple trees used in this benchmarking.

Murcia fire test

The Murcia Atrium Fire Tests (Gutiérrez-Montes et al., 2009) were conducted in a $19.5 \times 19.5 \times 20 \text{ m}^3$ structure with walls and roof made of steel plate (see Figure 5). The experimental series consist of different setups regarding fire size and ventilation conditions. The test data used in this paper originates from a test (Test#3) where the roof exhaust fans were shut off and only used for natural ventilation. Four equally sized vents at ground level were used for makeup-air. A 1 m^2 fuel pan with heptane was used as fire source and the maximum heat release rate was 2340 kW. A more detailed description of the experimental setup is given by Gutiérrez-Montes et al. (2009).

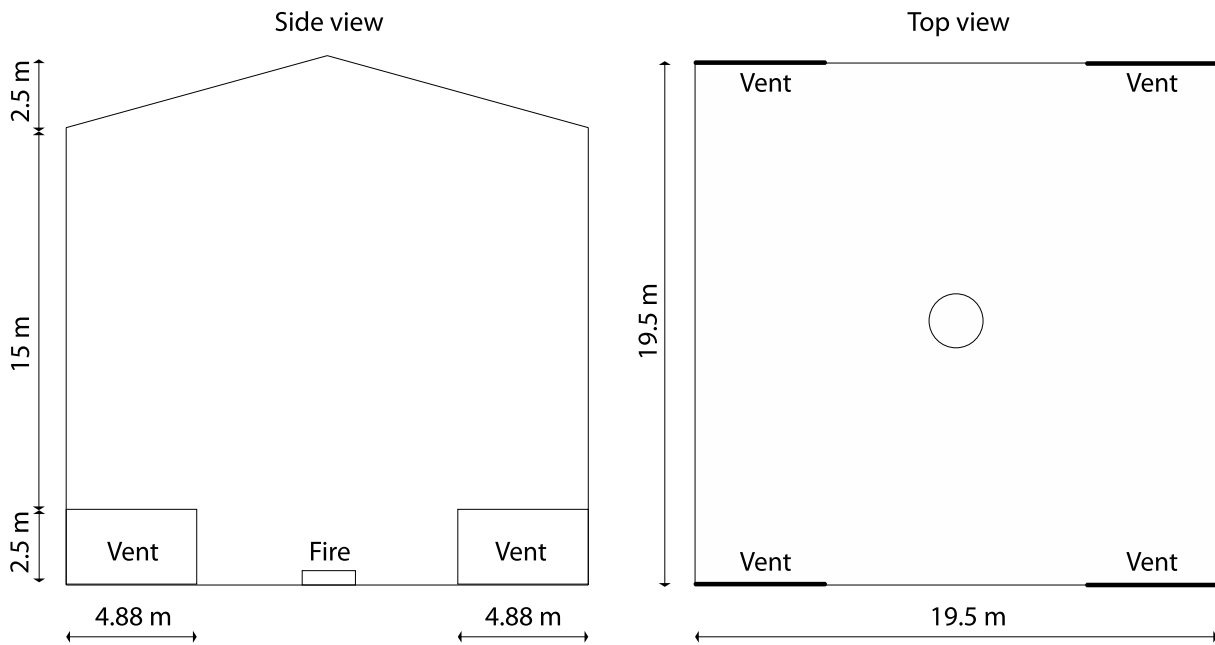


Figure 5: Overview of the enclosure used in the Murcia fire tests.

Benelux tunnel fire test

In 2000 and 2001 a total of fourteen full-scale fire tests were performed in a 840 m tunnel for road traffic that runs under the New Meuse River outside Rotterdam (Lemaire & Kenyon, 2006). The width and height of the tunnel were 9.8 m and 5.2 m, respectively. The tunnel had a slope gradient of 4.4° and the test site was located 265 m from the northern portal. The ventilation system was in the south part, and the measurements were performed from 50 m upstream to 200 m downstream of the fire. A summary of the ventilation and fire conditions in the two tests used in this paper are presented in Table 2.

