A Comparison Between FDS and the Multi-Zone Fire Model

Regarding Gas Temperature and Visibility in Enclosure Fires

|Benjamin Waldeck | Division of Fire Safety Engineering |
| LTH | LUNDS UNIVERSITET |

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Benjamin Waldeck

Lund 2020

Titel
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Author
Benjamin Waldeck

Report 5607
ISRN: LUTVDG/TVBB--5607--SE

Antal sidor/Number of pages: 82
Illustrationer/Illustrations: 34

Sökord/Keywords
Enclosure fire, FDS, Multi-Zone Fire Model, Gas temperature, Visibility.

Abstract
When designing large buildings with complex geometry there is often a need for performance-based design and the use of computer models. CFD models like FDS that are available and validated for this purpose are typically time consuming and require large amounts of computing power. Zone models which are often faster and require less computing power are limited to simple geometries and smaller sized enclosures. The Multi-Zone Fire Model has been developed as an attempt to run less time-consuming simulations of large enclosures, but still with reasonable accuracy of the temperature and soot distribution in the enclosure. There have been previous efforts to produce models like this with multiple zones although limited to two dimensions while the Multi-Zone Fire Model, which is based on the same principals, is a three-dimensional model. The aim of this thesis has been to compare that newly developed model to FDS regarding gas temperature and visibility. The comparison is carried out by simulating a total of six scenarios, output data from measuring devices is then compared for each scenario. Results show that the Multi-Zone Fire Model can predict values which come close to simulated values from FDS for several of the simulated scenarios regarding both temperature and visibility. Like most models the MZ-model also has limitations that need to be considered before use and the process of comparing both models has highlighted some of the limitations and difficulties when setting up a simulation in the Multi-Zone Fire Model.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

www.brand.lth.se
Telefon: 046 - 222 73 60

Division of Fire Safety Engineering
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

www.brand.lth.se
Telephone: +46 46 222 73 60

Summary

The use of computer models for performance-based fire safety design in buildings is not a new occurrence but the models often used in projects of today are the same as fifteen or twenty years ago. Some of these models have been updated once or several times during the past two decades, but the choice when opting for computer assisted performance-based design still lies between zone models or CFD models. If a building or enclosure has a relatively simple geometry and is not too big most zone models would be sufficient for the task and produce results very quickly. If a building consists of a large enclosure or has a complex geometry the only choice is and has been for a long time to use a CFD-model which can be both time consuming and expensive due to the necessary computing power. In addition to being time consuming CFD-models can be complicated to set up and there are a lot of variables that need to be checked before running a simulation to avoid mistakes that could affect the outcome.

In an attempt to bridge the gap between existing model types the Multi-Zone Fire Model (MZ) has been developed with the purpose of running less time-consuming simulations on large enclosures and complex geometries. The hope is that this new model can facilitate the use of CFD-modeling by being able to first run faster less accurate simulations to gather information to help set up a better CFD-simulation. Being based on similar principals as traditional zone models the MZ-model instead divides an enclosure into many large zones and will therefore not produce as accurate results as a CFD-model would in the same circumstances. However, having the ability to run fast simulations for several scenarios before running more detailed and time-consuming models will hopefully result in a more efficient process.

With the purpose of evaluating the performance of the MZ-model a comparison has been conducted using the Fire Dynamics Simulator (FDS) as a benchmark. Several enclosure fires were simulated in both models to see how well the MZ-model could predict variations in gas temperature and species concentration compared to FDS. The comparison included a total of six scenarios spread over three enclosures of different size that all had geometries not suitable for zone models. Each enclosure was simulated with a different size of fire using two different fire growth rates.

The results of the comparison show that the MZ-model is able to predict variations in gas temperature and visibility that come close to predictions by Fire Dynamics Simulator for several of the simulated scenarios. Results also show that the MZ-model has problems predicting visibility and temperatures similar to FDS for one of the enclosures where there is a large fire and moderate ceiling height. The reason for the models predicting different values is not known at this time. In whole the MZ-model shows promising results in its ability to handle non-uniform conditions regarding temperature and visibility for several scenarios even though there were significant differences for two of the scenarios. Further research is needed to conclude why results are different for some of the enclosures and to further evaluate the MZ-models' abilities.

Acknowledgments

This Bachelor's thesis corresponds to 22,5 ECTS and is the final requisite for a bachelor's degree in Fire Safety Engineering. This thesis was produced under the Division of Fire Safety Engineering at Lund University in the fall of 2019.

The author would like to thank the following for their contribution:

Nils Johansson, Associate Senior Lecturer at the Department of Fire Safety Engineering, Lund University. Thank you for guidance and educating discussions in the role as head supervisor.

Jonathan Wahlquist, Postdoc at the Department of Fire Safety Engineering, Lund University. Thank you for valuable insight and help regarding setup of FDS.

Lund 2020

Acronyms

ASET	Available Safe Egress Time
CFD	Computational Fluid Dynamics
D*	Characteristic diameter of the dire
dx	Length of the cells smallest side
EPRI	Electric Power Research Institute
FDS	Fire Dynamics Simulator
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
MLZ	Multi-Layer Zone model
MZ	Multi-Zone model
NIST	National Institute for Standards and Technology
NFPA	National Fire Protection Association
RSET	Required Safe Egress Time
SFPE	Society of Fire Protection Engineers

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1. Introduction

1.1 Background

When trying to create a model of an enclosure fire one method is to use simulation software to look at how smoke could spread in the event of a fire. There are different types of software available but two commonly used models for this purpose are CFD models and zone models (Karlsson & Quintiere, 2000; Bong, 2011). Although widely used for simulating enclosure fires both types of models have drawbacks which mean they are not applicable in every situation and the user must take this into account when choosing which model to use. Zone-models are often appropriate for smaller enclosures however, guidelines for zone models (ISO, 2013) state that the ratio between width and length should not be more than five or the height more than five times the distance of the shortest wall as shown in Table 1. Caution is required when using zone models for enclosures that do not lie within these dimensions since the result might not be accurate enough.

Table 1. Appropriate ratios for Zone-models regarding length (L), width (W) and height (H)

Accepted dimensions	Caution required
$L/W<5$	$L/W > 5$
$H/\min(L,W)<5$	$H/\min(L,W)>5$

Zone models assume that conditions in the smoke layer are uniform by approximating a value to represent the whole smoke layer. In most cases conditions in the smoke layer are going to be non-uniform even if there are only small variations. In large enclosures this approximation is therefore less appropriate due to more cooling of hot gases and loss of buoyancy far away from the fire (Johansson, 2018).

CFD models however can handle a non-uniform smoke layer and provide much more detailed resolution of the smoke layer properties than zone-models but it comes with a cost of increased simulation time. Using a modern CPU equipped with multiple cores it can take days or even weeks to run a simulation of a large enclosure. As increased computer power becomes available less time will be needed to run simulations but the ambition to run more detailed simulations as the software develops also means increased simulation times. The user guide for the sixth version of Fire Dynamics Simulator (FDS), which is one of the most commonly used CFD models for fire simulation, even states that the accuracy of simulations has been increased from previous versions at the cost of increased computing time and memory usage (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019). Due to the large amount of time it can take to run a simulation it is crucial that the user really understands the model to reduce the risk of faulty input or misleading simulations which can render the results useless.

With the purpose of combining good qualities from both two-zone fire models and CFD-models the Multi-zone Fire Model (MZ) (Multi-Zone Fire Model, 2019) has been developed to run simulations in large enclosures where zone models are not appropriate. Furthermore, the model provides much lower simulation times than FDS, and results can be available in minutes instead of days. Consequently, the Multi-zone Fire Model can be used as a complement to a more complex CFD model. The Multi-zone Fire Model is not intended to produce as detailed results as a CFD-model, but it could give valuable information in how different factors affect the smoke spread and the possibility to test outcomes of different scenarios before running a more detailed and time-consuming CFD-simulation.

1.2 Purpose and objectives

The purpose of this thesis has been to compare differences in results from the Multi-zone Fire Model and Fire Dynamics Simulator for identical enclosures with near identical fire scenarios.

The objective was to evaluate how well the Multi-zone Fire Model can simulate variations of temperature and visibility in an enclosure fire scenario compared to the Fire Dynamics Simulator.

1.3 Method

Using version 6.7.1 of the FDS and the Multi-zone Fire Model, which is still being developed, three enclosures of different sizes where created to be as similar as possible in both programs. It has been shown in previous research (McGrattan, Peacock, & Overholt, 2014) that FDS has good capabilities for predicting smoke movement and temperatures in enclosure fires. to Fire scenarios were selected from recommendations for performance based designed from the Swedish housing authority (Boverket, 2013). Guidelines for zone models (ISO, 2013) were used to select enclosures scenarios with geometries where such models are not deemed to be suitable. Devices to measure visibility and temperature were placed in both models to compare results. Data from the devices were studied with MATLAB in order to compare temperature and visibility contours resembling slice files from FDS that are usually visualized with Smokeview. This was done since there is no way to visualize data from the MZ-model and contour plots provides a way of visualizing data from the two models that are comparable.

1.4 Limitations and delimitations

In general, the comparison is limited to the scenarios studied. Consequently, the results are only transferable to scenarios that are similar to the studied ones. Furthermore, this comparison will only study scenarios where ignition has already occurred, and the fires will not be allowed to reach flashover. Only well-ventilated fires that are not controlled by the amount of oxygen will be used in the simulations and focus will lay on variations in gas temperature and visibility. The MZ- model does not account for the effects of turbulence and since FDS does simulate turbulence it might be mentioned when comparing results, however the effects of turbulence will not be discussed in detail.

The computational resources used for running the FDS simulations is based on a que-system where your place in the que is based on the estimated runtime with higher runtimes having lower priority. The maximum run time of a simulation therefore had to be estimated and efforts were made to reduce runtime. Exceeding the allocated resources means being placed in a separate que with lower priority and for this reason the number of simulations was kept to the minimum needed for the comparison.

2. Review of existing model types

With the emergence of performance-based fire safety regulations around the world in the late 1990's computer modeling was increasingly used to determine movement of smoke and heat through buildings (Karlsson & Quintiere, 2000). Two decades later computer modeling is still being used to model movement of smoke and heat for performance-based building design meanwhile new models have been developed and existing models have been updated. Since the one of the primary areas of use for these models is to determine the Available Safe Egress Time (ASET) for an enclosure or building the growth phase of a fire is usually simulated. Before running a simulation in any model, the growth rate and maximum heat release rate for a fire must be decided. Depending on the amount of fuel available a growth rate and maximum heat release rate can be calculated, or they can be determined by different guidelines for performance-based design.

There are currently three different methods widely used for calculating conditions in enclosure fires of which two are computer models. The three methods and the principles behind them will be discussed in this section as well as common areas of use for the two kinds of computer models.

2.1 Hand-calculations

The simplest way of calculating temperatures and smoke filing in an enclosure fire is using hand-calculations. This can be done by using simplified equations that rely on commonly applied assumptions (Karlsson & Quintiere, 2000) supported by empirical equations like different equations for a calculating plume mass flow. Using simplified equations based on assumptions however means that hand-calculations are often limited to the circumstances that allow the assumptions to be made which also limits the use of this method. Several of the equations for plume mass flow like the Heskestad or Zukoski models rely on assumptions and controlled experiments (Deal & Beyler, 1990) which may not resemble the situations in which the equations are later used. Methods for calculating smoke filling also rely on assumptions and experimental data, for instance the model by MacCaffrey, Quintierre and Harkleroad (MQH) is based on a correlation from experiments done with a single opening naturally ventilated fire in enclosures with a maximum size of 12m^2 and maximum ceiling height of 2.7 meters (Deal & Beyler, 1990). Assumptions like this imply the user must be aware of the limitations of a method in order to use that method in a correct manor and acquire desired results.

In addition to being a simpler way several advantages with using hand-calculations compared to computer modeling methods are described by Johansson (2016). Johansson describes how hand-calculations are time efficient compared to more advanced methods and how rough and conservative calculations can help determine if more advanced methods are needed to provide detailed calculations. Johansson also describes how being able to use advanced computer models without understanding the fundamentals behind them can lead to the user not knowing limitations in how the model operates and using hand-calculations instead can increases the users understanding of fire dynamics. Although hand-calculations can increase understanding of a fire dynamics problem the user must be aware of underlying assumptions in order to use equations correctly. Given the right circumstances hand-calculations can be a good approach to perform time efficient calculations or if there are uncertainties in inputs to a more complex model that can be analyzed with a hand-calculation model.

2.2 Zone models

Zone models are often a fast and efficient way of simulating smoke layer height in enclosure fires. Although this type of model can be useful in small to medium size rooms, they cannot show variations of temperature in the smoke layer and they also lack the ability to show variations in visibility in the smoke layer. Most Zone-models divide each room into two control volumes with an upper zone and a lower zone. The upper zone represents the smoke layer and the lower zone represents cold air (Silvia, Marco, & Renato, 2014). In small enclosures such models can give good results because of the smoke layer being well mixed which means concentrations of soot particles and temperature do not differ much within the smoke layer. In order to assume a uniform smoke layer Zone-models must approximation a single temperature for the entire volume that represents the smoke layer. Since there is likely some variations of gas temperatures, both vertically and horizontally, in an enclosure fire the simplified way in which Zone-models render the enclosure fire will, to some extent, in most cases be incorrect. Approximations like this can however be acceptable if the result is reasonably close the actual conditions although caution is required when circumstances indicate the approximation can result in unreasonable values. Circumstances where caution is required have been presented earlier in Table 1.

The main reason zone models are less appropriate for simulations of large enclosures is the fact that they assume a uniform temperature in the smoke layer. Due to cooling of gases which leads to a lack of buoyancy for gases far away from the fire contributing to more variations in the non-uniform smoke layer for both temperature and soot particles at different heights (Johansson, 2018). Experiments have also shown that with increased enclosure size and ceiling height the validity of assumptions made by zone models decrease (Johansson, 2016).

For most zone models the equations for conservation of mass and energy are applied to each zone, the fire then acts as an energy source in the lower zone and the plume transports mass to the upper zone as seen in Figure 1 . The theory behind zone models has been described in more detail in Enclosure Fire Dynamics (Karlsson & Quintiere, 2000).

