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Estimating gas temperatures in large enclosures

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ABSTRACT

A case study is used in this paper to study and analyse drawbacks and advantages of three different numerical fire models when used to model horizontal and vertical gas temperature distributions in a 1200m² large enclosure. The three methods are: a CFD model, a two-zone model and a multi-layer zone model. This is the first time the three models are used and compared in a large enclosure situation. The problem with using the two-zone model in the studied case is underlying assumption that the hot gas layer has a uniform temperature. Results from both the CFD and the multi-layer zone models shows that there is a vertical temperature distribution and it cannot be modelled in a conventional two-zone model. The multi-layer zone model has several benefits; however, the model requires further development and evaluation.

1. INTRODUCTION

The spread of hot gases and the hazardous conditions produced by a fire in a building will depend on several different factors, like the size of the fire, the building, HVAC system and weather conditions. Buildings can be constructed and designed in a large variety of ways depending on the use of the building. The size of the enclosure that the fire is contained within is one parameter that will have an obvious effect on different gas properties like temperature and visibility. The turbulence caused by the fire will mix the hot gases in a small enclosure and the gas properties will be rather homogenous both in vertical and horizontal direction. This type of fire situation is often referred to as a “compartment fire”, while the term “fires in large enclosures” is used for fires in larger spaces where the hot gas layer cannot be regarded as uniform in regard to temperature and composition. The compartment fire concept is in general valid for small and medium sized enclosures (see Figure 1).

The homogenous gas layer assumption has made it possible to derive equations and find correlations with the help of experimental data. The non-uniform gas layer in the large enclosures is more difficult to study both theoretically and experimentally. The first comprehensive work dealing with the compartment fire concept was done by Kawagoe in the 1950s [1] and a lot of effort and research has been conducted within that area since then. Even though there are limitations in how the compartment fire concept should be

used, it provides a robust and simple way of describing fire conditions for certain fire and enclosure characteristics; accordingly, it is important to know when these models are applicable.

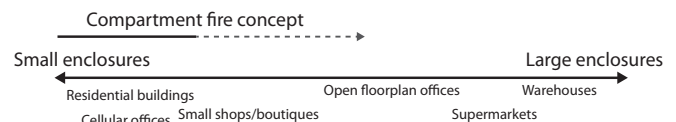


Figure 1: Applicability of the compartment fire concept.

The horizontal temperature distribution in an enclosure will become more non-uniform as the enclosure area increases. However, there are few studies of the relation between enclosure size, heat release rate and the temperature distribution. Alpert [2] studied ceiling jets and derived correlations that can be used to calculate temperatures under ceilings at a certain radial distance from the fire. Alpert assumed an axisymmetric fire plume beneath a flat, horizontal ceiling, unobstructed by walls and derived correlations for the ceiling jet temperature and velocity. Alpert also conducted a numerical study of ceiling jets and found, among other things, that there was no large effect due to heat transfer to the ceiling on the ceiling jet temperature and thickness within a radial distance (r) of less than 1 ceiling height ($r/H < 1$) from the fire. However, at distances of 3 to 5 ceiling heights, the effects were significant. The ceiling jet correlations are generally good for estimating the gas temperatures in the early stages of the fire. However, the correlations are not suitable to use in order to study gas temperatures in an enclosed space where

a hot gas layer, which will affect the temperature, forms.

Two-zone modelling is a fire modelling method that is based on the compartment fire concept, i.e. that there is a hot upper layer (or zone) with a uniform temperature and a cooler lower layer. There are several different two-zone models available and they generally perform well in cases where the compartment fire concept is applicable. However, caution is needed when modelling long hallways or tall shafts (see Table 1). Furthermore, a small fire in relation to the enclosure size will not fulfil the compartment fire concept. A fire size of 0.1 kW/m^3 of enclosure volume has been suggested as a guide for ensuring the establishment of a hot layer [3].

Table 1: Acceptable ratios between enclosure length (L), width (W) and height (H) [Fel! Hittar inte referensskälla.].

