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Johansson, Nils

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Evaluation of a Zone Model for Fire Safety Engineering in Large Spaces

Nils Johansson*

Division of Fire Safety Engineering, Lund University, Lund, Sweden,
nils.johansson@brand.lth.se

*Corresponding author

Highlights:

- Presentation of a novel numerical multi-zone model.
- Data from three large-scale experiments are compared to data from numerical models.
- Multi-zone model predicts gas temperatures within 5% of FDS predictions.
- Multi-zone model predicts gas temperatures within 10% of experimental data for the well-ventilated scenarios.

Abstract:

Thanks to simple and straightforward calculation methods it is rather easy to estimate gas temperatures in small- or medium sized enclosures; however, the problem becomes more complex if fire safety analyses are to be performed in large spaces where the hot gas layer cannot be regarded as uniform. Using a multi-zone modelling concept could be a good alternative for such situations. However, few such models exist and the evaluation of the concept is scarce. This paper is therefore dedicated to study the multi-zone modelling concept and its usefulness in fire safety engineering by comparing results from such a model with results from a more established numerical method as well as experimental data. The results indicate that the multi-zone model gives reasonable estimates of gas temperatures in well-ventilated large spaces. It is also concluded that there is a potential for the multi-zone concept to be a complement to more advanced numerical modelling methods like Computational Fluid Dynamics.

Keywords: modelling; performance-based design; compartment fires

1. Introduction

Fires in small- and medium-sized enclosures will cause turbulence that mixes the hot gases, which results in a hot gas layer with rather uniform temperature. This has sometimes been referred to as the "compartment fire framework", and it applies to both the stratified pre-flashover fire and the post-flashover fire. The framework also includes the concept of flashover, which occurs when the heat from the stratified hot gas layer is so intense that all combustibles in the enclosure will ignite. The first comprehensive work in this area was done by Kawagoe in the 1950s [1], and a lot of effort has been conducted within the area since then. This has resulted in different types of analytical methods, like the time-temperature curves in Eurocode 1 [2], and numerical models, like 2-zone models, that are very valuable for fire safety engineering under certain conditions.

The situation becomes more complex in large spaces where the hot gas layer cannot be regarded as uniform. Outside the compartment fire framework, the concepts of flashover, and pre- and post-flashover fires becomes obsolete, and the non-uniform hot gas layer calls for other modelling methods. There is no clear definition when the compartment fire framework should or should not be applied. However, the International Standards Organization have published some guidance on the use of zone models [3], which gives some hints of the possible enclosure dimension limits of the compartment fire framework.

In the compartment fire framework, the fire is normally considered to be fuel-controlled initially and grows in size until flashover occurs. The fire then becomes ventilation-controlled, and the heat release rate is controlled by the supply of oxygen. The terms regime I and regime II [4] are sometimes used to distinguish between ventilation-controlled and the fuel controlled-burning, respectively. It has been argued that fires in large spaces are likely to be within regime II [4], since the availability of air most likely will be high due to the presence of large openings and leakages to the surroundings.

Stern-Gottfried and Rein [5] present the so-called traveling fires framework in which the thermal field induced by the fire is divided into two regions: the near field and far-field. The position and size of the regions are relative to the position of the fire, and moves within the enclosure as the fire spreads. The near field is the burning region of the fire, and the far-field is the region where no burning or flames are present and where the hot gas layer will provide a thermal exposure. The near field temperatures can be modelled with methods like the localised fire in Eurocode 1 [2] or with some “worst-case” flame temperature. The far-field temperature is however more challenging to model.

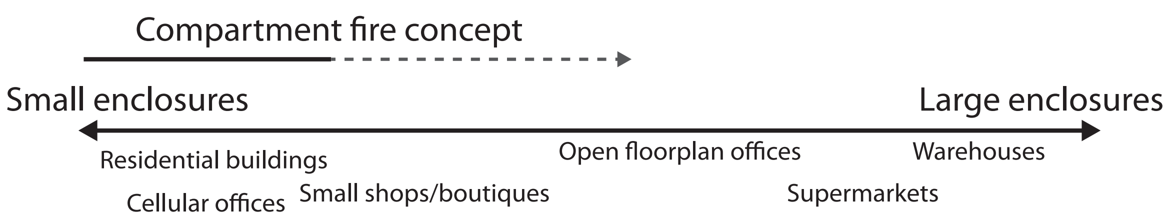

Figure 1: Applicability of the compartment fire concept.