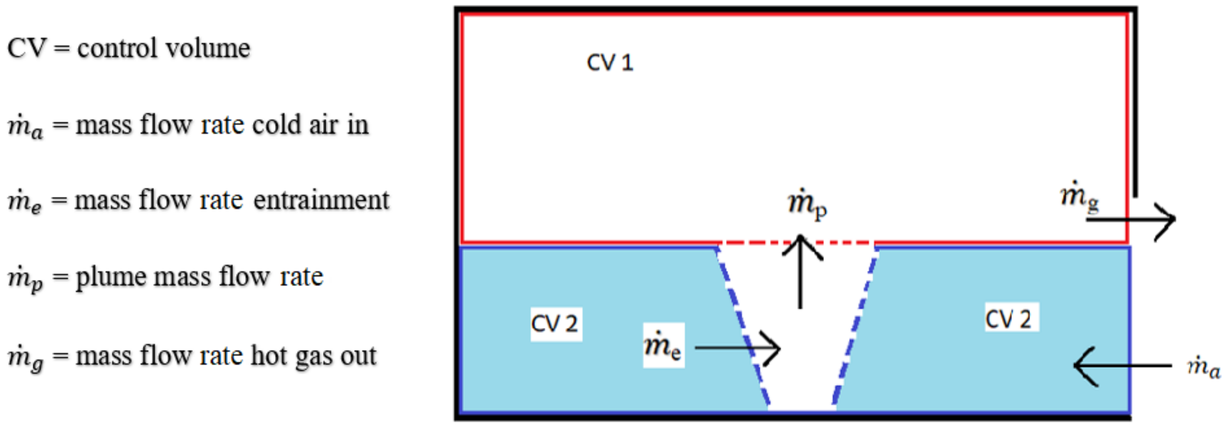


Figure 1. Control volumes of a zone model

2.3 Fire Dynamics Simulator

Fire Dynamics simulator is a CFD type software developed by NIST and has been used worldwide to simulate enclosure fires since its first release in the year 2000. FDS as it is commonly called solves a numerical version of the Navier-Stokes equations that have been developed for thermally driven flow at low speeds (McGrattan, Hostikka, McDermott, Floyd, & Vanella, Fire Dynamics Simulator User's Guide, Sixth Edition, 2019). Like Zone-models FDS also divides a volume into cells but instead of two cells the volume is divided into many cells with cell size depending on the total volume and characteristics of the fire. A simplified description of a CFD-model is shown in Figure 2 where the red cells resemble the fire and middle of the plume and the orange cells resemble hot gases.

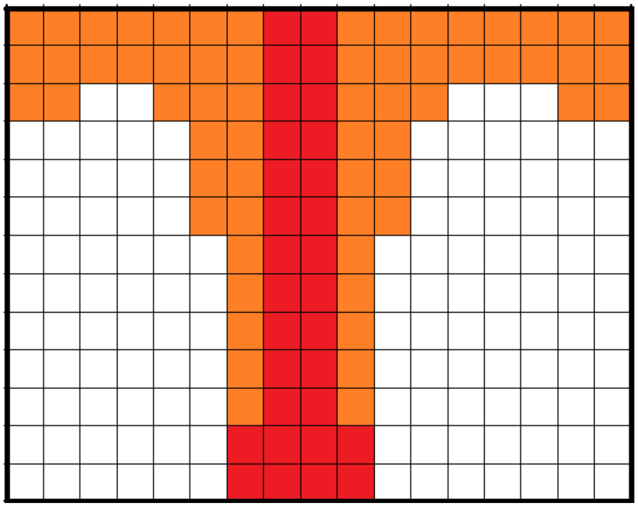


Figure 2. Structure of a CFD model

Several studies have been conducted regarding connection between cell size and characteristic fire diameter. A study conducted for nuclear facilities in the USA (Kassawara & Salley, 2007) stated that past experience has shown favorable results with a ratio for D*/dx between 5-10 at a moderate computational cost. Simulations run in the study showed a ratio for D*/dx between 4-16 could be used to accurately resolve the fire. On the other hand a manual for ensuring good quality of fire safety for nuclear facilities in Sweden (Frantzich & Nystedt, 2011) determined that the ratio D*/dx should be between10-20 close to the fire.

According to the study conducted by NUREG & EPRI (2007) "FDS uses second-order accurate approximations of both the temporal and spatial derivatives of the Navier-Stokes equations, meaning that the discretization error is proportional to the square of the time step or cell size". This means having a higher ratio for D*/dx means less approximations have to be made giving more accurate fire dynamics. The study by NUREG &EPRI (2007) states that reducing the cell size by a factor 2 will theoretically increase the computing time by 16 times while the discretizational error is decreased by 4 times. The side of a square cell in meters is given by dx and *Equation 1* is used for calculating D* (McGrattan, Hostikka, McDermott, Floyd, & Vanella, Fire Dynamics Simulator User's Guide, Sixth Edition, 2019).

$$\boldsymbol{D}^* = \left(\frac{\dot{\boldsymbol{Q}}}{\varphi_\infty c_p \boldsymbol{T}_\infty \sqrt{g}}\right)^{2/5} \qquad \text{Equation 1}$$

Cells can be divided into multiple different meshes which enables a CPU with multiple cores to calculate several meshes at the same time. Mesh-boundaries should not be placed in areas with high velocities of gas flow (Back, et al., 2013), for this reason fires should be placed inside one mesh and not on one ore more of the mesh-boundaries.

3. Description of the Multi-Zone Fire Model

3.1 Multi-Zone Fire Model

There have been previous efforts to produce a model with multiple zones and improve the abilities of a zone model while still using significantly less computing power than a CFD type model. The Multi-layer zone model (MLZ) was developed to predict vertical variations in temperature and concentrations of chemical species in an enclosure fire by dividing an enclosure into many vertical layers instead of just two layers like a conventional Zone model (Suzuki, Harada, & Tanaka, 2003). Like a zone-model the MLZ model uses equations for conservation of mass and energy but applies this method for the boundaries between each vertical layer while still allowing the plume to rise through the layers until it hits the ceiling. The MLZ model assumes temperature and species concentration to be uniform in each separate layer which effectively means the model produces a two-dimensional model of an enclosure. The MLZ model was later modified by Suzuki et al. (2004) so that the volume could be divided horizontally into several cells to calculate horizontal variations in gas temperatures and species concentration in two directions seen in Figure 3. Even though the modified model is divided into several regions it is still a 2-dimensional model and can have some use in long narrow enclosures like tunnels or corridors. However, in wide enclosures with high depth to height ratios non-uniform horizontal temperatures are likely (Torero, Majdalani, Abecassis-Empis, & Cowlard, 2014) and the assumption that a horizontal layer has a uniform temperature would not be accurate.

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 layer above the fire. Radiation from the fire to and in-between zones are modeled as well as heat transfer to and through the boundaries. The entrainment into the fire plume is modelled with the empirical Zukoski plume model. The way in which the MLZ-model calculates mass flow is described in Figure 3 where the plume will rise through the layers until it hits the ceiling while air and hot gases are entrained in the plume from the different layers that it passes through. 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 layer.

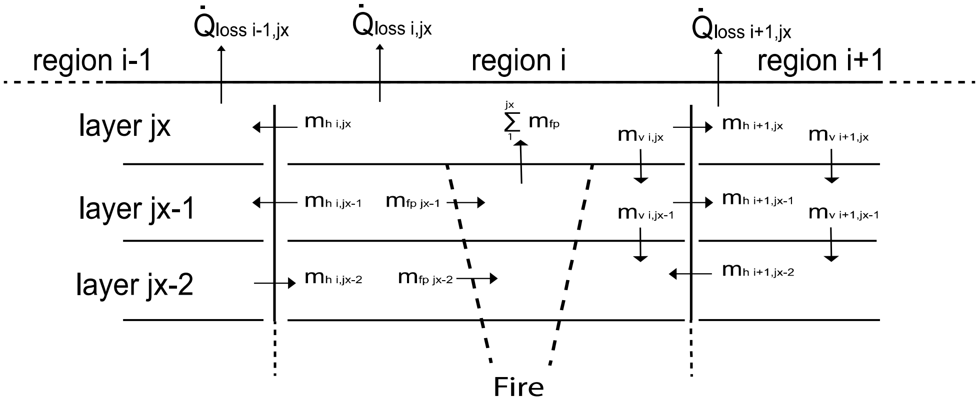


Figure 3. Zone structure of the MLZ and MZ models

The Multi-Zone Fire Model (MZ) is based on the same principals as the MLZ model, but there are some differences with the major difference being that the MZ model divides an enclosure into multiple cells in three dimensions. Where the MLZ model uses the Zukoski plume model the MZ model instead uses the Heskestad plume model to calculate plume mass flow (Johansson, Associate senior lecturer, 2019).

Although the two models share the same basic principles and parts of the MZ model are based on publications on the MLZ model it is unknown if there are more similarities between the two models since the code for the MLZ model has not been published. The MZ model can be seen as an improved version of the MLZ model however, since the two models have been developed 15 years apart and the developer of the MZ model has not had any more knowledge of the MLZ model than has been published (Suzuki, Harada, & Tanaka, 2003) (Suzuki, Harada, Tanaka, & Yoshida, 2004) they are to be seen as two separate models (Johansson, Associate senior lecturer, 2019).

The goal with this type of model is to combine the ability to split the room into multiple zones in a similar way as a CFD model but still be able to run simulations of large enclosures without needing large amounts of computing power. The user can decide on which size to use for the zones although it is most efficient to use as large a zone as possible while reasonable values can be expected. A recommended starting point for zone-size is 4 x 4 x 0.5 meters (L x W x H) as it is also recommended that the fire and plume should fit inside the area of the zone where the fire is placed (Johansson, Associate senior lecturer, 2019). The plume will expand with entrainment as it rises (Karlsson & Quintiere, 2000) which means the zone needs to have a larger area than the surface of the fire.

4. Simulations

To make sure an enclosure fire does not become depleted of oxygen the enclosure has to have openings of a suitable size to allow the required air flow. Using Equation 2 found in Enclosure Fire Dynamics (Karlsson & Quintiere, 2000) the required minimum size of opening was calculated for each enclosure and maximum HRR.

$$\dot{Q}_{max} = 1.518 * A_o * \sqrt{H_o} \qquad \text{Equation 2}$$

The enclosures for both models are all made out of 0.2-meter-thick concrete which is described in Table 2 except the wide enclosure which has an emissivity fraction of 0.9 which is default in FDS (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019). Openings in the shape of doors are placed in all the enclosures and assumed to be open. No other openings are placed meaning there are no smoke hatches in the ceiling to vent hot gases. Calculations for values presented in this section regarding grid cell size and simulation time can be found in Appendix A. Fires for the two bigger enclosures are based on guidelines for performance based design (Boverket, 2013) from the Swedish housing authority and are shown Table 2 along with the fire for the corridors which has a HRR based on limitations of zone models. Molecular structures have been selected from guidelines (Back, et al., 2013) published by the Swedish branch of SFPE. To ensure that the HRR of the simulated fire followed the desired fire curve simulations of the fires were run in advance.

Table 2. Input values for concrete

Density	Specific heat capacity	conductivity	Emissivity
2100 [kg/m^3]	0.88 [kJ/(kg*K)]	1.1 [W/(m*K)]	0.85

Table 3. Input data for enclosure fires

Enclosure	Growth rates	Maximum HRR	Heat of combustion	Soot yield	Molecular structure (Input only to FDS)
Large	Fast α=0.047 Medium α=0.012	10 MW	20 MJ/kg	0.1 g/g	C=4.56, H=6.56, O=2.34, N=0.4
Wide	Fast α=0.047 Medium α=0.012	14.4 MW	20 MJ/kg	0.1 g/g	C=4.56, H=6.56, O=2.34, N=0.4
Corridor	Fast α=0.047 Medium α=0.012	200 kW	16 MJ/kg	0.1 g/g	C=3.4, H=6.2, O=2.5, N=0

The MZ model can only measure species concentrations in percentage obscuration in its current form and therefore Optical density was calculated from the measured obscuration with Equation 3 (Nilsson & Holmstedt, 2007).

$$D_L = -10 * \frac{1}{L} * log_{10} \frac{I}{I_0} \qquad \text{Equation 3}$$

With the optical density visibility could be calculated with Equation 4 (Drysdale, 2011).

$$S = \frac{10 log_{10} 10}{D_L} \qquad \text{Equation 4}$$

4.1 Large enclosure

In large enclosures with high ceilings cold air entrains the fire plume and ceiling jets causing gases to lose buoyancy which creates a non-uniform smoke layer. To simulate this type of fire an enclosure measuring 60 x 40 x 10 meters, which is representative of box stores, warehouses or atriums, has been selected. Even larger enclosures with higher ceilings could also be modeled for this purpose however, to reduce time needed for simulation it was decided to use the selected size of enclosure. Devices for capturing temperature and visibility were placed from the floor up to ceiling height near one of the doors and between the fire and one of the shorter walls. Run time for simulations of this enclosure was 500 seconds, all meshes in FDS had cubic cells with a side of 0.2 meters and the ratio D*/dx for these scenarios was 12.04 for a maximum HRR of 10 MW. Two different growth rates were studied.

Zones in the MZ-model are 4 meters wide, 4 meters long and 0.5 meters high. There are four openings in total with two on each long side placed opposite each other. Measuring points are marked with red stars and openings are marked with green arrows in the figures describing the geometry of the enclosures.

Table 4. Placement of measuring points in large enclosure

Placement	x-coordinate	y-coordinate
Door	18	2
Middle	14	19

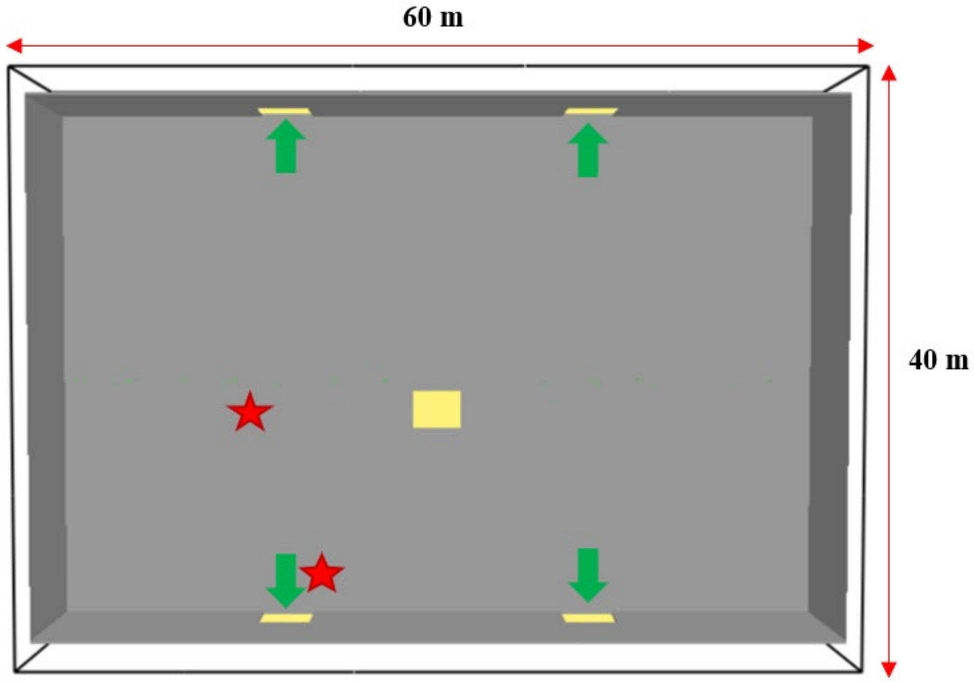


Figure 4. Geometry of the large enclosure and position of fire, openings and measurements (red star)

4.2 Wide enclosure

As presented in section 2.2 zone models are not recommended for wide enclosures where the shortest wall is more than five times the ceiling height shown in Table 1. For this scenario an enclosure of 38 x 38 x 5 meters has been selected and openings have been placed to resemble a typical retail store with entrance and exit in one part of the building and a bigger loading entrance on the opposite side of the enclosure. In this enclosure the fire has not been placed in the middle of the enclosure and therefor one of the measuring points has been placed near the middle.