Acceptable value	Special consideration required
$L/W \leq 3$	$3 < L/W < 5$
$L/H \leq 3$	$3 < L/H < 6$

The two-zone model, BRANZFIRE, have been seen to give very good predictions of the hot gas layer temperature and layer height, compared to data from the Computational Fluid Dynamics (CFD) model FDS, for enclosures up to 600 m^2 and relatively good predictions up to 1200 m^2 [4]. However, for larger enclosures the two-zone model tended to under-predict the average temperature close to the fire. The results from the FDS simulations in the BRANZFIRE study [4] showed that there was a non-uniform temperature distribution in both the horizontal and vertical direction.

Bong [5] did a comprehensive work to provide guidance to fire engineers on how to determine which of the computer methods to use for different enclosures sizes. It was found that BRANZFIRE gave reasonable results, comparable with FDS results, for Q^* between 0.002 and 0.15 in cases with an instantaneous stable fires. Bong also conducted a review of studies where results from two-zone and CFD modelling in large enclosures were compared.

Even though a handful of studies in the area exist there is still little guidance available on how fires

in large enclosures should be analysed. Three different numerical methods to calculate the gas temperature in large enclosures will therefore be reviewed and analysed in this paper. The three methods are: a CFD model, a two-zone model and a multi-layer zone (MLZ) model.

2. SCOPE

The three methods will be used in a case study in order to present drawbacks and advantages of each numerical method when used to simulate a fire in a large enclosure.

3. STUDIED MODELS

The three methods are: a CFD model, a two-zone model and a MLZ model (see Figure 2).

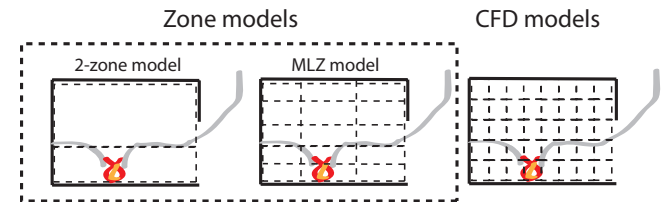


Figure 2: Principles of the three different types of models used in this paper.

3.1 CFD MODELS

The Fire Dynamics Simulator (FDS), developed by NIST, 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 [6].

The problem with using FDS to simulate fires in large enclosures is that the computational time increases when the physical domain increases.

3.2 TWO-ZONE MODELS

The conservation of mass and energy is used in zone models to calculate hot gas temperatures. The flows between zones are calculated with the help of pressure differences and the Bernoulli equation. As previously mentioned, two-zone models are more or less based on the compartment fires concept (uniform temperature) and they are consequently not applicable to use in large enclosure. A possibility, which could be used to simulate fires in large enclosures, is the so-called

multi-cell concept [8]. The idea of the multi-cell concept is to use virtual rooms in the two-zone model in order to model a large enclosure. There are considered to be two main drawbacks of this approach. Firstly, the two-zone model is not developed and, in general, not validated for this kind of use, secondly, the two-zone model will still provide uniform vertical temperature in the smoke layer. The two-zone model CFAST [7], developed by NIST, is used in this paper.

3.3 MULTI-LAYER ZONE MODEL

The MLZ model uses zone model principles; each enclosure is however modelled as several different zones, in contrast to the two-zone models where each room only consists of two zones (see Figure 2).

The MLZ model has been described in previous publications [9, 10]; therefore, only the major concepts of the model are described in this paper. In the MLZ model the enclosure is divided into several regions (horizontal) and layers (vertical) this means that the enclosure is divided in to several smaller volumes or zones. 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 layer in the fire region, i . Air and hot gases is also entrained in the plume from the layers that it passes through. Mass is transported horizontally to layers in adjacent regions due to hydrostatic pressure differences. There is also a flow of mass vertically between layers in each region, which is calculated based on the conservation of mass.