Rein et al [6] used the Computational Fluid Dynamics (CFD) model Fire Dynamics Simulator (FDS) to model the far-field temperatures but found it problematic due to the high computational cost. Therefore, later efforts to estimate far-field temperatures have focused on using the much simpler analytical methods like the ceiling jet correlation by Alpert [7]. The ceiling jet correlations are generally good for estimating gas temperatures in the early stages of fire. The problem with applying the Alpert correlation in enclosed spaces is that it is not applicable when a hot gas layer form. Furthermore, the correlations do not account for the thermal properties of the ceiling which in the original work by Alpert [7] was seen to be important at distances of 3 to 5 ceiling heights from the centre of the fire. More recently promising efforts have been made by the research group in at Edinburgh University to couple a simple zone model with a model for localized fires; however, the work is said to be on a conceptual stage [8].

In a thesis by Bong [9] guidance on how to determine which numerical model to use for different enclosures sizes is presented. The two-zone model, BRANZFIRE, 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 m^2 and relatively good predictions up to 1200 m^2. However, for larger enclosures the FDS simulations demonstrated a non-uniform temperature distribution in both the horizontal and vertical direction, which was not captured with the two-zone model.

It is obvious that two-zone models can be insufficient to use in large enclosures, as is the fact that CFD models requires an extensive computation time in such spaces. A possible middle ground can be so-called multi-zone (MZ) models [10][11]. The multi-zone concept it is based on the conservation of mass and energy to calculate hot gas temperatures, and the Bernoulli equation to calculate flows between the different zones. In contrast to two-zone models, like BRANZFIRE or CFAST [12], where each enclosure consists of two zones, each enclosure is divided into several regions (horizontal) and layers (vertical) in the multi-zone concept. The benefit of this is that properties like gas temperature can be calculated at many locations, and consequently the temperature distribution in the hot gas layer can be found.

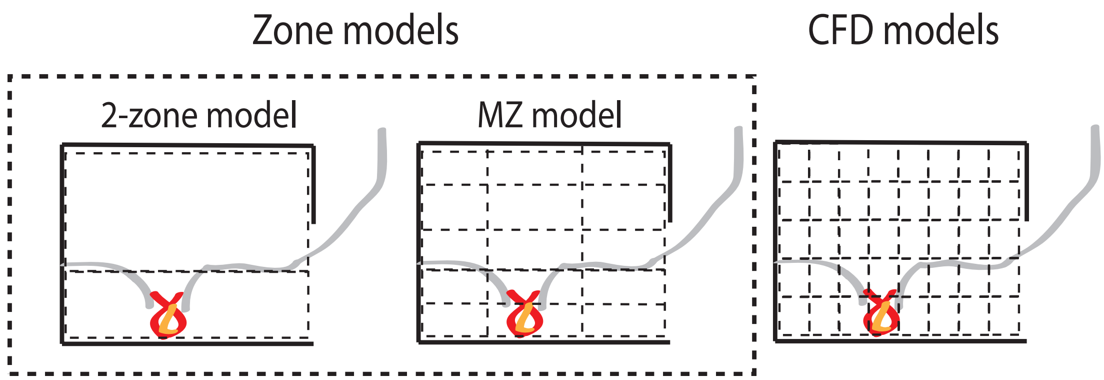

Figure 2: Principles of the different types of models.

The multi-zone concept is not as established as two-zone models since only a few models have been presented (see e.g. [11] and [13]). The accuracy and possible benefits of models using the multi-zone concept is therefore rather unknown. So, the scope of this paper is to evaluate the multi-zone concept and its usefulness in fire safety engineering compared to other more established numerical methods.

2. Method

The evaluation of the multi-zone concept is performed by comparing data from a MZ-model to previously published experimental data (see Section 3) and data from simulations with FDS. The comparisons between the models and between models and experimental data are preformed qualitatively, with graphs, and quantitatively, with functional analysis. Functional analysis is used to quantify the agreement between two sets of data by treating time series curves as vectors $x = (x_1, x_2, \ldots x_n)$ [14]. This makes it possible to quantify the length, angle and distance between two different sets of data or graphs. Three different metrics are used, the first one is Euclidean Relative Distance (ERD) which gives the average difference between the data sets. The second metric is the Euclidean Projection Coefficient (EPC) and the shift, which the value that if multiplied with the value of the test will give the best possible agreement. The final metric is the Secant Cosine (SC), which gives a value of how well the shape of the graphs correspond to each other.

2.1 Multi-Zone model

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The Multi-Zone Fire model (version 2019:02) [15] is used in this paper, and it is based on the general multi-zone concept has been described in previous publications [10][11]. The principles of how mass flow is modelled in the is described in Figure 3. The figure presents a 2-dimensional model; however, the MZ model extends in three dimensions.