Simulation time for the both scenarios of this enclosure was 400 seconds, all meshes in FDS had cubic cells with a side of 0.2 meters and the ratio D*/dx for these scenarios was 13.94 for a maximum HRR of 14.4 MW. Zones in the MZ-model were 3.8 meters wide, 3.8 meters long and 0.5 meters high. The enclosure has three openings with two placed at a corner and a third bigger opening in the opposite corner. The two smaller openings are 3 meters wide by 2 meters high and the bigger opening is 3 meters wide by 3 meters high.

Table 5. Placement of measuring points in wide enclosure

Placement	x-coordinate	y-coordinate
Wall	5	16
Middle	21	16

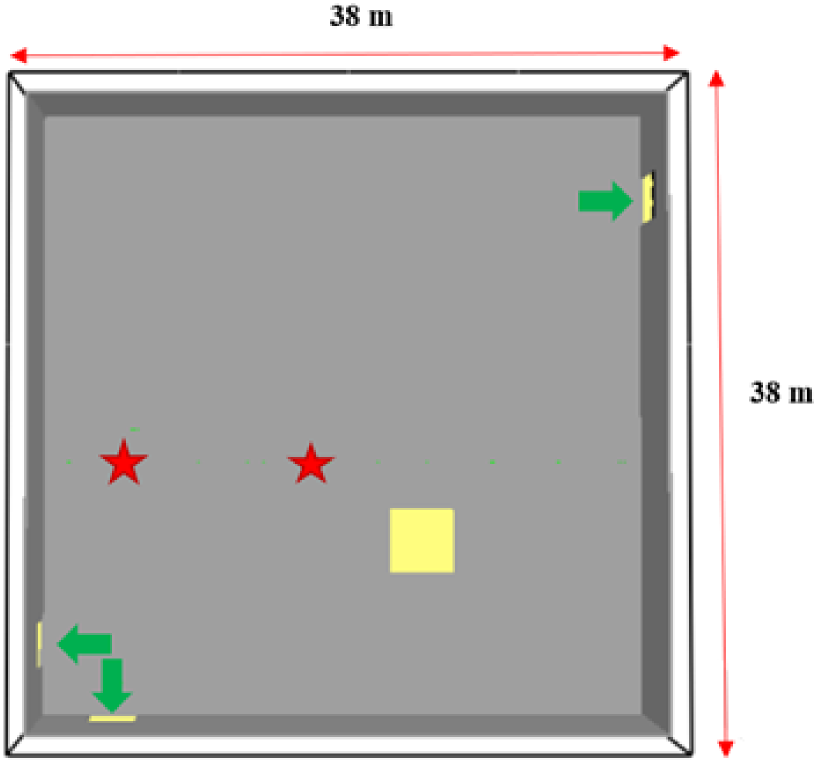


Figure 5. Geometry in wide enclosure and position of fire, openings and measurements (red star)

4.3 Corridor

As shown in Table 1 , Zone models are not recommended for long or wide enclosures with moderate ceiling heights. Perhaps the most common occurrence of this type of enclosure is in the case of corridors especially in large or complex buildings. Corridors can connect many different enclosures and are in many cases used as emergency egress routes. A large fire in this case would result in the enclosure being completely filled with smoke after only a short amount of time. For this enclosure it was therefore decided to simulate a small fire of 200 kW as zone models also sometimes struggle to accurately simulate small fires where temperature rises slowly in the top layer and temperature in the smoke layer is not uniform (ISO, 2013). The geometry of the corridor makes for relatively quick egress and it does not hold a large number of occupants. Considering possibilities for quick egress and the that the corridor would likely be filled with smoke in a few minutes due to its volume simulation time was set to 210 seconds.

All meshes in FDS had cubic cells with a side of 0.05 meters and the ratio D*/dx for these scenarios was 10.08. Zones in the MZ-model were 1.33 meters wide, 3 meters long and 0.5 meters high. In order to fit multiple zones in to the narrow width of the corridor it was zones had to be significantly narrower than recommended. Openings were placed one at each end of the corridor and the dimensions were 2 meters high and 1 meter wide.

Table 6. Placement of measuring points for the corridor

Placement	x-coordinate	y-coordinate
Door	2	1
Middle	11	1

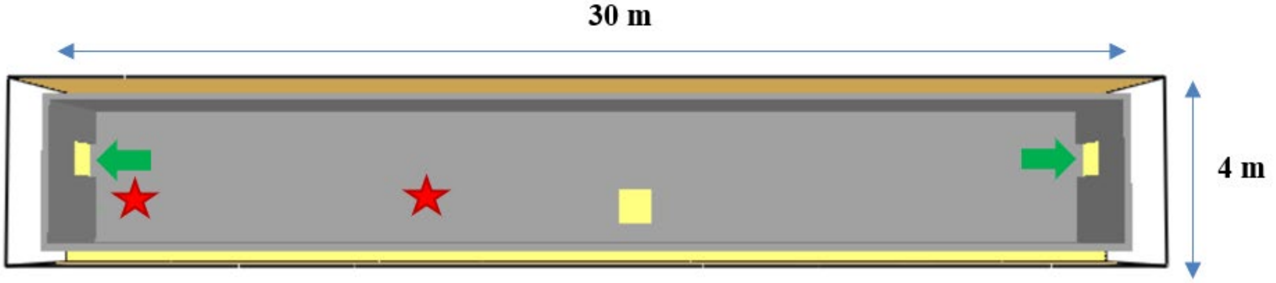


Figure 6. Geometry of the corridor and position of fire, openings and measurements (red star)

5. Results

In this section results of the simulations from the two models will be compared. Variations for temperature and species concentration are shown for different heights at two measuring points for each enclosure. Results for one measuring point from both models will be presented and compared it the same figure. Three figures per scenario are shown in this section as well as a figure containing two slice files that have been rendered with a contour plot in MATLAB, more figures for each scenario can be found in Appendix B.

5.1 Large enclosure – fast growth rate

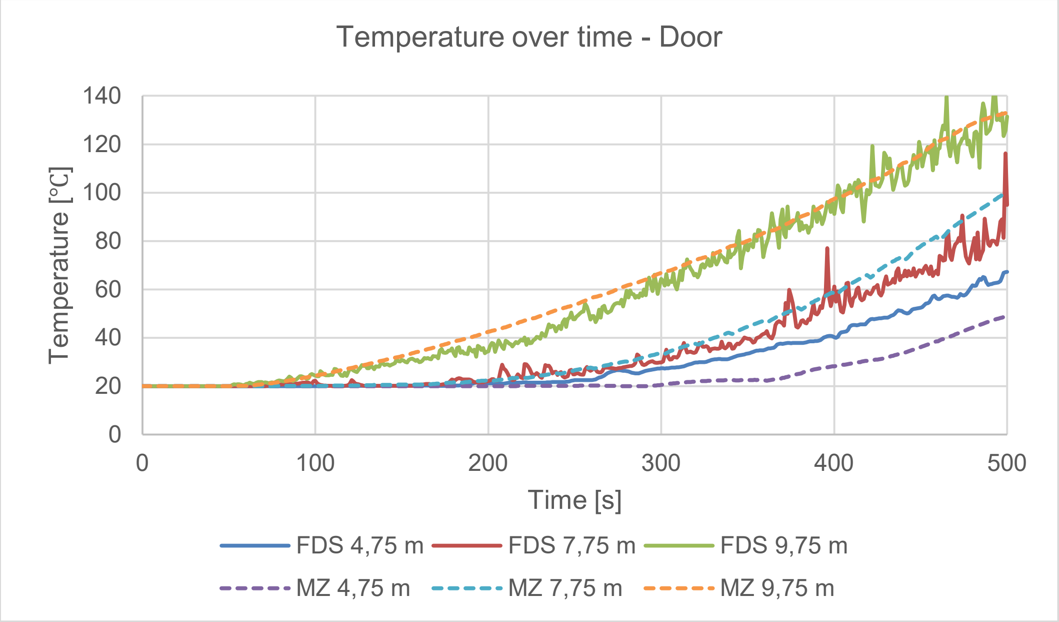


Figure 7. Temperature over time for large enclosure with fast growth rate

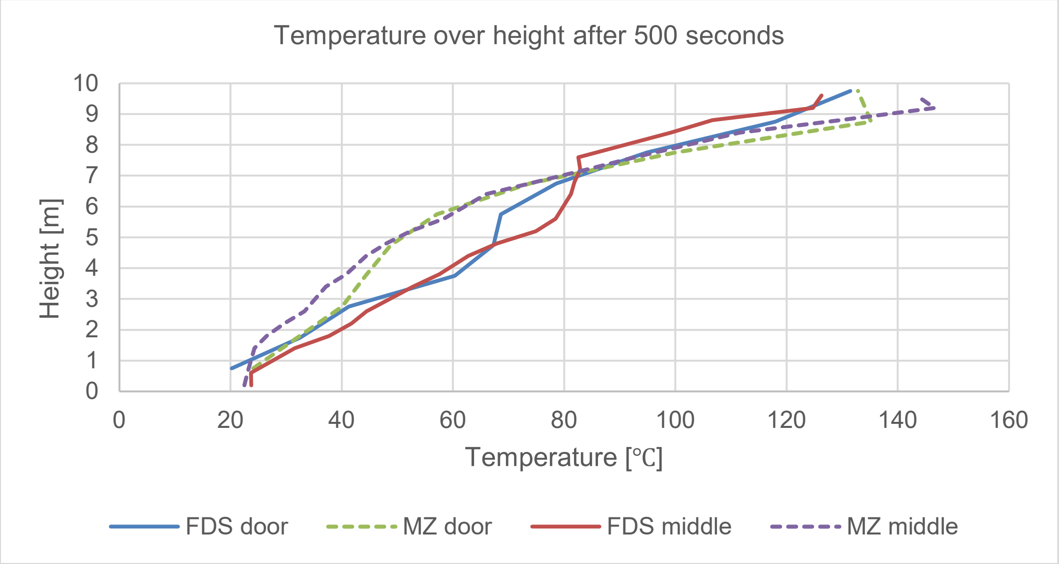


Figure 8. Temperature over height for large enclosure with fast growth rate

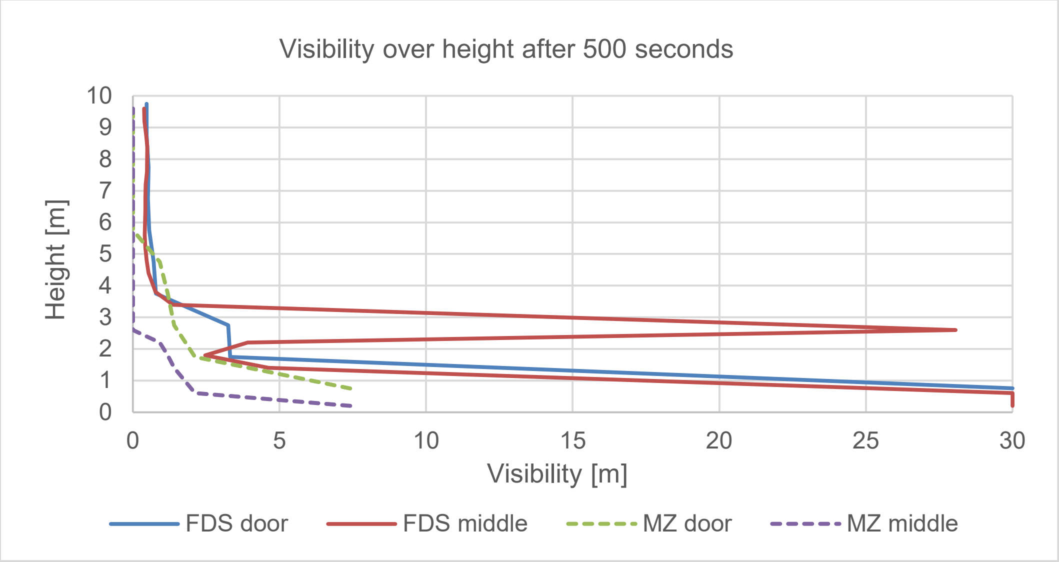


Figure 9. Visibility over height for large enclosure with fast growth rate

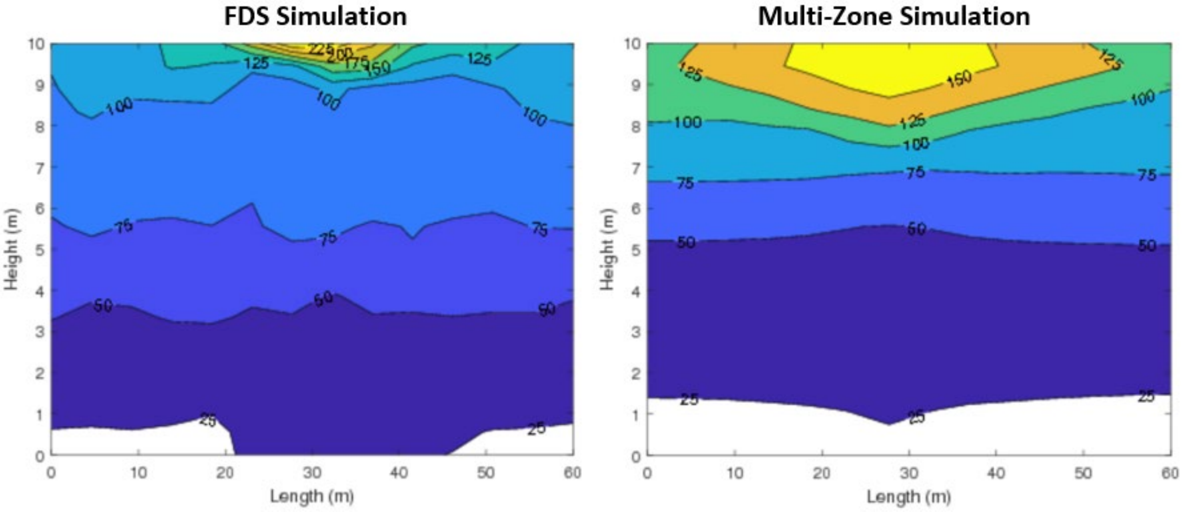


Figure 10. MATLAB temperature slice at 500 seconds for large enclosure with fast growth rate

Results show that the MZ model predicts slightly higher temperatures than FDS near the top of the enclosure and slightly lower temperatures near the bottom in Figure 7. Predictions for visibility seen in Figure 8 for this scenario are similar between the models at the door but the MZ-model predicts less visibility in the middle than FDS which is clear even though there is a spike in the data from FDS. Temperature slices from MATLAB in Figure 10 show layers have similar temperatures although they are thicker for the MZ-model and not as many layers. The slices also show that the MZ-model predicts higher temperatures over a bigger area at the top compared to FDS.