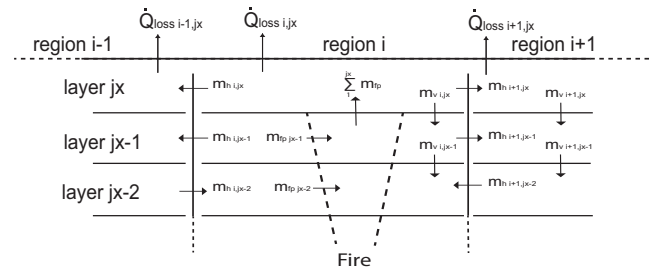


Figure 3: Principles of the MLZ model, recreated after Suzuki et al [9].

The principal equation for zone models, presented below, derived from the conservation equations of mass and energy is simplified and used in each

zone. The full derivation of the equation can be found in previous publications [11].

$$c_p V \rho \frac{dT}{dt} - V \frac{d\rho}{dt} + \sum_{j, in} \dot{m}_j c_p (T - T_j) = \dot{m}_{F, reacted} \Delta h_c + \dot{Q} - \dot{W}_{shaft}$$

The major differences in the model used in this paper and the MLZ model originally used by Suzuki et al [9] is that the volume is considered in three dimensions. In the previous studies, where the MLZ model has been used, only a single region or a multi-region (two-dimensional) corridor was studied. In this paper the MLZ model concept is extended to a three-dimensional volume with regions not only in the x- and z-direction, as illustrated in Figure 3, but also in the y-direction.

3.3 (a) Model Evaluation

The MLZ concept has been evaluated previously [9, 10]; however, it is considered important to evaluate the model used in this paper because it has been rewritten based on the description in the previous work [9, 10] and modified. Furthermore, it is important that the reader can get an idea of the accuracy of the model. The applied MLZ model is evaluated with the help of experimental data from the International Fire Model Benchmarking and Validation Exercise [12]. Two tests conducted in an experimental series (Test#2 and Test#3 in reference [12]) are used in this evaluation.

The enclosure that was used in both tests was 7 m x 21.7 m x 3.8 m and it was designed to represent a room in a nuclear power plant (see Figure 4). The fire was placed in the centre of the room and it was possible to open a door (2.0 m by 2.0 m) on one of the short ends of the enclosure. The boundaries were made of Marinite boards. A full description of the enclosure, instrumentation and the test are given in reference [12].

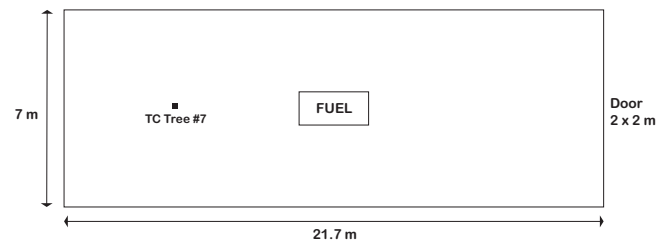


Figure 4: Overview of the enclosure used in the evaluation of the MLZ model.

Test #2 Closed room

A pan with heptane, corresponding to a maximum heat release rate of 1040 kW (corrected value: 1130 kW), was used as fire source. The fire was ramped up during 3 minutes and the total duration was 10 minutes. Seven different thermocouple trees were used in the test. Data from thermocouple tree seven (TC Tree#7) is used in this evaluation. TC Tree#7 was located between the fire and the short end that had no door (see Figure 4). The door was closed in Test#2.