Like a zone-model the MZ model uses equations for conservation of mass and energy. The temperature and species concentration are uniform in each separate zone. The flow between different zones is driven by temperature differences and calculated based on the principles of the Bernoulli equation, and there is no modelling turbulence. The driving force is the fire which is assigned as a heat release rate and the convective part of the heat release rate goes directly into the topmost cell above the fire. Radiation from the fire to and in-between zones are modelled as well as heat transfer to and through the boundaries. The plume rises through the layers in region i until it hits the ceiling, air and hot gases are entrained in the plume from the different layers that it passes through. The plume is modelled with the Heskestad's plume model. The horizontal mass flow is calculated based on hydrostatic pressure difference and the vertical mass flow is calculated based on the conservation of mass of each cell. and is based on the model used by Johansson [16]. Johansson made a minor evaluation study of the model and saw that it over predicted the temperatures under the ceiling by 30-40 °C, corresponding to around 10-15% of the measured gas temperature.

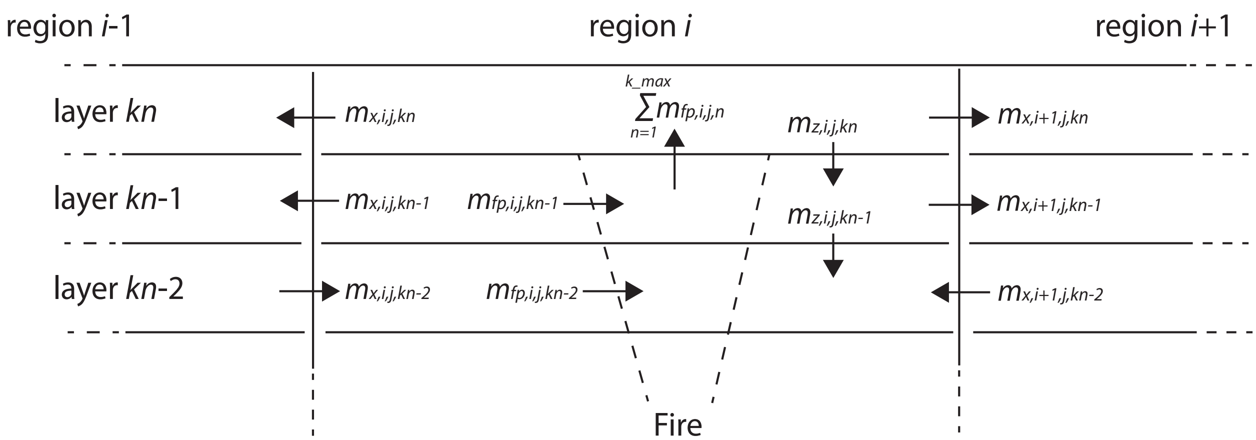

Figure 3: Principles of the multi-zone concept, recreated after Suzuki et al [11].

The general equation for conservation of mass used in the modelled is given in the following equation.

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

where $\rho_{i,j,k}$, [kg/m^3] and $V_{i,j,k}$, [m^3] are the density and the volume of the k-th layer 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 layer. 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 layer down to the (k-1)-th layer is $\dot{m}_{z,i,j,k}$. The plume mass flow enters the top layer in each fire region. There is no layer above the top layer in each region, this means that the conservation of mass for the top layer becomes as follows:

$$\frac{d}{dt}\left(\rho_{i,j,k\_max}V_{i,j,k\_max}\right) = \sum_{n=1}^{k\_max-1}\left(\dot{m}_{fp,i,j,n}\right) - \dot{m}_{z,i,j,k\_max} + \dot{m}_{x,i-1,j,k\_max} - \dot{m}_{x,i,j,k} + \dot{m}_{y,i,j-1,k\_max} - \dot{m}_{y,i,j,k\_max}$$

If there is no fire in the region the fire plume entrainment, $\dot{m}_{fp,i,j,k}$, will be zero. The conservation equation for energy is as follows:

$$\frac{d}{dt}\left(C_p T_{i,j,k}\rho_{i,j,k}V_{i,j,k}\right) = -C_p\dot{m}_{fp,i,j,k}T_{i,j,k} + h_{x,i-1,j,k} - h_{x,i,j,k} + h_{y,i,j-1,k} - h_{y,i,j,k} + h_{z,i,j,k+1} - h_{z,i,j,k} - \dot{Q}_{w,i,j,k} + \dot{Q}_{r,i,j,k}$$

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 any 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 with:

$$\frac{d}{dt}\left(C_p T_{i,j,k\_max}\rho_{i,j,k\_max}V_{i,j,k\_max}\right) = \sum_{n=1}^{k\_max-1} C_p\dot{m}_{fp,i,j,n}T_{i,j,n} + \dot{Q}_{c,i,j} + h_{x,i-1,j,k\_max} - h_{x,i,j,k\_max} + h_{y,i,j-1,k\_max} - h_{y,i,j,k\_max} - h_{z,i,j,k\_max} - \dot{Q}_{w,i,j,k\_max} + \dot{Q}_{r,i,j,k\_max}$$

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.