5.2 Large enclosure – Medium growth rate

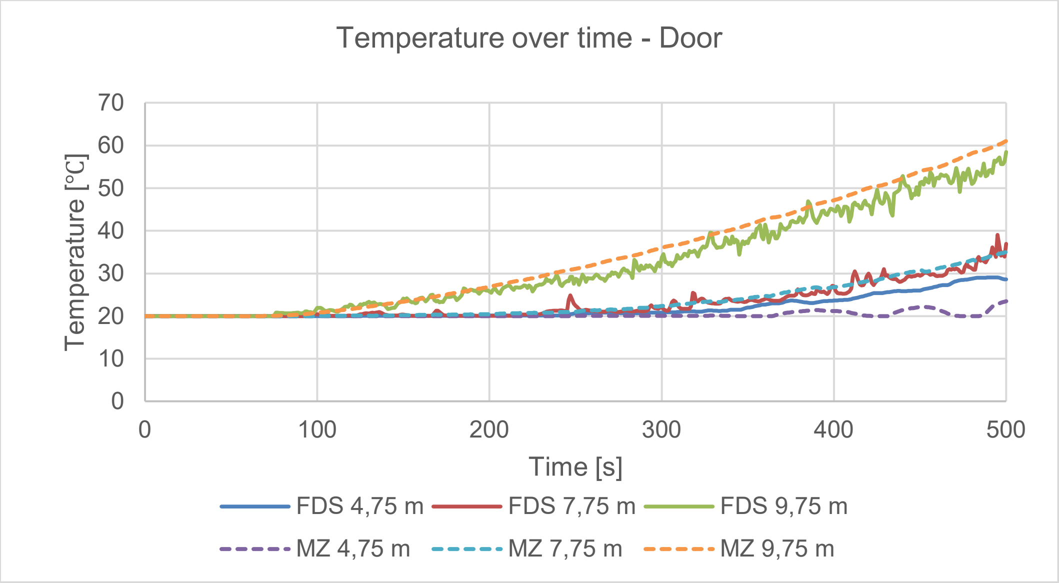


Figure 11. Temperature over time for large enclosure with medium growth rate

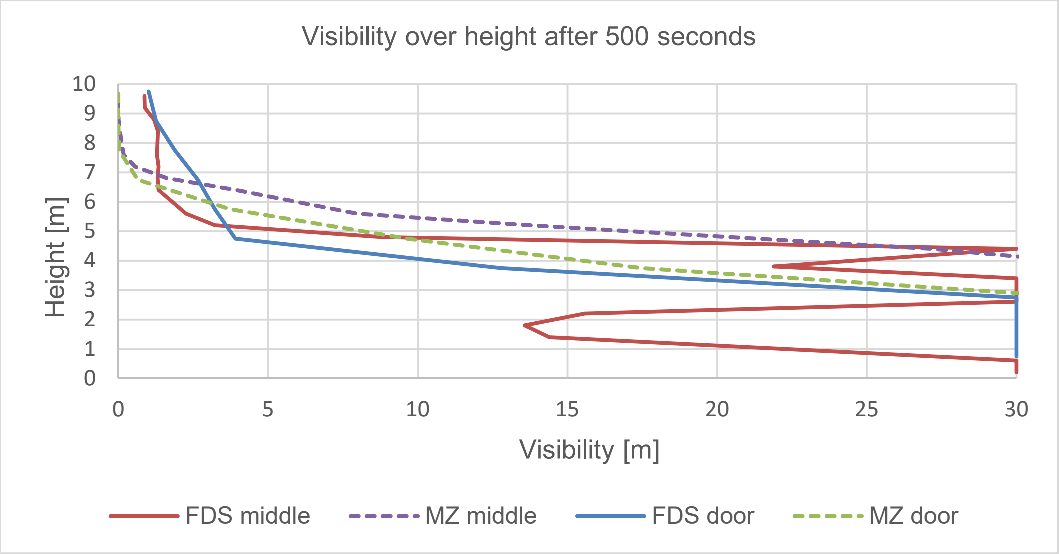


Figure 12. Visibility over height for large enclosure with medium growth rate

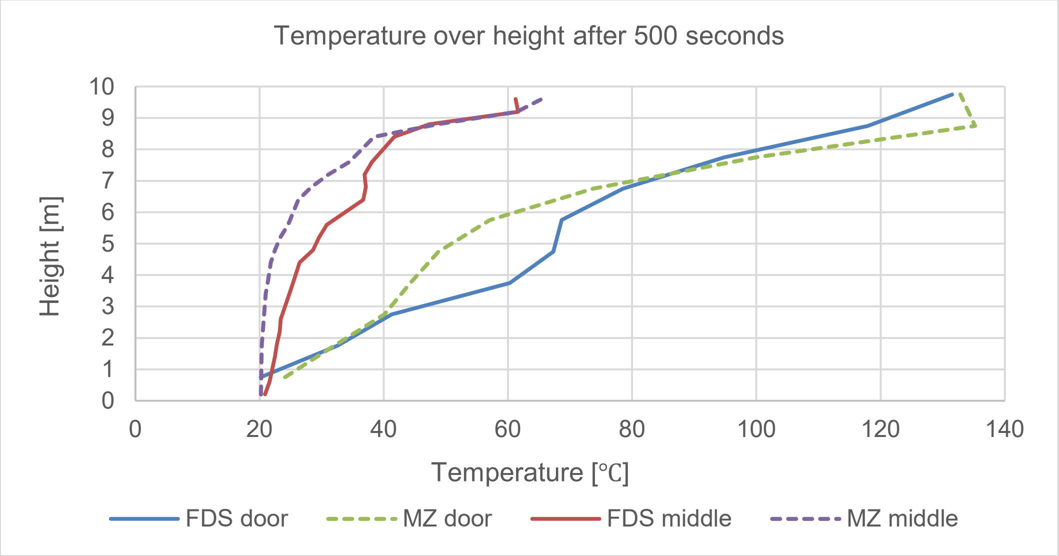


Figure 13. Temperature over height for large enclosure with medium growth rate

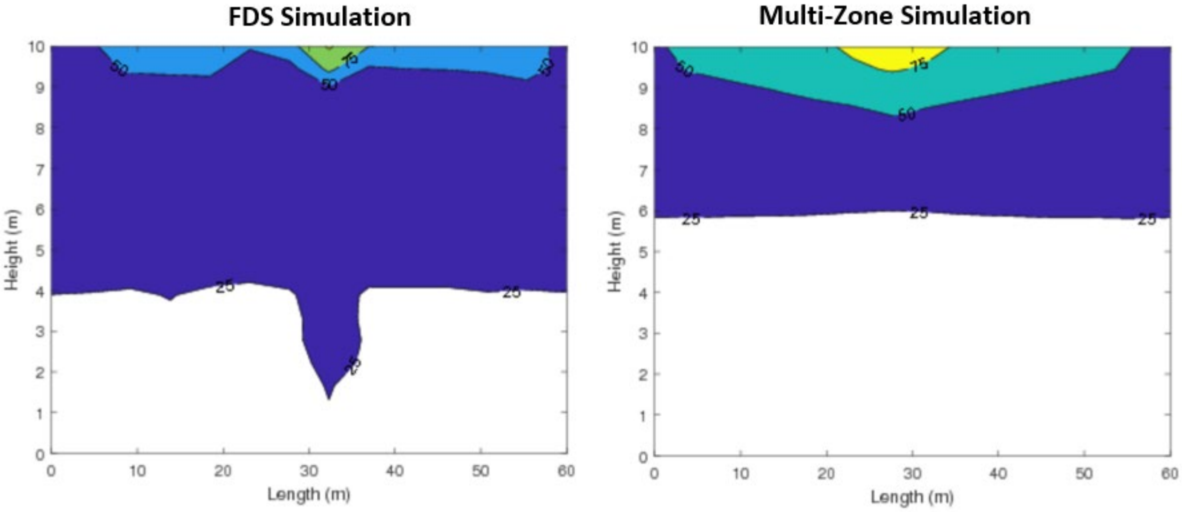


Figure 14. MATLAB temperature slice at 500 seconds for large enclosure with fast medium rate

For this scenario temperatures in Figure 11 are similar with the MZ-model again predicting slightly lower temperatures near the bottom compared to FDS but not showing much difference at the top of the enclosure. Visibility is similar for both models in Figure 12 with the exception of spikes for FDS in the middle of the enclosure. Slices from MATLAB in Figure 14 show similar layer structure and temperatures between the models with the bottom part of the smoke layer stretching about 2 meters lower in FDS.