Table 2: Type of ventilation and fire in the two BeNeLux tests.

Test	Ventilation	Type of fire	Maximum HRR (MW)
A	Natural ventilation	Car	5
B	Longitudinal ventilation max 6 m/s	Canvas covered wooden pallets	20

RESULTS

Results from the MZ Fire model and FDS simulations are presented together with experimental data for the five experimental setups in the following sections.

Fire model benchmarking and validation exercise (BE3)

Results from the simulations of the BE3 test is presented in Figure 6. The results from MZ corresponds well to the experimental data in the upper part of the enclosure ($z > 1.5\text{m}$). The vertical temperature profile (right part of Figure 6) illustrates a good agreement between MZ and FDS, however FDS predicts higher temperatures just underneath the ceiling.

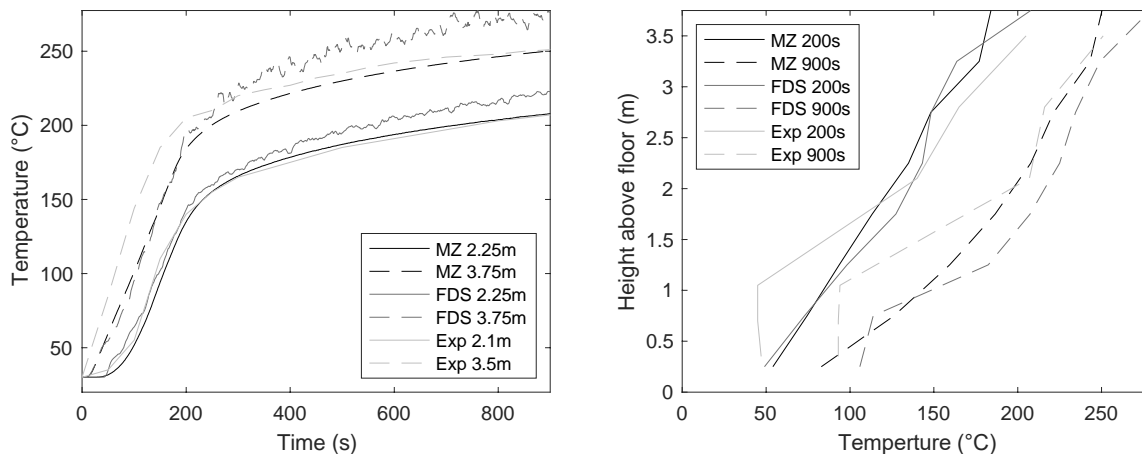


Figure 6: Temperature development at two different heights (left) and vertical temperature profile at two time points (right) in the BE3 test.

Wall and corner effects on plumes (NIST corner)

Results from the simulations NIST corner tests are presented in Figure 7 to Figure 9. For the scenario with 200kW corner fire (see Figure 7) FDS predicts the experimental values very well while MZ tends to slightly underpredict the elevated temperatures and overpredict temperatures at lower elevations.