The size of the zones is a user input in the Multi-Zone Fire model, and there is currently no general guidance on what zone size to use. However, at least three zones in each direction is needed to run the model. Furthermore, it is reasonable to think that the horizontal dimensions of the fire region should be large enough that the plume, that extends laterally as it moves upwards, can be enfolded by the region. Another aspect to consider is the expected property distribution (e.g. temperature) and the zone resolution needed to capture that distribution to a reasonable extent. In the simulations performed in this paper a zone size of 4×4×0.5 m^3 is used.

The Multi-Zone Fire model includes the possibility to model the influence of: multiple time dependent fires; vertical and horizontal vents in the enclosure boundaries; and internal obstacles like walls. The model uses a text-based input file and it is available for download online [15].

2.2 CFD model

The Fire Dynamics Simulator (FDS), developed by NIST [17], is often used in different fire safety design situations. FDS is a CFD model where fire-driven fluid flows are simulated. The software solves the Navier–Stokes equations numerically with an emphasis on heat and smoke transport. In order to resolve turbulence adequately the grid needs to be small enough. FDS version 6.7.1 is used in the simulations performed in this study. The grid size (dx) is kept in the interval $5 < D^*/dx < 10$ in order to get favourable results at a moderate computational cost [18]. Where D^* is the characteristic diameter. The FDS validation guide [19] includes a large amount of validation examples and there has also been a lot of validation work of the model by independent research teams. When it comes to gas temperatures, it has been shown that FDS gives predictions within the experimental uncertainty [20].

3. Description of experimental data

There are little data from fire experiments in large spaces available in the literature, and when it exists, it is common that the description of the experimental conditions is insufficient in order to use the data reliably. However, there are some examples of experimental data in large spaces that are considered useful for the purpose of this study. In this paper data from three different experimental setups are used. The experimental setups are considered to be complimentary since they include different types of enclosures (in regard to volume and boundaries) and fire sizes.

3.1 Fire model benchmarking and validation exercise

The first set of data originates from the International Fire Model Benchmarking and Validation Exercise #3 (BE#3) [21]. The experimental series was conducted in an enclosure that was designed to represent a room in a nuclear power plant and it measured 21.7×7×3.8 m^3, see Figure 4. The fire was placed in the center of the room and there was a door (2.0×2.0 m^2) on one of the short ends. The walls and ceiling were made of Marinite boards (ρ = 737 kg/m^3, c_p = 1250 J/kgK, k = 0.12 W/mK) and the floor was made of gypsum boards (ρ = 790 kg/m^3, c_p = 900 J/kgK, k = 0.16 W/mK). A full description of the enclosure, instrumentation and the test are given in reference [21].

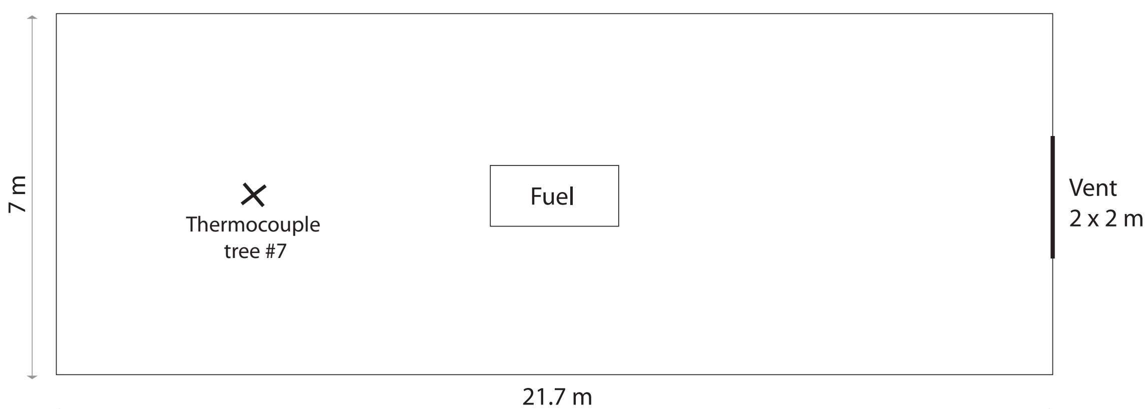

Figure 4: Overview of the enclosure used in the International Fire Model Benchmarking and Validation Exercise [21].