5.3 Wide enclosure – Fast growth rate

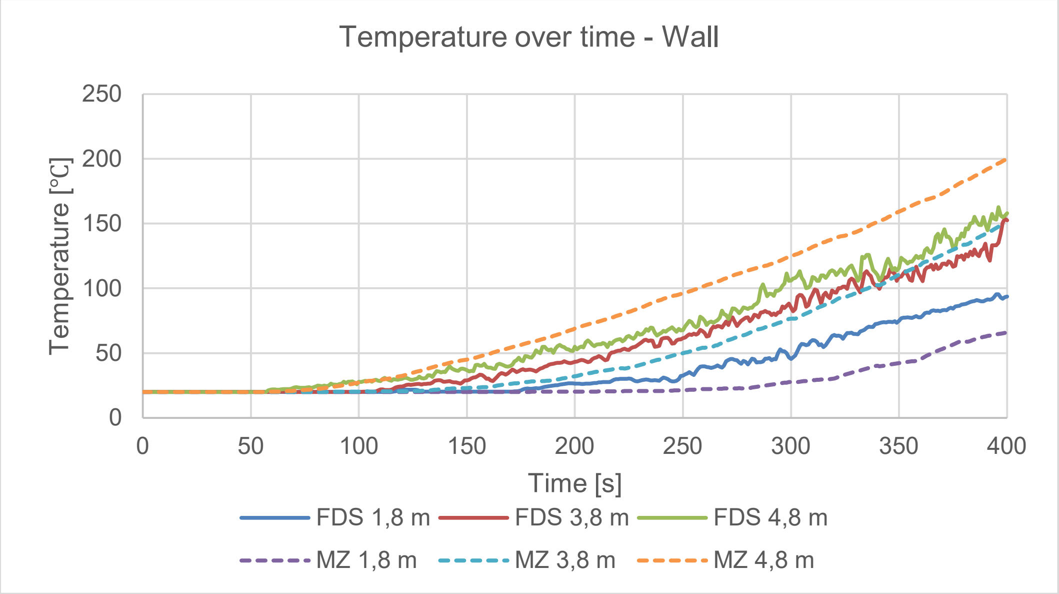


Figure 15. Temperature over time for wide enclosure with fast growth rate

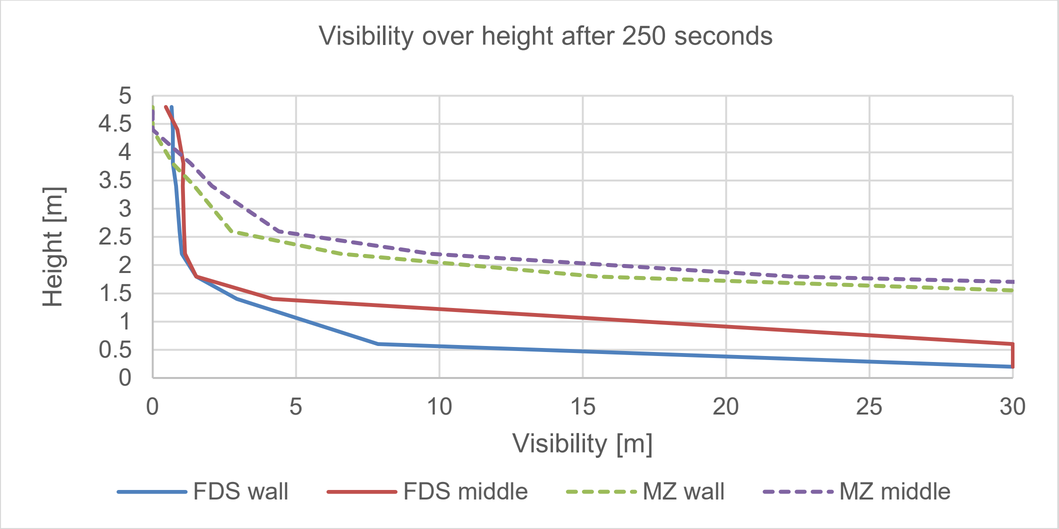


Figure 16. Visibility over height for wide enclosure with fast growth rate

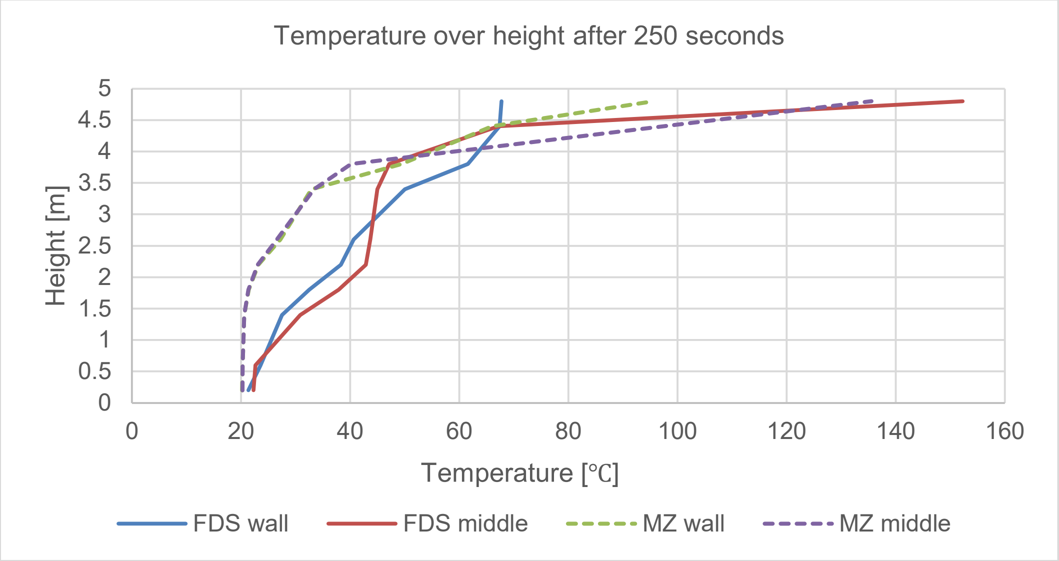


Figure 17. Temperature over height for wide enclosure with fast growth rate

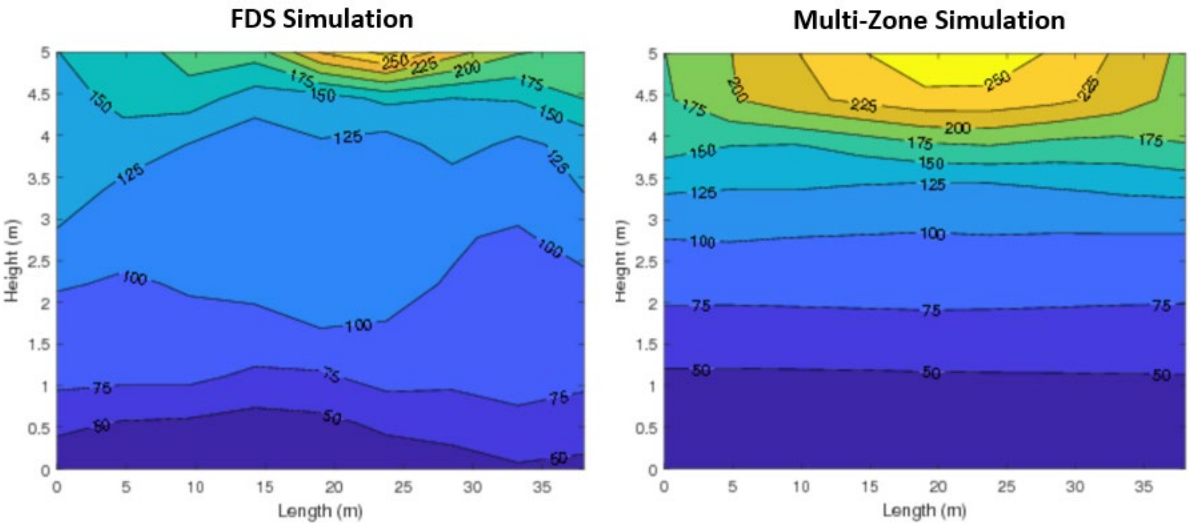


Figure 18. MATLAB temperature slice at 400 seconds for wide enclosure with fast growth rate

Temperatures for the MZ-model in Figure 15 are a bit lower than FDS below 4 meters while it is the other way around above 4 meters where the MZ-model shows higher temperatures. The MZ-model also estimates much higher visibility than FDS at 250 seconds seen in Figure 16. The MZ-model catches up a bit with FDS at the end of the simulation, which is shown in Appendix B. Temperature slices from MATLAB in Figure 18 show similar layers of temperature with the MZ-model showing higher temperatures in general at the top and FDS showing a much wider layer in the middle and overall more variation in the layers.

5.4 Wide enclosure – Medium growth rate

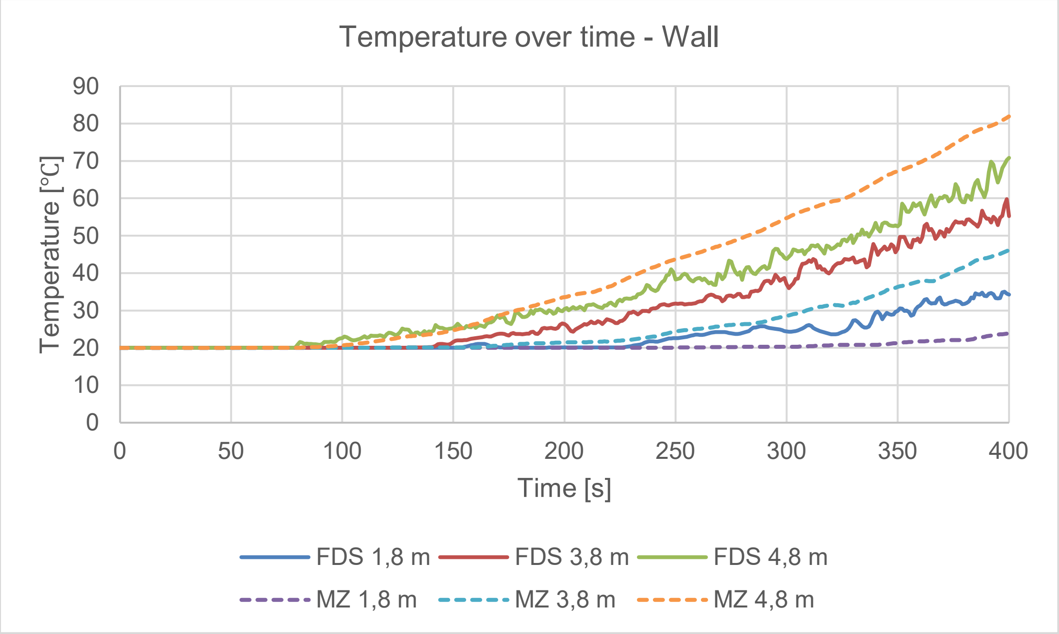


Figure 19. Temperature over time for wide enclosure with medium growth rate

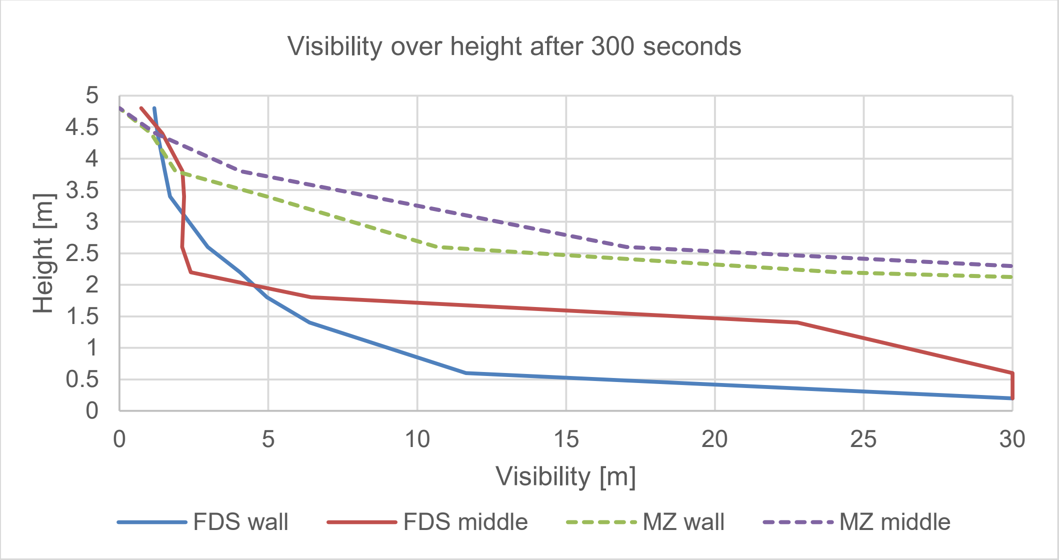


Figure 20. Visibility over height for wide enclosure with medium growth rate

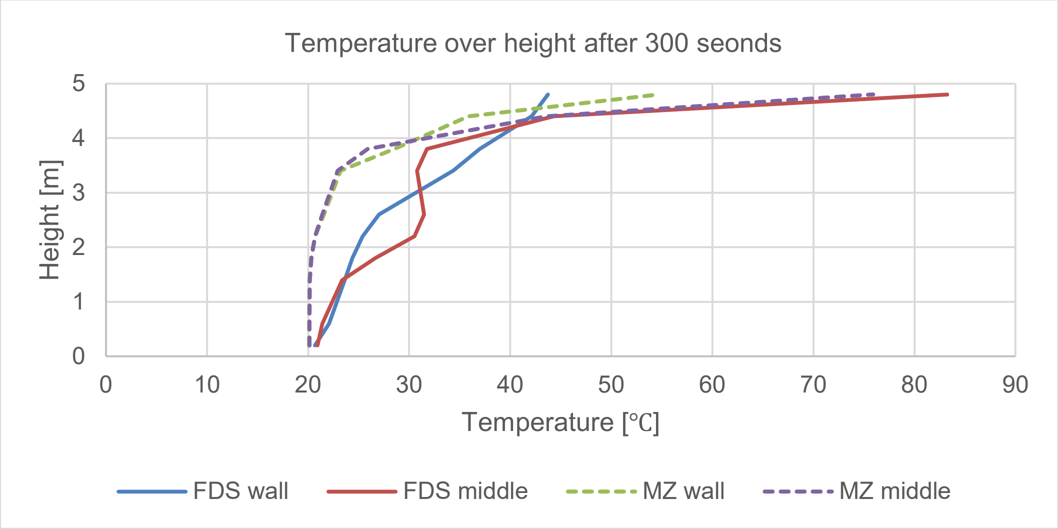


Figure 21. Temperature over height for wide enclosure with medium growth rate

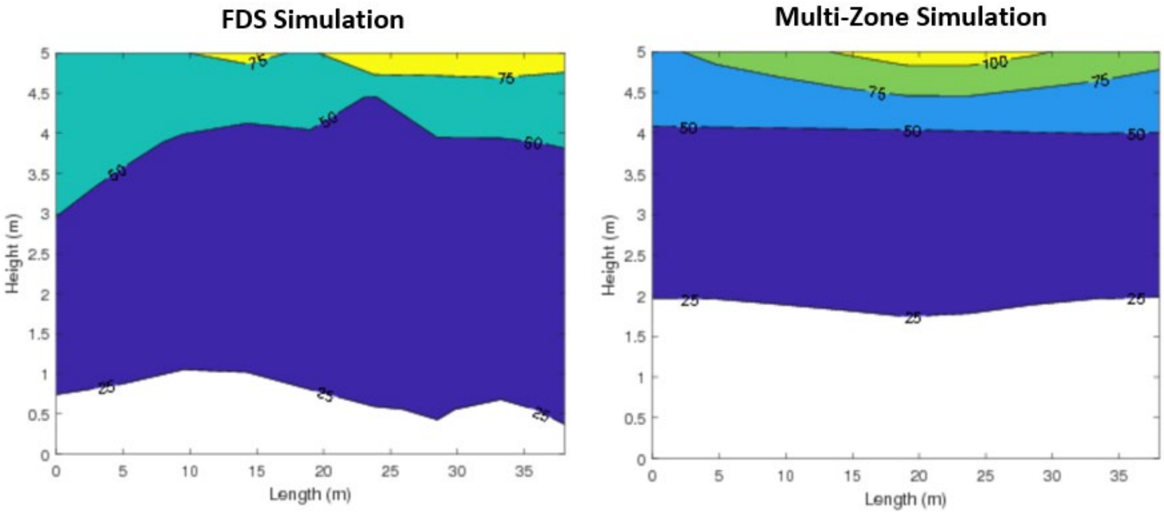


Figure 22. MATLAB temperature slice at 400 seconds for wide enclosure with medium growth rate

Temperatures in Figure 19 for this scenario show the same pattern as the for the scenario with fast growth rate where the MZ-model again shows lower temperatures than FDS except near the ceiling at the wall where the MZ-model shows higher temperatures. Predictions in visibility seen in Figure 20 differ even more during the middle part of this simulation but the MZ-model does catch up a bit towards the end of the simulation which is shown in Appendix B. Temperature slices from MATLAB in Figure 22 show similar layers at the top but with the bottom layer reaching much lower in FDS than in the MZ-model.