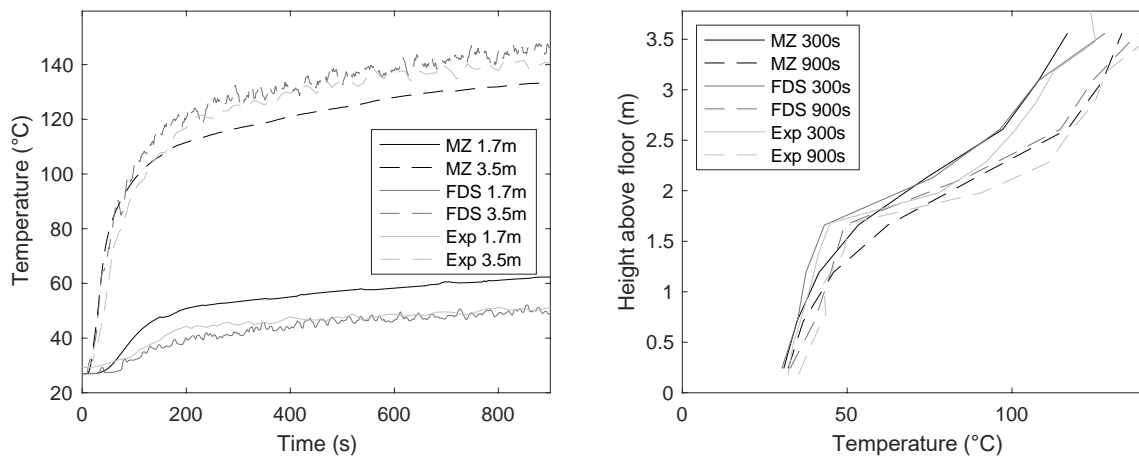


Figure 7: Temperature development at two different heights (left) and vertical temperature profile at two time points (right) in 200kW scenario in NIST corner.

For the 400kW corner fire (see Figure 8) the trend becomes more evident, MZ underpredicts the most elevated temperatures ($z=3.5$ m) and overpredict temperatures at lower elevations. In regard to the experimental data FDS performs better than MZ.

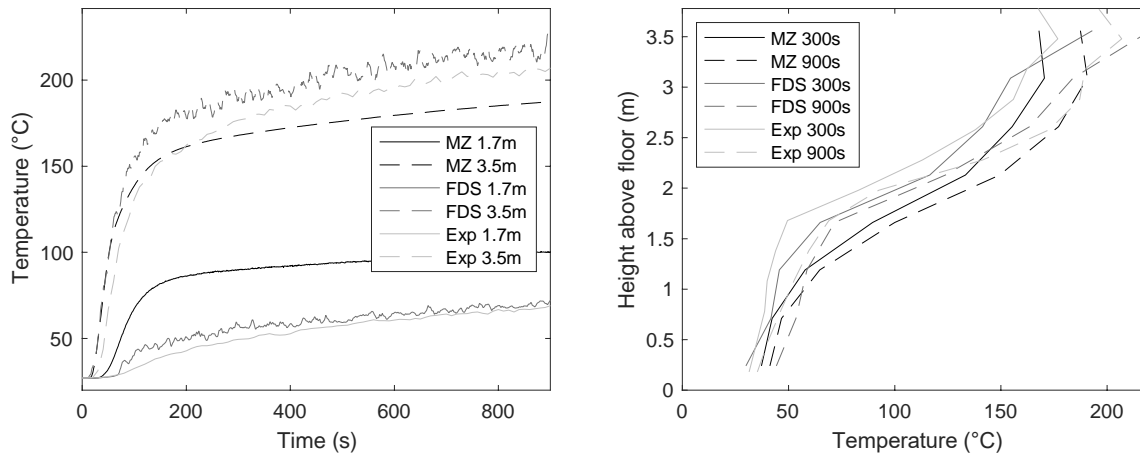


Figure 8: Temperature development at two different heights (left) and vertical temperature profile at two time points (right) in 400kW scenario in NIST corner.

In the NIST corner tests the burner was moved away from the corner after some time in the experiment, the tests then transitioned from corner tests to free burning test (no interaction between flame and corner/wall). In Figure 9 data from MZ are compared to the results from the free burning test of the 200 and 400kW scenarios (no FDS simulations have been performed for this case). The MZ Fire model performs well however the temperatures are slightly underpredicted for both scenarios.