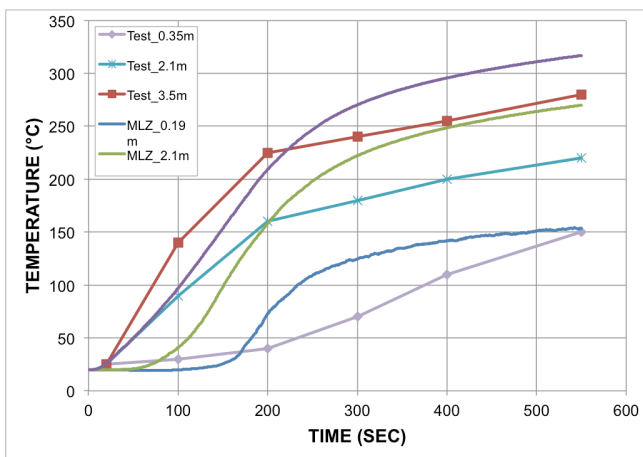


Figure 5: Results of the evaluation at three different vertical locations at TC Tree#7 in Test#2.

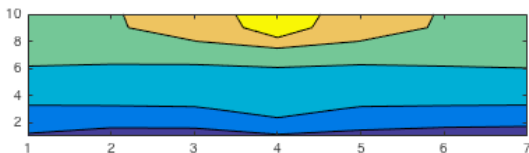


Figure 6: A section ($t=600s$) through the center of the room with results from the MLZ model in the Test#2 configuration. The axes correspond to the number of regions. Blue indicates low and yellow high temperature.

It is clear from Figure 5 and Figure 6 that the MLZ will give a vertical and horizontal temperature distribution. The temperatures are however over predicted with 30-40K.

Test #3 Open door room

The major difference between Test#3 and Test#2 is that the door is open in Test#3. The maximum heat release rate was 1050 kW (corrected value: 1140 kW), the ramp up time was 3 minutes and the total duration was 26 minutes. TC Tree#7 is used for the evaluation of the MLZ model.

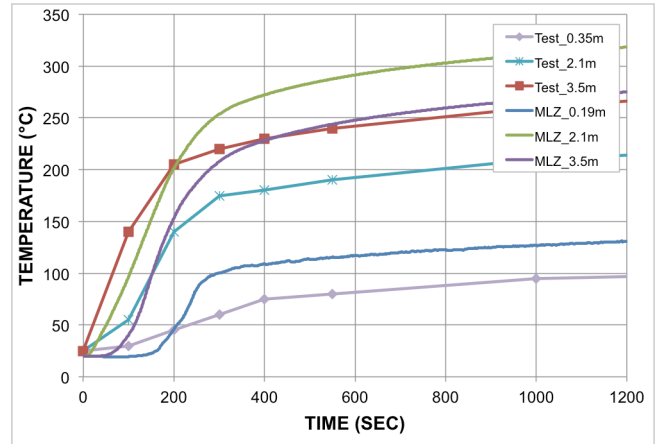


Figure 7: Results of the evaluation at three different vertical locations at TC Tree#7 in Test#3.

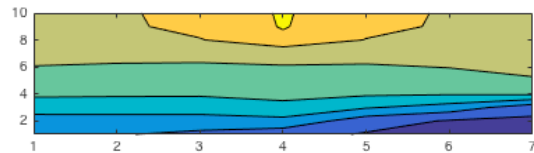


Figure 8: A section ($t=1200s$) through the center of the room with results from MLZ model in the Test#3 configuration. The axes correspond to the number of regions. The door is located on the right side. Blue indicates low and yellow high temperature.

Just as in Test#2, the MLZ model over predicted temperatures with 30-50K. The deviation is rather consistent during the fire.

4 ANALYSIS

A case study is used in order to compare the different methods presented in sections 3.1-3.3.

4.1 DESCRIPTION OF THE CASE

The building used in the case study is fictive and simple, however it is constructed in order to represent a large open space, i.e. an office, warehouse or supermarket. The building is 30 m x 40 m x 5 m and there is one door (4 x 3 m) that is placed in the middle of one of the short ends (see Figure 9). The size of enclosure can be considered to be on the borderline of what is suitable to model with a traditional two-zone model. The boundaries are made of 0.1 m thick lightweight concrete. The fire is placed close to one of the corners in the building. The fire is a heptane pool fire. The heat release rate is modelled as a fast growing fire (growth rate = 0.047 kW/s^2) with a maximum heat release rate of 5000 kW and a radiative fraction of 0.35.