5.5 Corridor – Fast growth rate

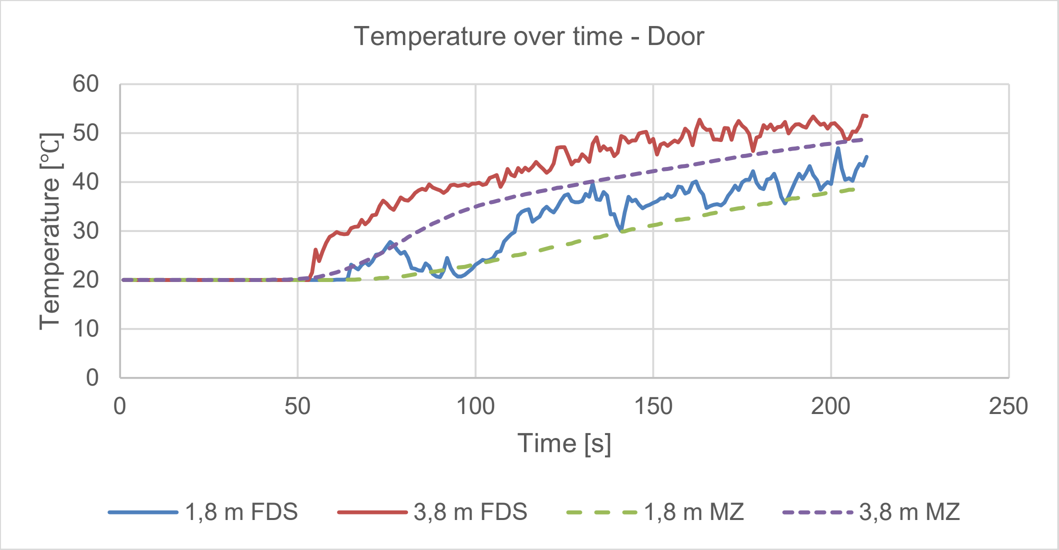


Figure 23. Temperature over time for the corridor with fast growth rate

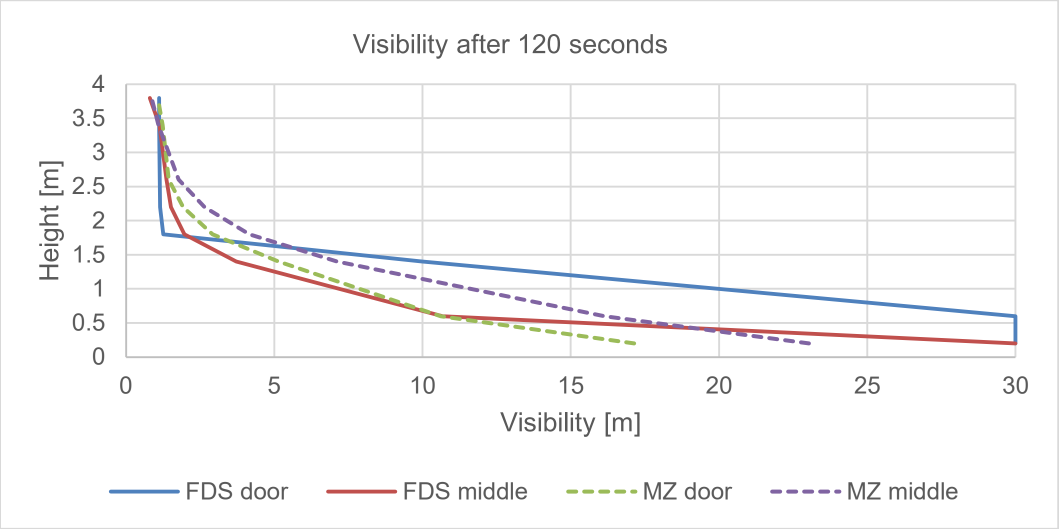


Figure 24. Visibility over height for the corridor with fast growth rate

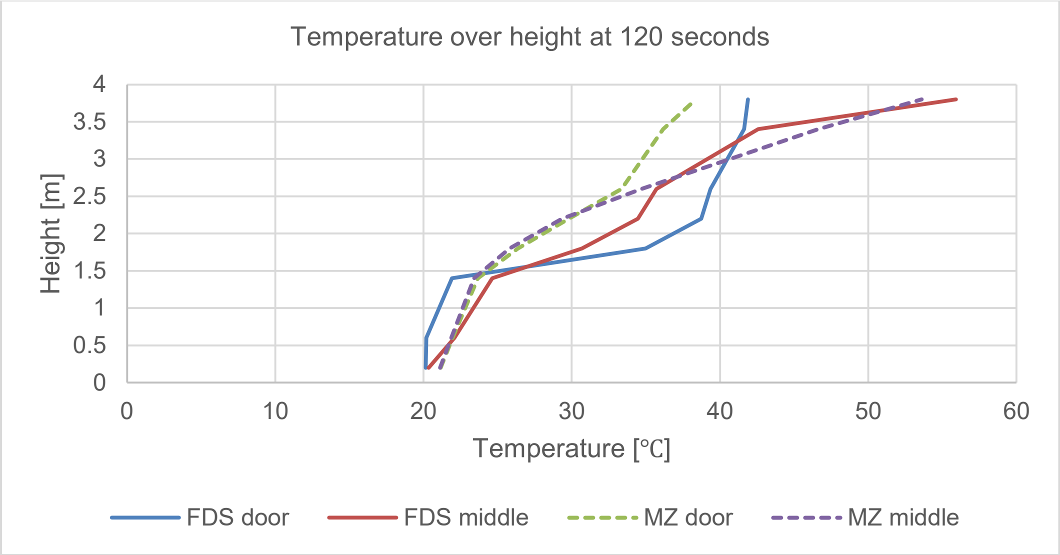
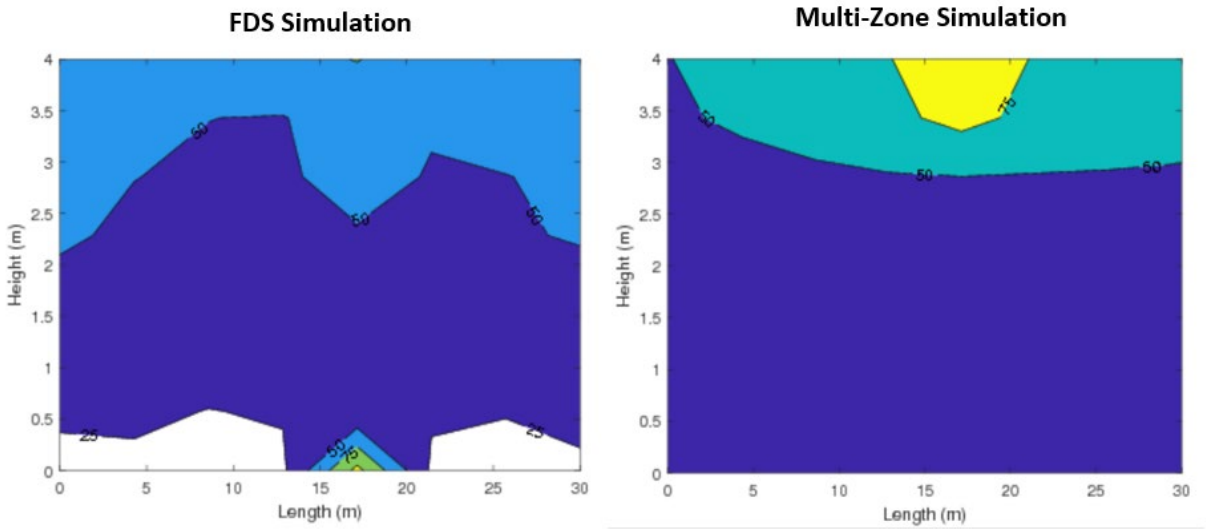


Figure 25. Temperature over height for corridor with fast growth rate


FDS Simulation

Multi-Zone Simulation

Figure 26. MATLAB temperature slice at 200 seconds for corridor with fast growth rate

Temperatures for the middle of the compartment seen in Figure 23 are similar while FDS shows higher temperatures at the door above 1.5 meters up to about 120 seconds where after the MZ-model shows higher temperatures below 1.5 meters at the door. Regarding visibility the results are similar until about 90 seconds as shown in Appendix B, and at 120 seconds FDS predicts higher visibility than the MZ-model at the door below 1.5 meters and less visibility in the middle seen in Figure 24. After 150 seconds both models show almost no visibility above 1.5 meters but FDS predicts much higher visibility than the MZ model below 1.5 meters. Temperature over time at the door show similar results for both models with results for FDS fluctuating around temperatures slightly above the MZ-model. MATAB-slices show similar layer structure with FDS showing the fire in the bottom and the MZ-model having slightly higher temperatures at the top just over the fire.

5.6 Corridor – Medium growth rate

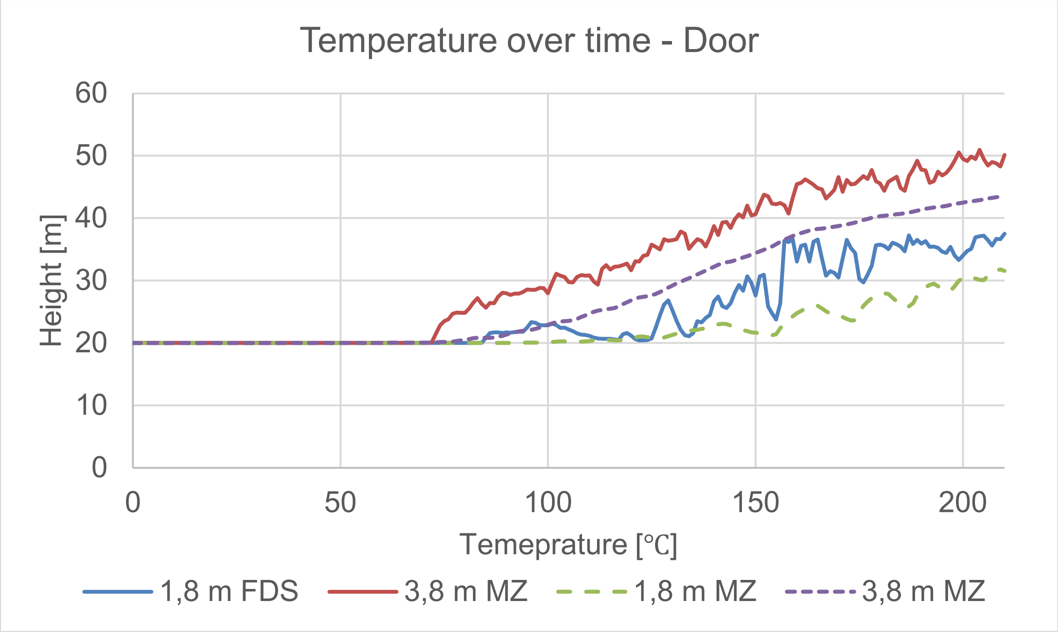


Figure 27. Temperature over time for corridor with medium growth rate

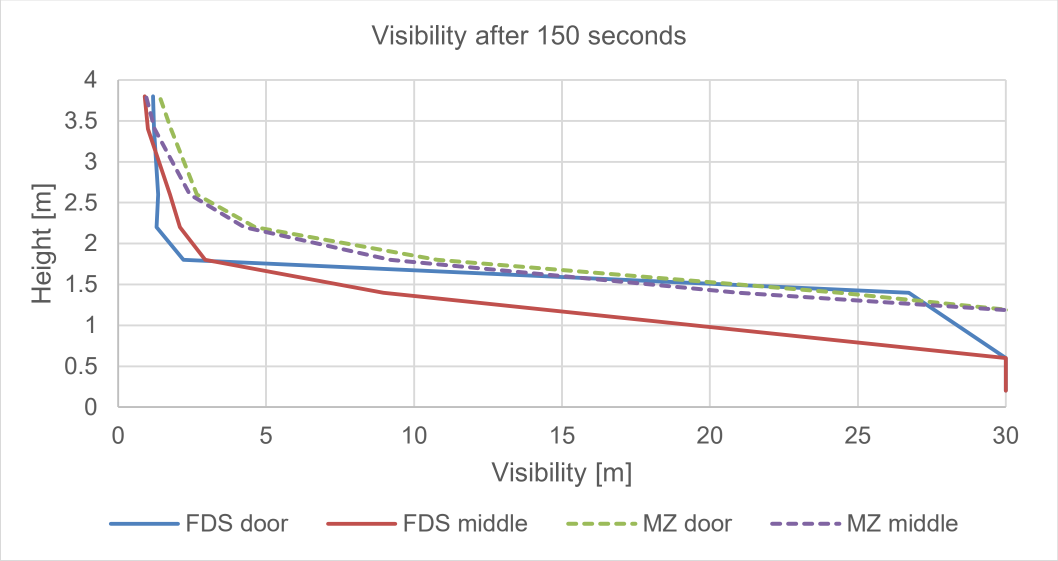


Figure 28. Visibility over height for corridor with medium growth rate

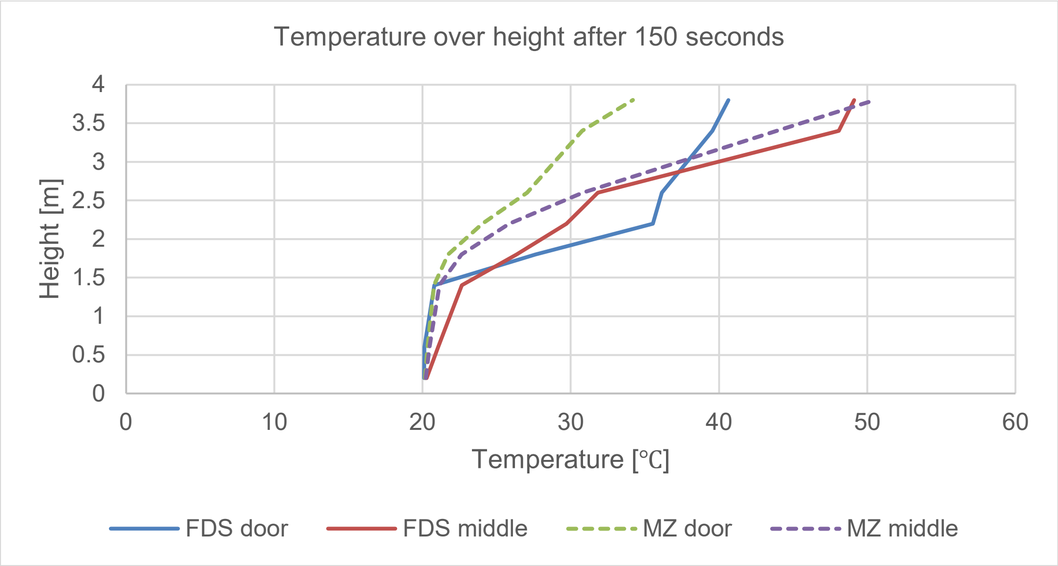


Figure 29. Temperature over height for corridor enclosure with medium growth rate

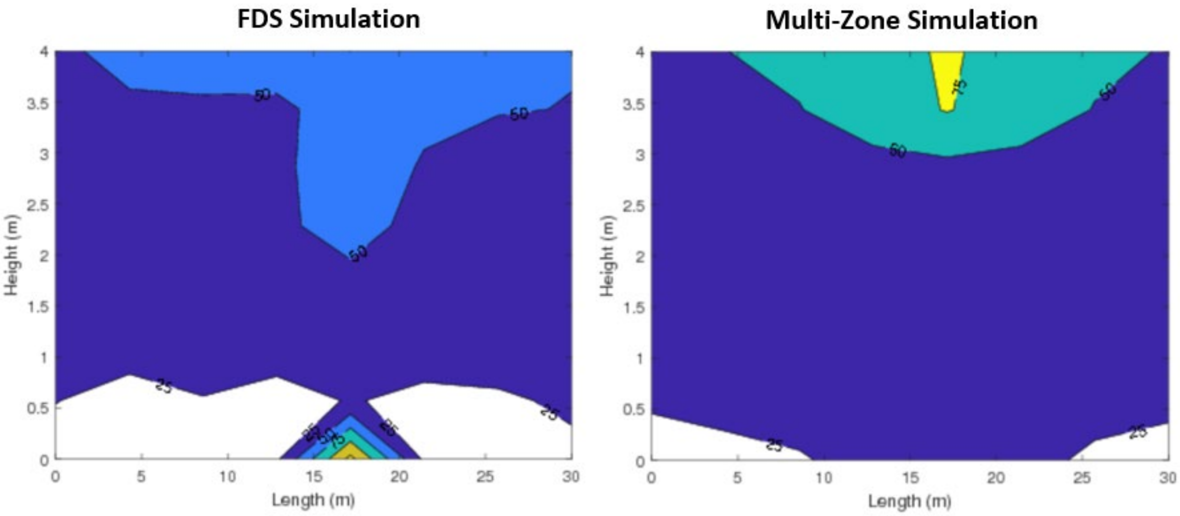


Figure 30. MATLAB temperature slice at 200 seconds for corridor with medium growth rate

Again, temperatures for the middle are more evenly similar while the MZ-model shows lower temperatures at the door during parts of the simulation. Temperatures for the door in FDS fluctuate heavily between 130-200 seconds but seems to be steadier after that and temperatures at the door for the MZ-model seem to grow closer to FDS around 200 seconds. Visibility is similar between the models below 1,5 meters in height apart from FDS generally predicting les visibility in the middle of the enclosure. Above 1,5 meters both measuring points in FDS show predicts slightly less visibility than the MZ-model. MATLAB-slices show a similar pattern in this scenario with the top layer extending a further down for in the middle for FDS.

5.7 Differences in temperature over time

Scatter plots for the three scenarios with a fast growth rate showing comparisons of estimated values for the two models are shown in this section.