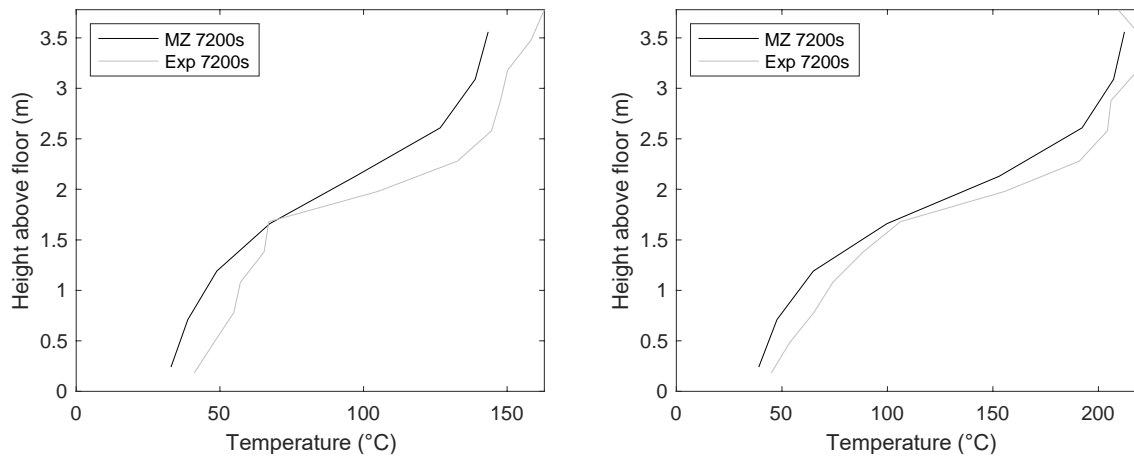


Figure 9: The vertical temperature profile for the free burning case in the 200kW (left) and 400kW (right) scenarios in the NIST corner tests.

PolyU atrium fire tests

It is clear from Figure 10 that the agreement between simulation results and experimental data is limited. Still, the results from FDS and the MZ simulations corresponds very well, even though the MZ results in a slightly lower temperatures compared to FDS in the final part of the simulations. The large differences between the experimentally measured and modelled temperature are likely due to the limited ventilation in the fire test, something that has not been accounted for in the modelling.

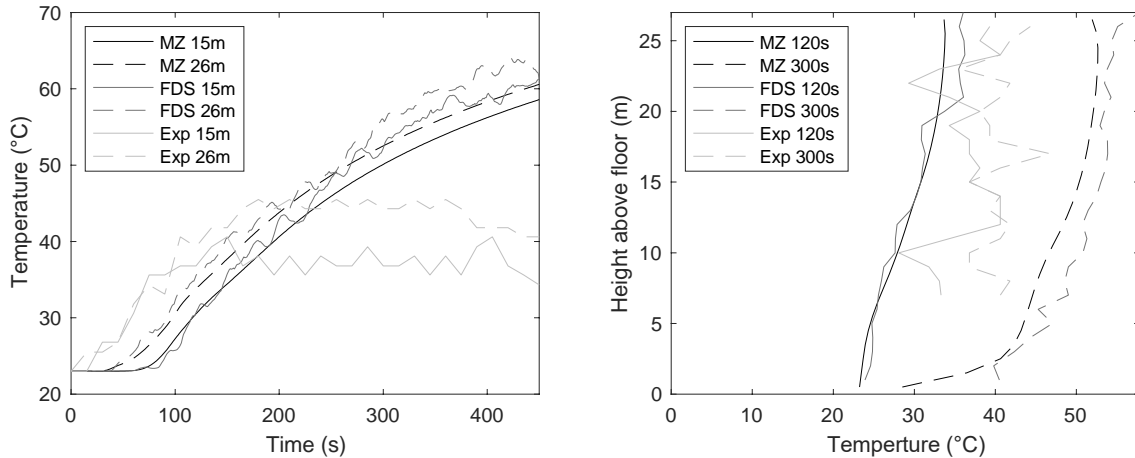


Figure 10: Temperature development at two different heights (left) and vertical temperature profile at two time points (right) in the PolyU test.

Murcia fire test

Results from the simulations of the Murcia fire test are presented in Figure 11. The results from FDS and the MZ simulations are similar. The temperature in the lower part of the enclosure (see right part of Figure 11) is however predicted to be higher in FDS than in MZ. Both models give lower temperatures at higher elevation ($z = 18$ m) compared to the test data. The fact that the two models yield in similar results, indicate that the difference between models and experiments are due to uncertainties in the input values.