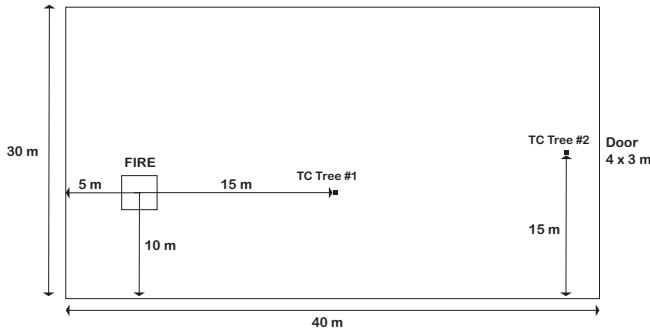


Figure 9: Overview of the enclosure in the case study.

Design criterion that are used in fire safety designs are usually, hot gas layer heights, temperature, visibility and toxicity. In this evaluation only temperature is used in order to compare the different modelling tools. The vertical temperatures are studied in two different points, TC Tree#1 and 2 (see Figure 9).

4.2 SETUP OF THE MODELS

Three different meshes were used in FDS, D^*/dx was 10 in the area surrounding the fire and 4 in the rest of the domain. In total 464 400 cells were used in the simulation.

The case study was modelled with two different technics in CFAST, as a single room and according to the multi-cell concept [8]. The enclosure is divided into four rooms when the multi-cell concept is used (see Figure 10). The fire is in Room 1, TC Tree 1 is placed in Room 3 and TC Tree 2 is placed close to the door in Room 4.

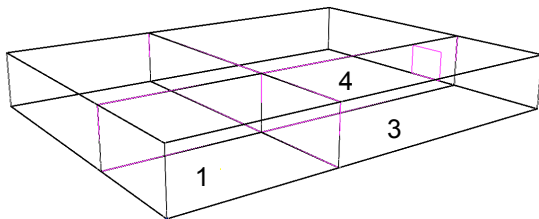


Figure 10: The enclosure as modeled with the multi-cell concept in CFAST.

The enclosure was divided into 70 regions (10x7) in the MLZ model and each region was divided into 10 cells. This means that a total of 700 cells were used in the MLZ model.

4.3 RESULTS

No effort is made here to compare the calculation times in detail. Even so, it is considered worth mentioning that the CFAST simulation was completed in a few seconds, the MLZ simulation in 2 hours and the FDS simulation in 50 hours. All simulations were performed on the same laptop computer a MacBook Air, mid 2012.

The results of the models are presented for TC Tree 1 and 2 in Figures 11-14.

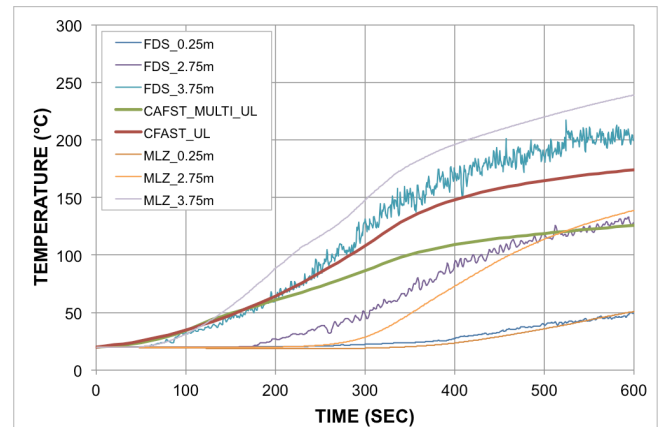


Figure 11: Temperatures, TC Tree 1.