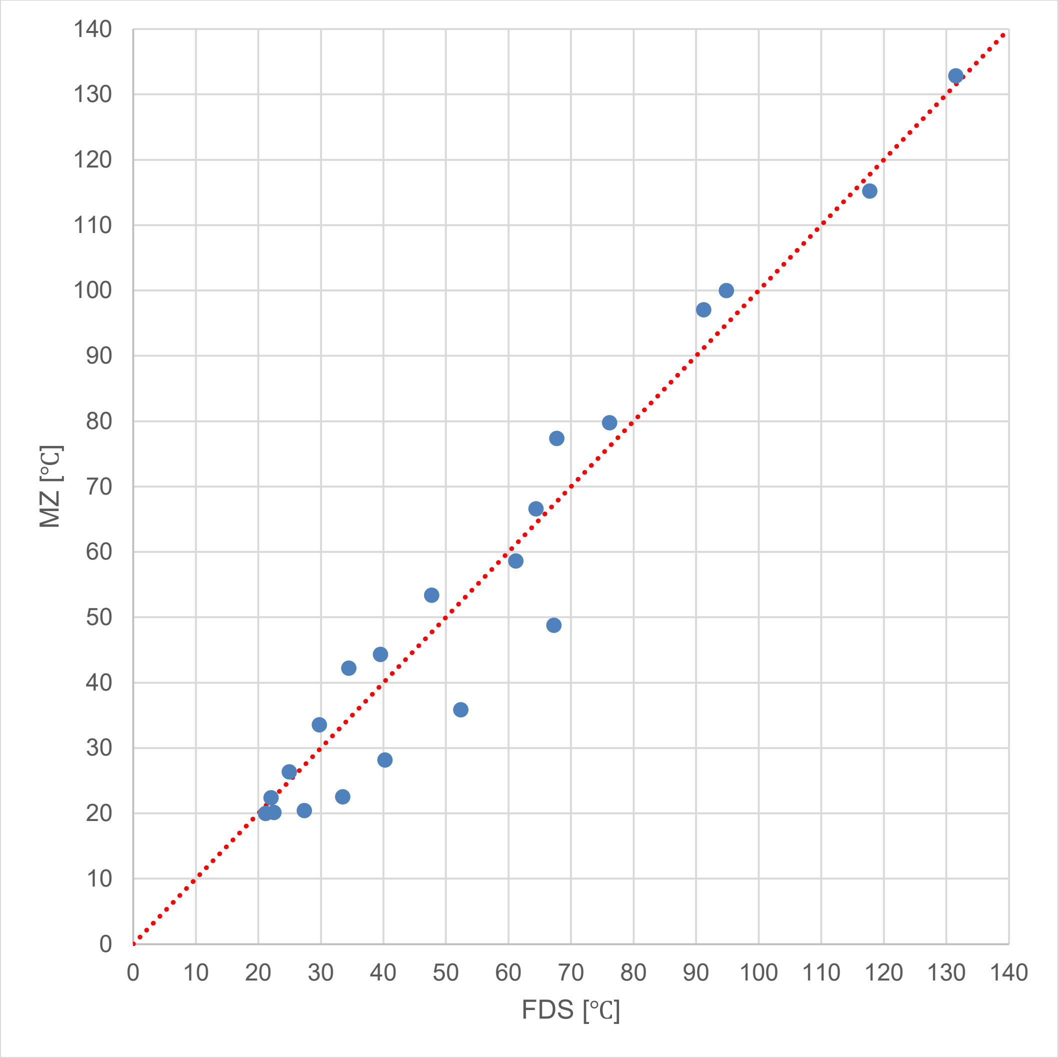


Figure 31. Differences in temperature over time for large enclosure with fast growth rate

Values plotted in Figure 31 show a moderate difference in the lower temperatures while there is little difference in the higher temperatures. This pattern is also seen in Figure 7.

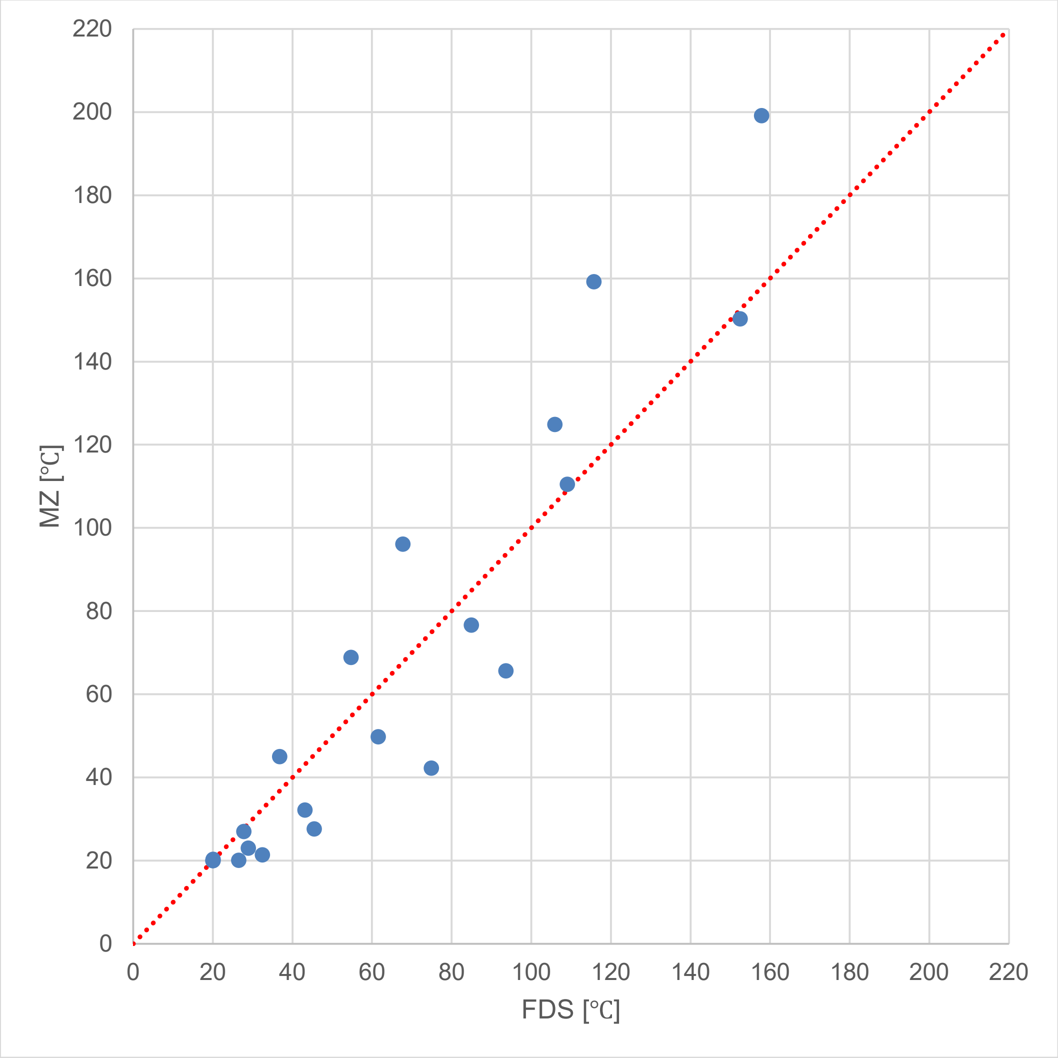


Figure 32. Differences in temperature over time for wide enclosure with fast growth rate

Values plotted in Figure 32 show a moderate difference in the lowest temperatures while there is a significant difference in the medium and high temperatures. Both models predict significantly higher temperatures than the other at different heights and times. The same tendencies can be seen in Figure 15 where the MZ-model predicts higher temperatures near the ceiling while FDS predicts higher values in the bottom half of the enclosure.

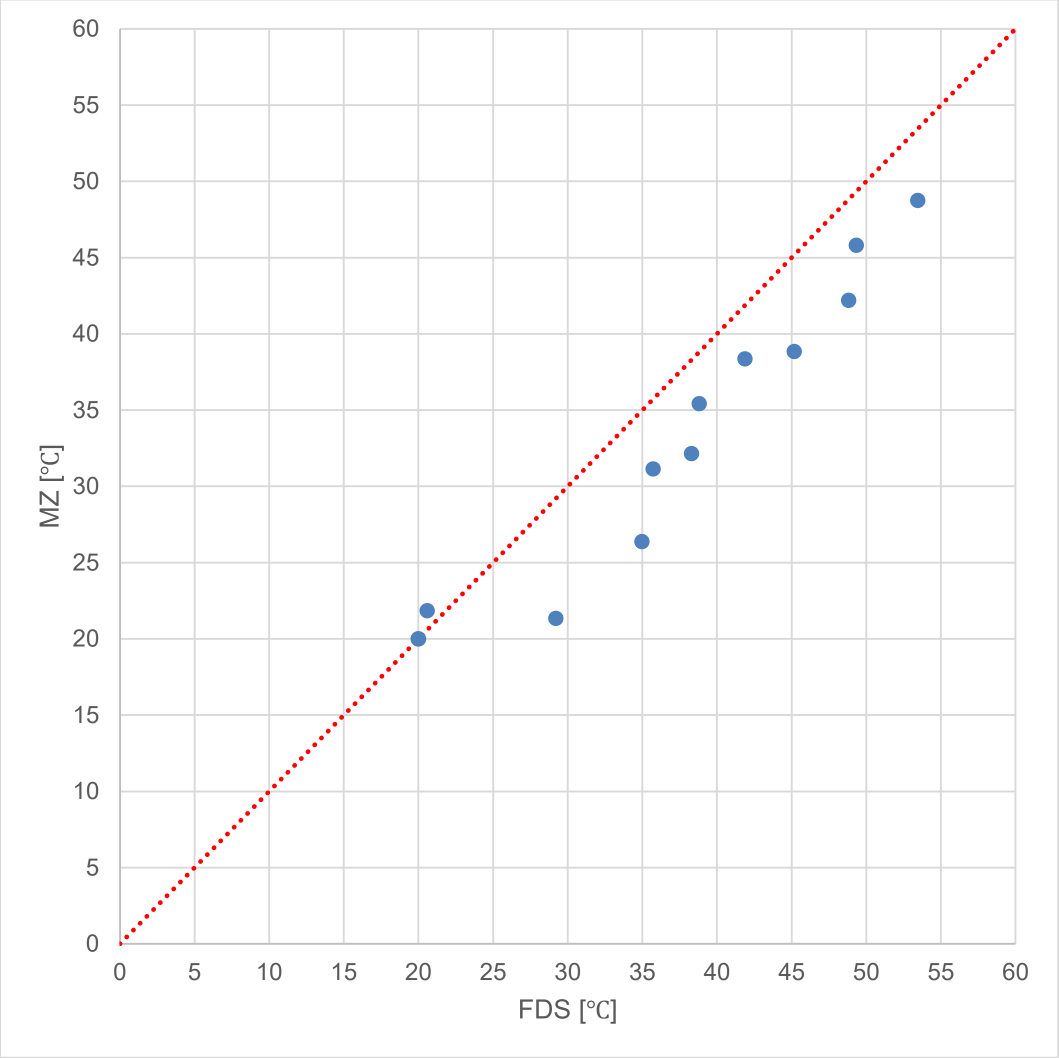


Figure 33. Differences in temperature over time for the corridor with fast growth rate

Values shown in Figure 33 show that FDS generally predict slightly higher values with about 5-10 degrees Celsius higher as seen in Figure 23. In difference to the wide enclosure temperatures for the corridor are consistently slightly higher in FDS.

6 Discussion

6.1 Results

The results generally show that predicted temperatures are similar for several scenarios with differences under 10 degrees Celsius for large parts of the simulations, although FDS tends to show slightly higher temperatures in the bottom half of the enclosures. Visibility is similar for both the large enclosure and the corridor with variations between the models of only a few meters but results for visibility are not similar in either of the simulations for the wide enclosure. Even though enclosures were made identical in the two models and efforts were made to make the fire scenarios as similar as possible there are several differences between the models and the way they were set up that might affect the results. The way in which the results might have been affected will be discussed in this section as well as ways to possibly prevent some of these differences in future simulations.

6.2 Method

Simulations were first run in FDS and simulations for the MZ model were then based on the finished FDS simulations. No experiments have been conducted and it is not assumed that FDS will produce result identical to those of a real enclosure fire. With this said previous research has shown FDS give adequate results for predicting smoke movement in enclosure fires and for that reason it is thought to be a good benchmark for this comparison. With the chosen approach a number of issues came to light regarding placement and size of the fire when choosing cell size in the MZ model. Due to layout of zones and meshes for the respective models the fire could not be placed in the exact same place in both models for the corridor and wide enclosure. In the case of the corridor the fire surface is placed slightly to the side in FDS while it is placed in the middle of the enclosure in the MZ model. As mentioned previously the fire should be kept inside one mesh for FDS and inside one cell for the MZ model which is why the fire was moved slightly in the MZ model in the case of the corridor and the wide enclosure. For the wide enclosure the size and HRRPUA of the fire is different I the two models for the same scenario to keep the fire inside a cell and mesh respectively. At first the fire did not fit inside one cell in the MZ model and the HRRPUA was there for increased to compensate for a smaller area resulting in a difference of only 6.5 kW between the two models. As mentioned, input data for the MZ model was changed so the fire ramp would be as similar as possible in both cases.

Devices were set to measure visibility in FDS while the MZ model can only measure percentage obscuration in its current form which demands that one of the units be converted for a comparison to be able. It was decided to convert values from one of the models because of the time and resources that would have been needed to run all the FDS simulations again. Maximum sight in FDS was set to the default of 30 meters and converting results from sight in meters to obscuration would give faulty values since two of the enclosures are longer than 30 meters. Results were instead converted from the from obscuration to visibility in meters for the MZ-model which led to results of sight longer than 30 meters, since FDS only measured sight up to 30 meters distances longer than that will not be compared. One could argue that 30 meters of visibility is quite good for being inside a building and it should not be necessary to discuss sight at that distance for the purpose of egress.

Zones in the corridor were made narrow to fit three zones into the width so at least one row of zones did not have contact with the walls. The zones were also made elongated which is not usually recommended, however the temperature profile in a narrow corridor is different from a temperature profile in a square room with the same length. Hot gases in the corridor will travel the path of least resistance along the long side of the corridor when reaching the ceiling. Because the hot gases will mostly travel in two directions, they are subject to less cooling and temperature differences are not likely to be as high far away from the fire. In a bigger room where hot gases can spread out in all directions, they would cover a bigger area and be subject to more cooling from the ceiling. Since the temperature profile is going to be different in the direction of the corridor it can be considered as reasonable to have elongated zones in the direction of the corridor.

6.3 Differences and validity

The zones in the MZ-model assumes uniform conditions within each zone just like cells in FDS but there are possible disadvantages with assuming uniform conditions in such a large zone. A measuring point in FDS might show higher values than a measuring point at the same place in the MZ-model if the average value of that zone is lower. For this reason, measuring points for comparing results between the models should be placed in the middle of a zone in the MZ-model and preferably at the same place in FDS, where devices should also be placed in the middle of a cell for the same reason. If the devices cannot be placed in the same location for some reason measured values are likely to be similar if the device is only moved a short distance in either model but still close to what would be the middle of the zone.