In the test used in this paper (Test#3) a pan with heptane, corresponding to a maximum heat release rate of 1050 kW (corrected value: 1140 kW), was used as fire source. The fire was ramped up during 3 minutes and the total duration of the test was 26 minutes. Seven different thermocouple trees were used; however, only data from thermocouple TC Tree#7 (see Figure 4) is used in this study. The combined relative expanded uncertainty of the data in BE#3 have been estimated in connection with work done by NRC [22].

3.2. Murcia fire test

The Murcia Atrium Fire Tests were conducted in a 19.5×19.5×20 m^3 open space (see Figure 5). The enclosure boundaries were made of steel plate ((ρ = 7800 kg/m^3, c_p = 460 J/kgK, k = 45 W/mK). The experimental series consist of different setups in regard to fire size and ventilation conditions. Four exhaust fans were installed on the roof, each one with a diameter of 0.56 m, there were also 4.88×2.5 m^2 vents located in the lower part of the room. More than sixty sensors were used in the tests to measure transient temperatures as well as pressure drop at the exhaust fans.

The test data used in this paper originates from a test (Test#3 in reference [23]) where the exhaust fans were shut off and only used for natural ventilation. Four equally sized vents on ground level (A1, A3, C1 and C2) were used for makeup-air, see Figure 5. A fuel pan (Ø 1.17 m) with heptane was used as fire source and the maximum heat release rate was estimated to be 2.34 MW. The weather was cloudy and the wind speed less than 1 m/s.

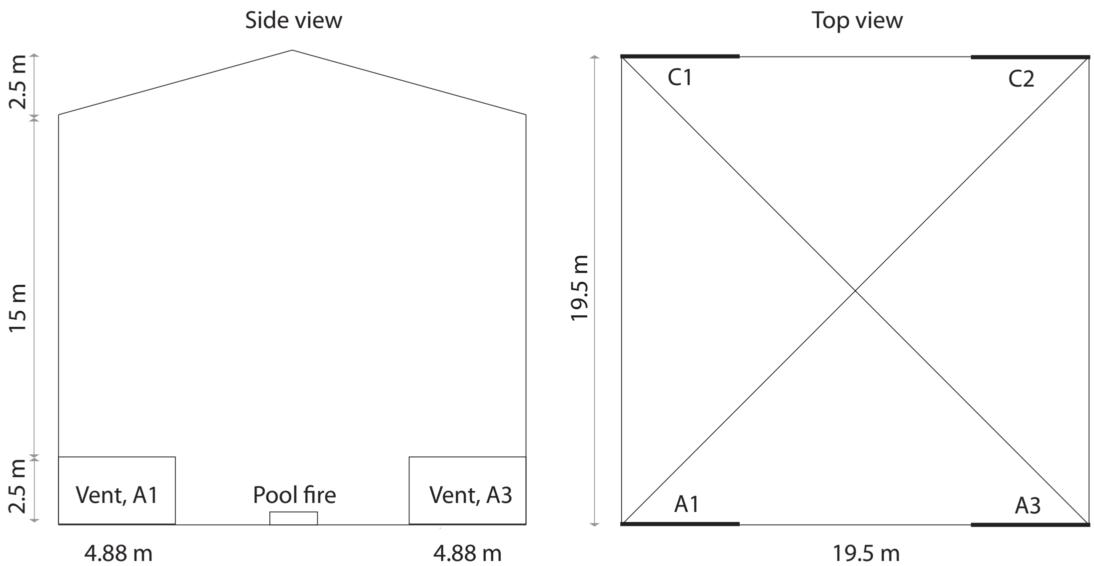

Figure 5: Overview of the enclosure used in the Murcia fire tests [23].

3.3 PolyU/USTC Atrium

The PolyU/USTC Atrium was used to study smoke filling, and Chow et al [24] have published average data from five identical fire tests in the facility. The facility consisted of a single volume constructed of concrete (ρ = 1860 kg/m^3, c_p = 780 J/kgK, k = 0.72 W/mK) that measured 22.4×11.9×27 m^3. A 2×2 m^2 diesel pool fire was placed in the center of the building. The only opening in the building was a 0.2 m high gap at floor level. The average heat release rate was estimated, based on measured fuel mass during the five tests, to be 1660 kW. Two racks consisting of 20 thermocouples each was used to measure gas temperatures at different elevations close to the short ends of the room.