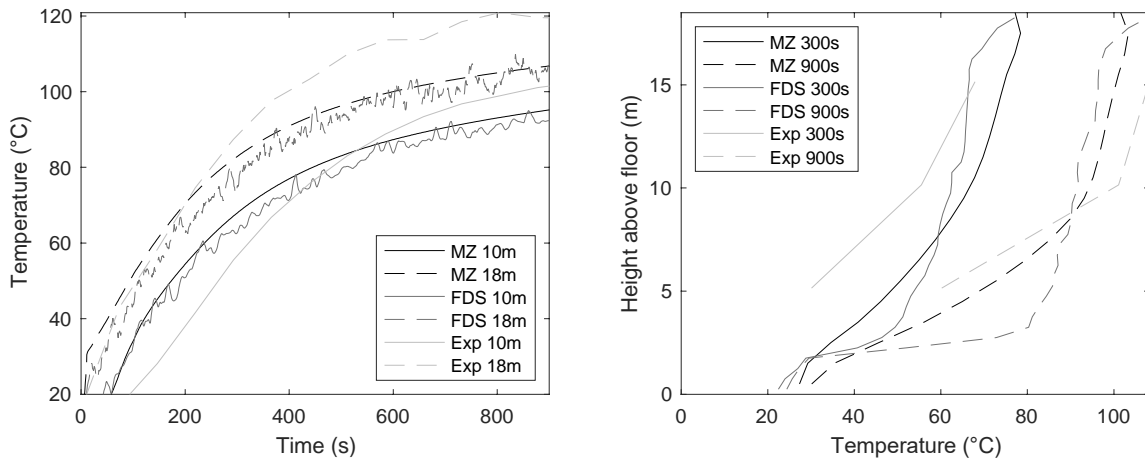


Figure 11: Temperature development at two different heights (left) and vertical temperature profile at two time points (right) in the Murcia test.

Benelux tunnel fire test

A comparison of average of the temperatures (at 1 and 2 m above the floor) between simulations and experimental data is presented in Figure 12 and Figure 13. In Test A the absolute temperatures are small and both numerical models predict the temperatures within a couple of degrees of the experimental measurements. In Test B the heat release rate is higher and consequently is also the temperature higher compared to Test A. The MZ Fire model predicts the shape of the temperature and the absolute temperature rather well except for in the vicinity of the fire (20 m). An explanation for the discrepancy close to the fire source is limitations in the plume model used in MZ.