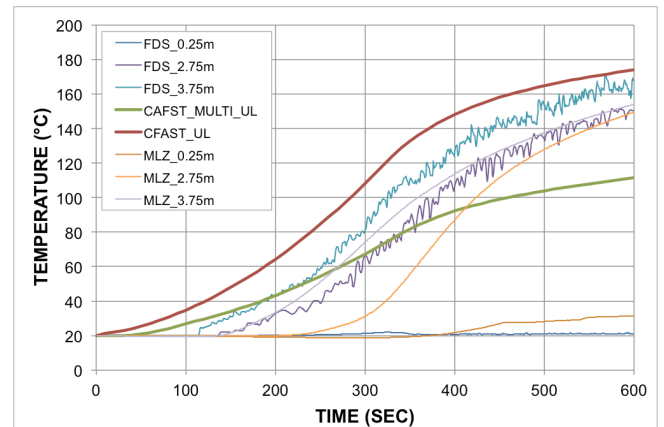


Figure 12: Temperatures, TC Tree 2.

Figures 11-12 show the temperature development at TC Tree 1 and 2. The MLZ models predicts slightly higher temperatures compared to FDS under the ceiling at TC Tree 1, while the MLZ temperatures in general are lower at TC Tree 2 compared to FDS. When the enclosure is modelled as one room in CFAST, the calculated temperature is higher than the average of the calculated temperatures (TC Tree 2) in both FDS and MLZ. However, the multi-cell setup in CFAST gives a gas temperature that is more similar to the average

of the calculated temperatures in the other two models.

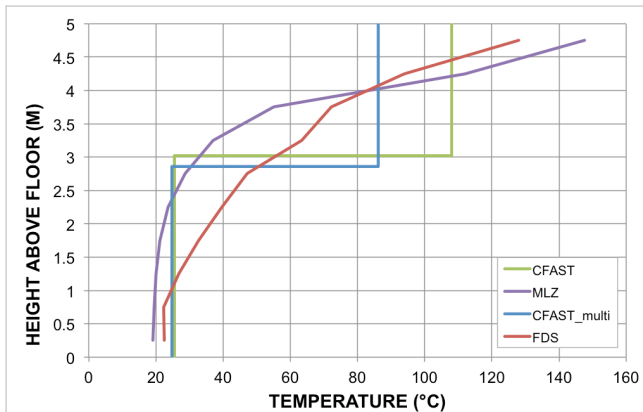


Figure 13: Temperature profile at 300 seconds, TC Tree 1.

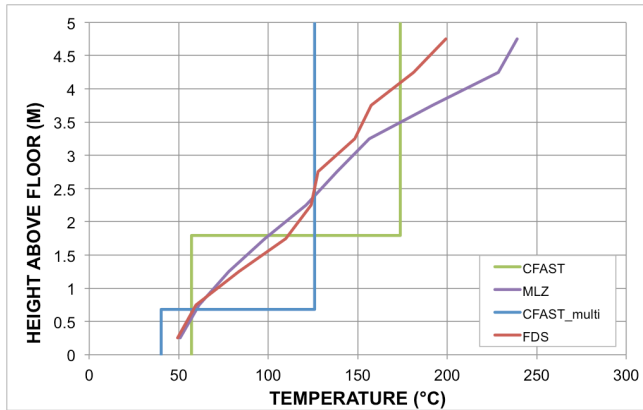


Figure 14: Temperature profile at 600 seconds, TC Tree 1.

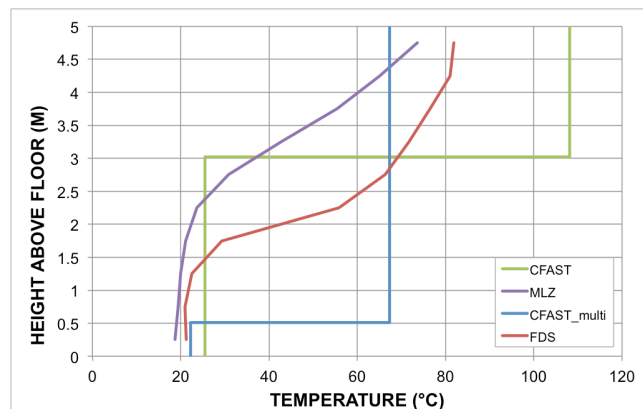


Figure 15: Temperature profile at 300 seconds, TC Tree 2.