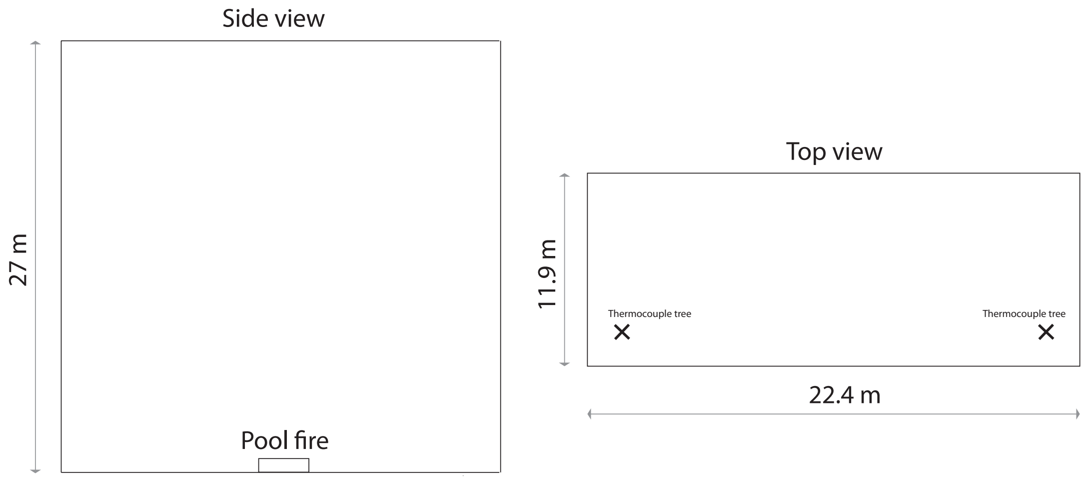

Figure 6: Overview of the enclosure used in the PolyU/USTC fire tests [24].

4. Results

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

4.1 Fire model benchmarking and validation exercise

Results from the simulations of test 3 in BE#3 is presented in Figure 7. The results from FDS and the MZ model corresponds well, whilst the test data indicates a more rapid temperature increase during the first 100 s in the top of the enclosure (z = 3.5 m).

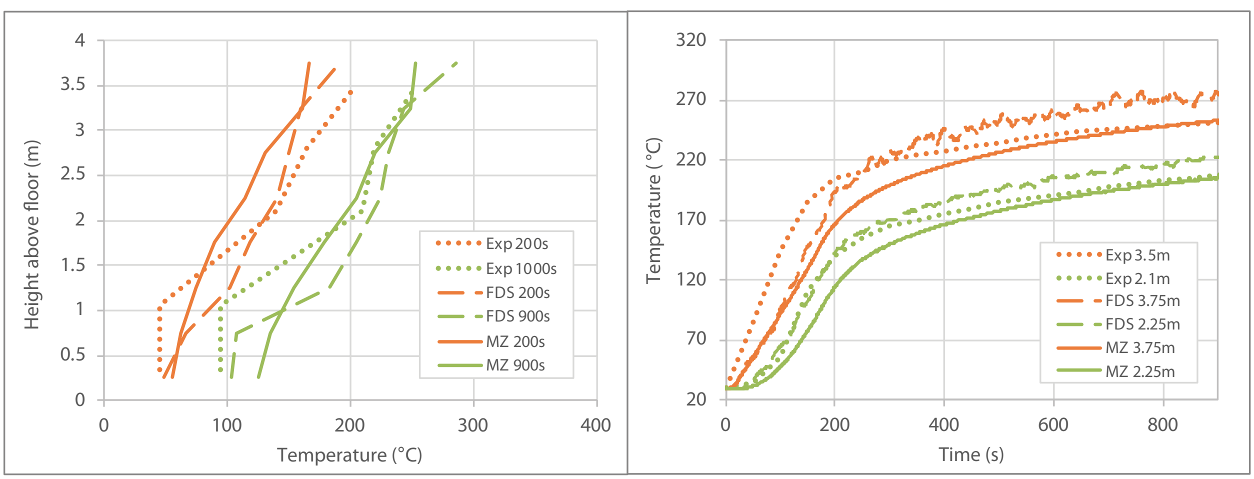

Figure 7: Vertical temperature profile at two time points (left) and temperature development at two different heights (right) in the BE#3 test.

The time-temperature curves at z = 2.25 m (green curves in the right part of Figure 7) are analysed with functional analysis. The results in Table 1 confirms that the results from FDS and the MZ model are similar. The average distance (ERD) between FDS and MZ is low (1%), the shift (EPC) is close to 1 and the curves are more or less identical, i.e. SC-value close to 1.

Table 1: Functional analysis of data (between 0 and 900 s) at z =2.25 m above floor in the BE#3 test.