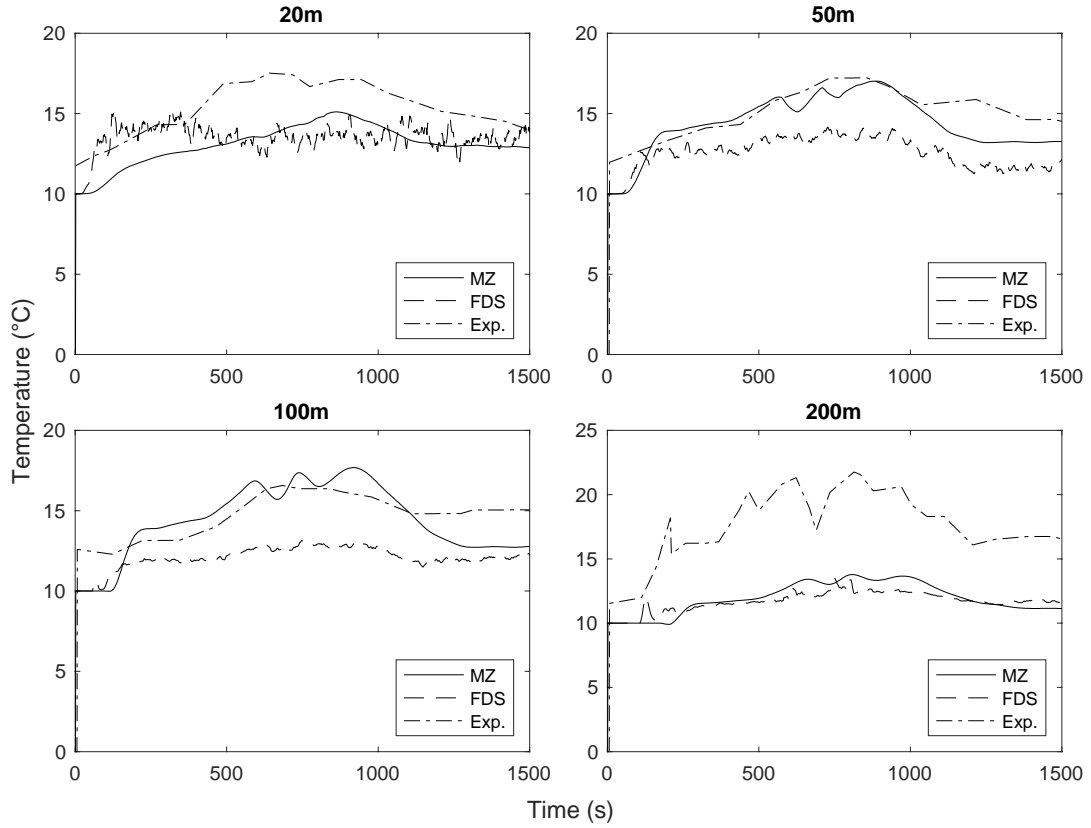


Figure 12: Averaged temperature at 1 and 2 m above the floor in Test A.