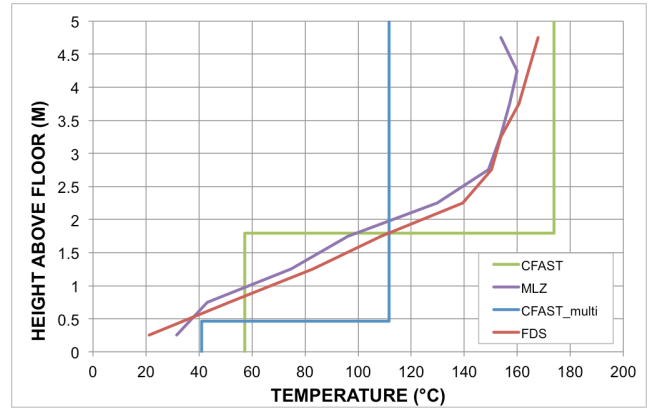


Figure 16: Temperature profile at 600 seconds, TC Tree 2.

Figures 13-16 shows the temperature profile at TC Tree 1 and 2 at 300 and 600 seconds. The results from FDS and the MLZ model clearly indicate that there is a vertical temperature distribution that is not possible to catch with the two-zone model.

5. DISCUSSION

No experimental data are available for the case analysed in this paper; consequently, it is not possible to state which model that is most accurate in this study. However, it is reasonable to believe that FDS gives good predictions since it has shown to predict gas temperatures well in previous validation studies [6]. The major drawback of FDS in this study is the long calculation time.

CFAST has been validated against average smoke layer temperatures [7], which means that it should give a reasonable representation of the case. The problem with using CFAST in this case is the underlying assumption that the hot gas layer has a uniform temperature. Both FDS and the MLZ models indicates that there is a vertical temperature distribution and it is not possible to modelled in CFAST,

The MLZ script that has been used in this study was verified as it was developed and written, however, the verification process has probably not been as thoroughly as that of FDS and CFAST. Furthermore, the evaluation study done in this paper is rather limited and it shows that the model overestimates the temperature with 30-40K. Even so, the case study indicates that MLZ models can be used to get an estimate of both the vertical and horizontal gas temperature in a large enclosure fire.

Results from FDS are sensitive to the cell size. No sensitivity study on the cell size has been performed in this study; however the D^*/dx values are within values that are normally recommended for FDS [13]. Neither has any cell size sensitivity study been performed for the MLZ model. Smaller regions and cells will give a finer resolution of the horizontal and vertical temperature profiles; however, the MLZ model results should not depend on the cell size. Even so, this is something that needs to be confirmed in future studies.

The main benefits of the MLZ model is the low computational time and that it provides temperature profiles both horizontally and vertically in a large enclosure. It would be desirable to investigate if there is potential for this kind of model to be a complement to the models currently available for fire safety design and research. The computer power available for fire safety designers are constantly improving, this means that the time to run a CFD models is constantly decreasing, which lessens the need for a quicker and less accurate tool like the MLZ model. However, the MLZ concept is simple and easy to grasp which means that users are more likely to understand what they are doing and how the model works, which can result in less mistakes and more robust designs.

6. CONCLUSIONS

FDS and the MLZ model predict rather similar temperatures in the studied case. There will most likely be a non-uniform temperature in the hot-gas layer and this is that not possible to model with a two-zone model like CFAST. The multi-cell CFAST model results are more in line with the results from FDS and the MLZ model. The MLZ model is a zone model, however, the level of detail obtained and the low computational time makes the model interesting to develop and evaluate further.

The novel work of this paper includes the further development of the MLZ model and the actual comparison of the three models. It is, to the knowledge of the author, the first time these models are compared in this type of case study.

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