	ERD		EPC		SC	
	Exp.	FDS	Exp.	FDS	Exp.	FDS
FDS	0.00	-	0.94	-	0.94	-
MZ	0.01	0.01	1.04	1.11	0.90	0.95

4.2. Murcia fire test

Results from the simulations of the Murcia fire test are presented in Figure 8. The results from FDS and the MZ model simulations are similar. The temperature in the lower part of the enclosure (see left part of Figure 8) is however predicted to be higher with FDS than with the MZ model. Both models give lower temperatures at higher elevation (z = 18 m) than the test data.

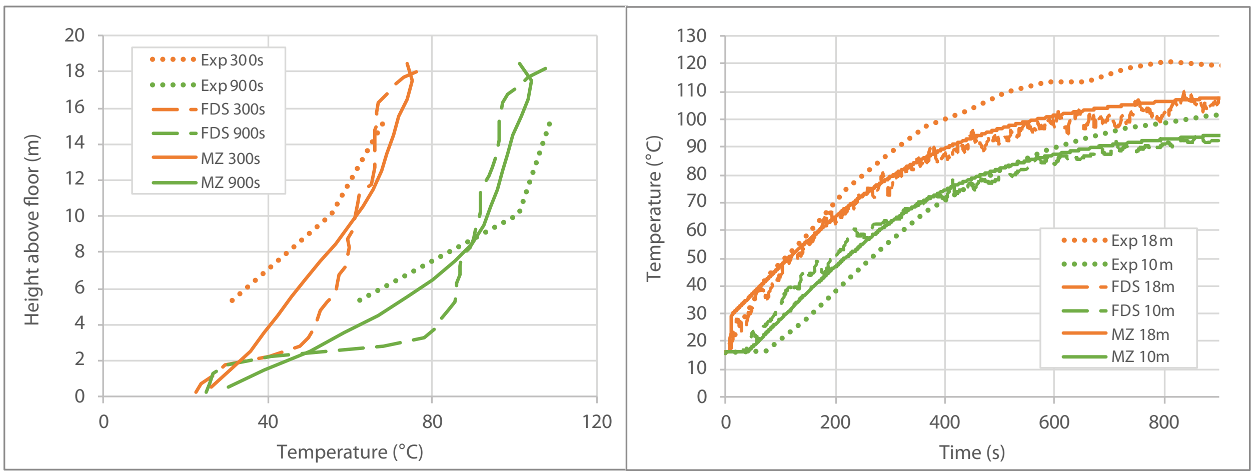

Figure 8: Vertical temperature profile at two time points (left) and temperature development at two different heights (right) in the Murcia test.

Data from z = 10 m (green curves in the right part of Figure 8) are analysed in the functional analysis, and it confirms the findings in Figure 8. The average distance (ERD) and the shift (EPC) give similar values as for the BE#3 test; however, the shape of the curves (SC) does not correspond as well in this case.

Table 2: Functional analysis of data (between 0 and 870 s) at z = 10 m above the floor in the Murcia test.

	ERD		EPC		SC	
	Exp.	FDS	Exp.	FDS	Exp.	FDS
FDS	0.01	-	1.00	-	0.90	-
MZ	0.01	0.01	1.01	0.99	0.75	0.75

4.3 PolyU/USTC Atrium

It is clear from Figure 9 that the conformity between simulation results and experimental data is not as good in the PolyU/USTC case as in the two other cases. Still, the results from FDS and the

MZ model simulations corresponds rather well, even though the MZ model results in a slightly slower temperature development compared to FDS.