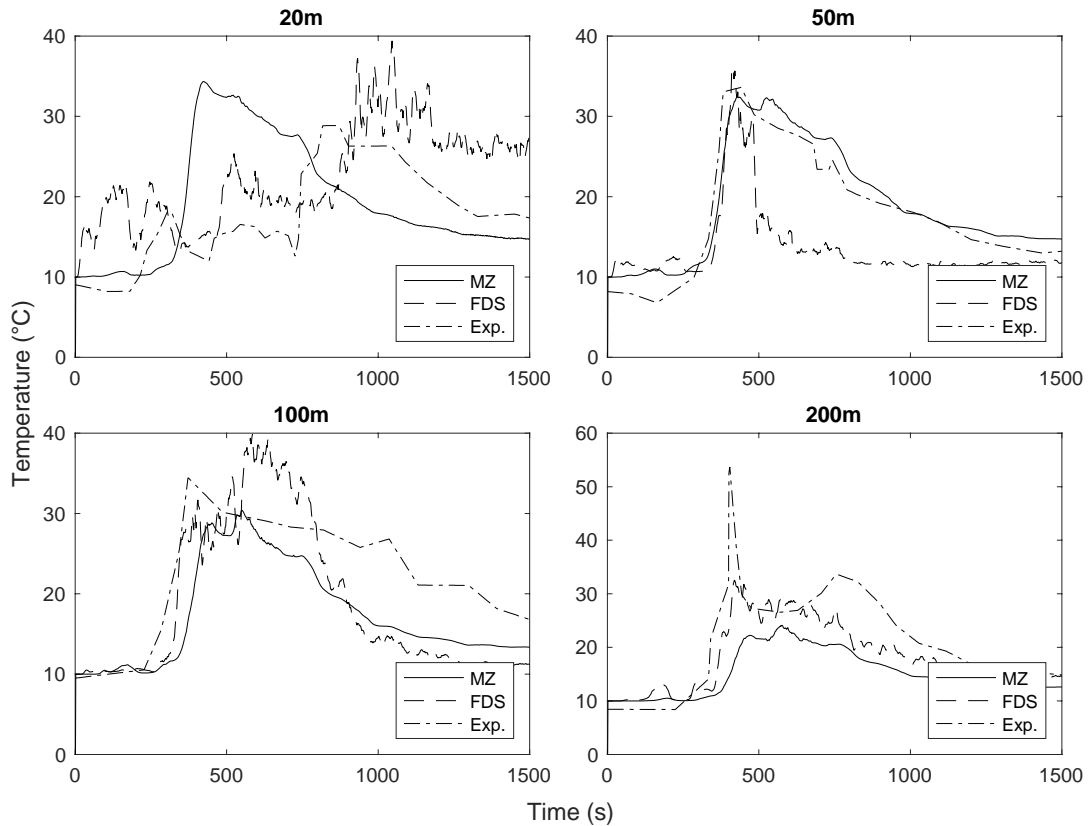


Figure 13: Averaged temperature at 1 and 2 m above the floor in Test B.

In Figure 14 the average simulated cross-section temperatures at different distances from the fire source in MZ and FDS are compared. MZ tends to give higher temperatures closer to the fire source than FDS. A possible reason for the higher temperatures in MZ can be related to limitations in the model regarding plume and how plume entrainment is modelled.

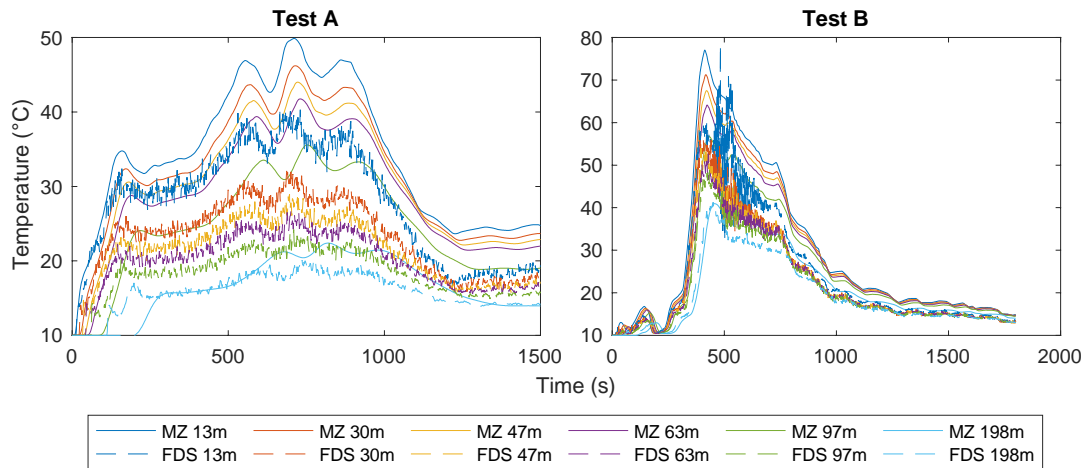


Figure 14: Simulated averaged cross-section temperature in Test A (left) and Test B (right).

CONCLUSIONS

Experimental data and simulations with FDS are used in this paper to benchmark the MZ model in large enclosures and tunnels. The results show that the MZ Fire model predicts gas temperatures similar to those predicted by FDS in well-ventilated large spaces. The MZ Fire model does not take the influence of walls and corners on the flame and plume into account. This can be an explanation to why the MZ results deviate more from FDS and the experiment in the NIST corner tests compared to the BE3 and Murica tests. When it comes to the PolyU test there is a fairly large difference between experimental and model results. The reason for this is probably the limited ventilation (limited ventilation is not accounted for in the MZ Fire model). So, regarding fires in large enclosures the results indicate that the MZ Fire model can be useful tool for fire safety engineering when studying well-ventilated fires that are not disturbed by corners and walls.

Regarding the BeNeLux tunnel fires it be seen that the MZ Fire model performed well 50-200 m from the fire for heat release rates in the magnitude of 5-20 MW and moderate longitudinal ventilation flows. Even if the results are promising, more benchmarking against tunnel fire experiments and other simulation tools are needed.

ACKNOWLEDGEMENT

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