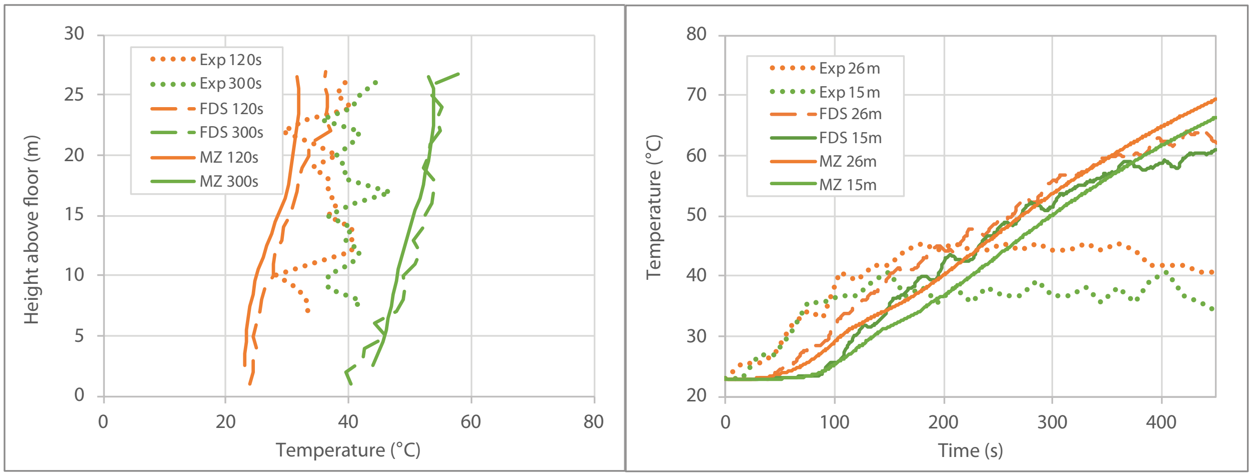

Figure 9: Vertical temperature profile at two time points (left) and temperature development at two different heights (right) in the PolyU/USTC test.

A functional analysis is performed on the data at z =15 m (green curves in the right part of Figure 9), see Table 3. The average distance (ERD) and the shift (EPC) shows a close agreement between FDS and the MZ model, and the shape of the two curves are considered to correspond rather well (SC=0.83). The experimental data deviates rather much from the model results, especially after 150 seconds when the shapes of the curves diverge.

Table 3: Functional analysis of data (between 0 and 450 s) at z = 15 m above floor in the PolyU/USTC Atrium test.

	ERD		EPC		SC	
	Exp.	FDS	Exp.	FDS	Exp.	FDS
FDS	0.15	-	0.77	-	0.32	-
MZ	0.17	0.00	0.77	1.02	0.02	0.83

5. Discussion

The results from the FDS and the MZ model simulations correspond rather well in the BE#3 and Murcia scenarios, the deviation compared to the experimental data is larger. This could partly be explained by uncertainties in the inputs that are introduced by misinterpretation of the experimental setups presented in the original papers. It is demanding to give a full presentation of the experimental setup, environmental conditions, outputs etc. in a scientific paper. Consequently, it is more or less evident that assumptions are needed in order to be able to simulate experimental setups found in the literature. This introduces uncertainties in the input values used for the simulations. That different modellers can interpret input data differently is well known [25], and it is illustrated in this case by the fact that Gutiérrez-Montes et al [23] got a better agreement, than seen in Figure 8, between test data and FDS simulations.

When it comes to the PolyU/USTC case there is a larger difference between experimental and model results than in the two other cases. The main reason for this is probably the limited ventilation. The only opening in the building was a 0.2 m high gap at floor level, which most likely will result in that the flames were in the hot gas layer after a couple of minutes which probably influenced the combustion negatively. The mass loss rate is used in the original paper [24] to estimate the heat release rate, and no effort have been made in the paper to present if or how the heat release rate is affected by the descending hot gas layer. Under-ventilated fires are in general difficult to model and limited ventilation is not accounted for in the MZ model. This probably explains the larger difference between model and experimental results in this case.

The MZ model is much simpler than FDS and has a more limited area of use. For example, the rather course zone resolution makes it difficult to include obstructions with fine details. There is no modelling of turbulence and the plume, that drives the flow of gases is based on an empirical plume model. Even so, there are benefits of the model. The main benefit is that simulations of scenarios like the cases used in this paper are performed within 1-2 minutes. This is in the order of 0.1% of the time to perform a similar FDS simulation on a desktop computer. The computation time for CFD simulations will most likely decrease with increased computer capacity, which might reduce the need for a quicker and less accurate tools like the MZ model. However, the multi-zone concept is still so much quicker that it could be of value, especially for fire safety analyses in large spaces. A possible increased demand for multiple simulations as inputs to fire risk analyses, might also make this type of model appealing.

There is limited information to do any detailed assessment of the experimental uncertainty of the test data used in this study, which makes it difficult to assess the model uncertainty. Nevertheless, in the case of the BE#3 tests the relative expanded uncertainty of the hot gas layer temperature rise has been estimated to 12% in a previous study [22], and it was shown that FDS can make predictions within this uncertainty. Additional studies are needed in order to further quantify the accuracy of the MZ model, as have been done with other fire models.

6. Conclusions

Experimental data and simulations with FDS are used in this paper in order to evaluate the MZ model in large spaces. The results show that the MZ model predicts gas temperatures within 5% of FDS results and within 10% of the experimental data in two well-ventilated large spaces. In the third case there is a discrepancy between the modelling and the experimental data, the main reason for this is most likely the limited ventilation in the experimental test. The results are promising and there might be a future for the MZ model; however, further studies are needed in order to quantify the accuracy of the model and its limitations.

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