Results from FDS for the large enclosure show spikes in visibility at several times for simulations of both the medium and fast growth rates. When looking at slice files for visibility in Smokeview there is turbulent air flow around the measuring point at these times in the simulation which explain the spikes in visibility When measuring values for temperature or visibility over time data from several different timesteps can be compiled to create an average value for that period of time. Although not used in this comparison the method could decrease the likelihood of spikes in the graphs from local variations. Since the MZ-model does not simulate large eddies or turbulence it will not show these kinds of spikes.

The MZ-model seems to struggle in the wide enclosure predicting higher visibility than FDS especially for the lower half of the enclosure. The size of fire in the wide enclosure was adjusted to fit inside one zone but the fire was only made slightly smaller than the zone which means the results might be affected if the plume grows outside the area of the zone. The effects of the plume growing outside the zone of the fire are not known at this time but could be part of the reason why the visibility is different in the two models. It is also possible that turbulent conditions occur in FDS and soot from the smoke layer is mixed with the cold air below, this would lower the visibility in FDS but would not show in the MZ-model since it cannot simulate turbulence. There are also differences in temperature for the wide enclosure although not as significant as for the visibility. There are also differences in temperature for the wide enclosure although not as significant as for the visibility.

The method used for this comparison was chosen in part so input data for the fires could be selected from guidelines for CFD and no experiments had to be made. Since the MZ-model is much less time consuming it was decided to set up and run the FDS simulation first and then recreate the simulations in the MZ-model. As mentioned earlier this proved to have some complications and there were issues with placement of the fire as well as size of the zones in the MZ-model when trying to replicate simulations from FDS. In hindsight it would probably have been easier to first run simulations in the MZ-model and then replicate them with FDS since it is more versatile and has a greater possibility to adapt to the geometry with its much smaller cells. One must also be cautious when setting up a simulation in the MZ-model so measuring devices do not end up on the wrong side of a zone boundary. If a device is mistakenly placed in the adjacent zone it will effectively be placed an entire cell width away from where it was intended which can be several meters.

Another method which would perhaps have been better is to do real experiments and then set up simulations in both FDS, the MZ-model and a zone model to compare the models with each other and the experiments. The aim of this comparison however ass been to see how the MZ-model performs in enclosures where Zone models are not recommended and in order to do full-size tests in enclosures with similar dimensions a lot of resources would be needed. Both the resources and workload required for this would be far outside the limits of which is reasonable for a bachelor's thesis. It would make for a very interesting comparison if such test were conducted and compared with different models. One could instead base simulations on enclosures where experiments have already been done to validate other models and use the parameters for those tests. An effort was made to find suitable enclosures in the validation guide for FDS but most of the compartments had complicated geometries and did not have desirable dimensions.

The purpose of this thesis was to compare results from the two models for near identical fire scenarios in identical enclosures which has been accomplished. The objective was to evaluate how well the Multi-zone Fire Model can simulate variations of temperature and visibility in an enclosure fire scenario compared to the Fire Dynamics Simulator. Not considering effects of turbulence the MZ-model simulates variations in temperature and visibility well compared to FDS for the large enclosure with a high ceiling and the narrow corridor. The MZ-model also managed to simulate variations in temperature reasonably well compared to FDS for the wide enclosure with a lower ceiling, but variations of visibility for the same enclosure were not very close to the conditions simulated in FDS.

6.4 Possible areas of use

There are several areas where the MZ-model could be used in fire safety engineering if validated properly. Such areas might include small fires where FDS needs small cells and large enclosures with complex geometries to see if desirable results are likely. As the results have shown, the MZ-model can predict similar conditions as FDS for the large enclosure with a big fire and the corridor with a small fire but it does not seem to work that well in the wide enclosure with the circumstances in this comparison.

Another possible issue is that having such large zones as the MZ-model might increase effects of errors made by the user and impact the simulation, large zones can also mean compromises have to be made if trying to simulate complex geometries. If problems or errors are recognized by the user, simulations can easily be altered and run again in a short period of time to see if the problems are solved. The same cannot be said for FDS where mistakes and errors that are noticed after the simulation is done can result in having to re-run a simulation which can take several hours, days or even weeks. With simulation times that long running simulations several times to see if the problem is fixed or to check the impact of different variables might not be an option.

If the MZ-model proves to perform well in different types of large and possibly complex geometries it can be used as a tool when considering different options for performance-based design. Before running CFD-simulations to acquire more parameters and more accurate values several simulations can be run quickly in the MZ-model to get estimated outcomes of different scenarios. If proven to work well on enclosures where zone models are used today the MZ-model can also be used as an alternative to get more detailed simulations of these enclosures.

7 Conclusion

The comparison conducted is the first of this kind on the performance of the Multi-Zone Fire Model and is not to be viewed as validation for the model. The MZ-model did however show promising results in that it could produce simulations with similar results to ones produced in FDS regarding temperature and visibility for two of the three enclosures compared. With similar predictions meaning the models rendering visibility within a few meters of each other and temperatures mostly within ten degrees Celsius. The third wide enclosure however did not show the same similarities between the two models. It is not clear why there is a larger difference in temperature and the visibility is significantly higher in the MZ-model compared to FDS. Furthermore, the MZ-model is not appropriate for enclosures where turbulence can be expected to affect the overall outcome of a fire scenario simulation. Further research is needed to determine exactly what type of enclosures the MZ-model is appropriate to use for simulating fire scenarios and how the model should be used in performance-based design.

8 Suggestions for further research

No research has been done yet on optimal cell size and which size is most cost effective if the cost is measured in simulation time. Several simulations of the same compartment with different cell seize could be run with the Multi-zone Fire Model to research how the cell size could affect the results of a simulation. The impact of having a fire in a zone where the plume stretches outside the zone has not been tested either. Knowing how this might affect the outcome of a simulation can be important for future simulations and how much effort should be made when deciding size of fire for the MZ-model.

The enclosures in this comparison have all been of a simple box shape consisting of four walls, roof and floor. Future research would be needed to see if the MZ model can be used to simulate enclosures with mor complex geometries like internal walls that have openings. None of the enclosures in this comparison had openings in the ceiling to vent hot gases. Since many buildings are equipped with smoke hatches that open either automatically or manually operated it would also make a good subject for future research to analyze the possibilities of using openings in the ceiling in the MZ model. It can also be interesting to see how the MZ-model would perform with a combination of internal walls and smoke hatches.

Comparing the MZ-model to CFAST or other zone models for different enclosures to see how the results differ, both of appropriate and non-appropriate size for zone models to see differences in results. The MZ-model is developed to simulate enclosure fires for geometries where zone models are not appropriate however, it would be interesting to see how it performs compared to a zone model for these types of enclosures and if the MZ-model will have similar but more detailed results

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Appendix

Appendix A

To make sure the selected cell size is appropriate a ratio between the characteristic fire diameter and the cell size is calculated using Equation 1.

$$D^* = \left(\frac{\dot{Q}}{\varphi_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \qquad \text{Equation 1}$$

Where:

D^* = characteristic fire diameter [m]

$\dot{Q}$ = heat release rate [W]

φ_∞ = density of the air [kg/m^3]

c_p = specific heat capacity of the air [kJ/(kg*K)]

T_∞ = ambient temperature [K]

g = gravity constant [9.81 m/s^2]

Heat release rate depends on the fire, but the other values used are:

$\varphi_\infty = 1.204$

$c_p = 1.005$

$T_\infty = 293$

$g = 9.81$

Large enclosure:

$$D^* = \left(\frac{10000}{1.204*1.005*293*\sqrt{9.81}}\right)^{\frac{2}{5}} = 2.409$$

$$\frac{D^*}{dx} = \frac{2.4088}{0.2} = 12.04$$

Wide enclosure:

$$D^* = \left(\frac{14400}{1.204*1.005*293*\sqrt{9.81}}\right)^{\frac{2}{5}} = 2.787$$

$$\frac{D^*}{dx} = \frac{2.787}{0.2} = 13.94$$

Corridor:

$$D^* = \left(\frac{200}{1.204*1.005*293*\sqrt{9.81}}\right)^{\frac{2}{5}} = 0.504$$

$$\frac{D^*}{dx} = \frac{0.504}{0.05} = 10.08$$

Appendix B

Further results for the six scenarios are presented here in the same order as above. The figures shown previously are not shown here.

Large enclosure – fast growth rate

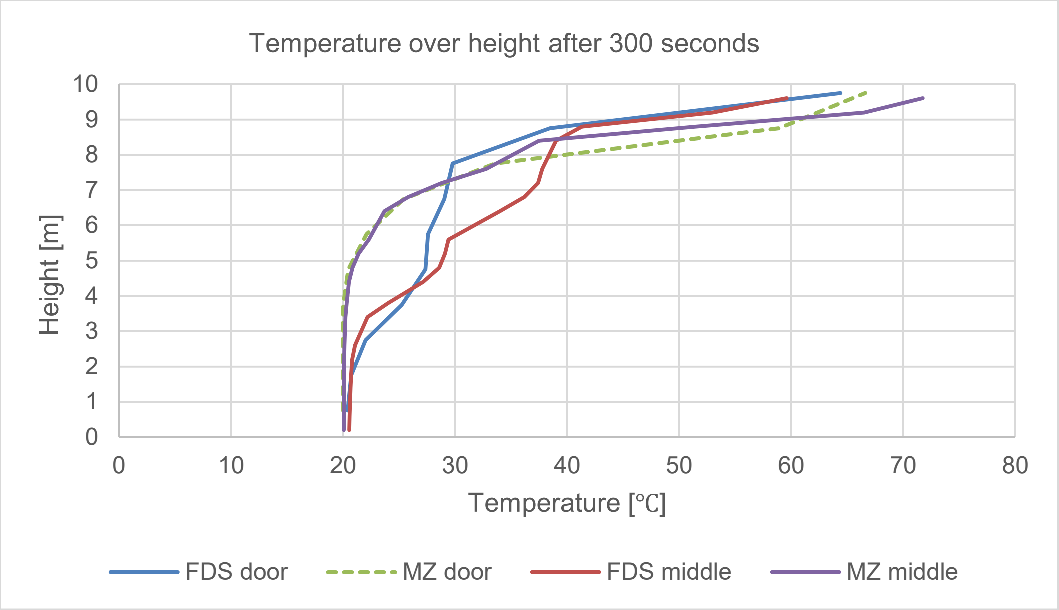

Figure B 1. Temperature over height, large enclosure with fast growth rate at 300 seconds

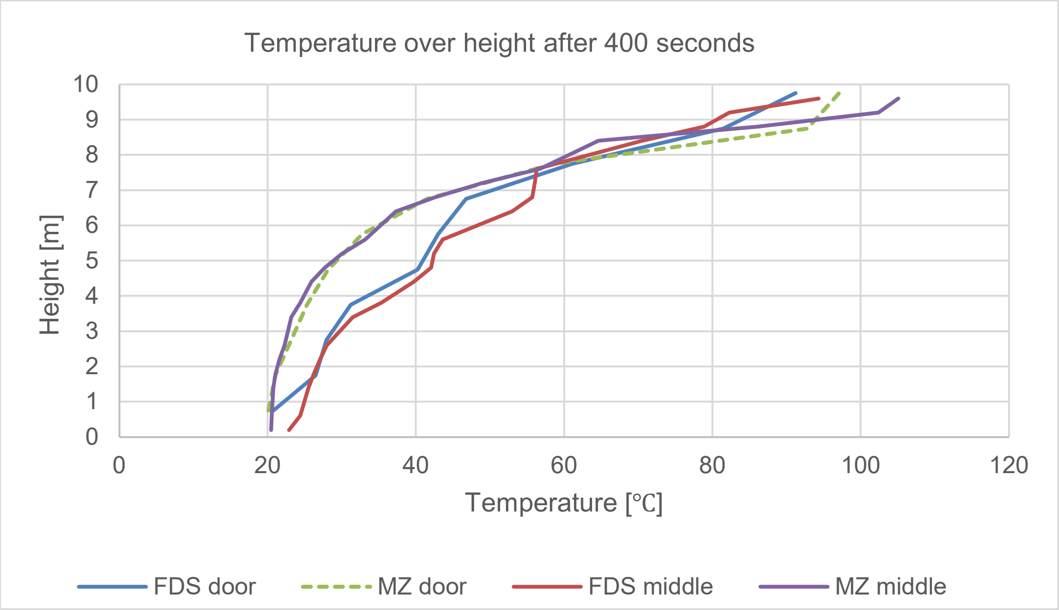

Figure B 2. Temperature over height, large enclosure with fast growth rate at 400 seconds

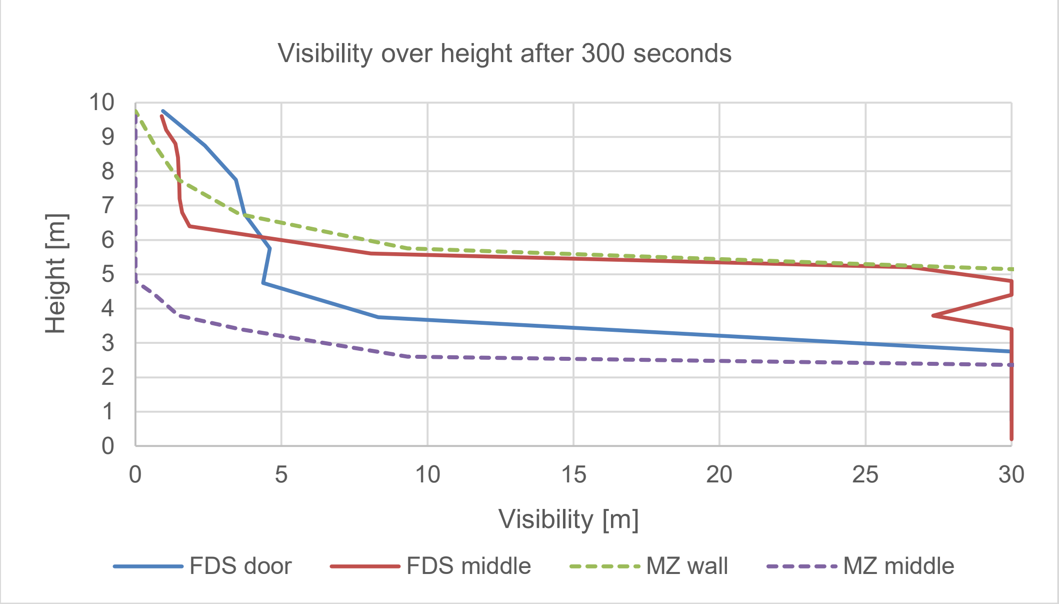

Figure B 3. Visibility over height, large enclosure with fast growth rate at 300 seconds

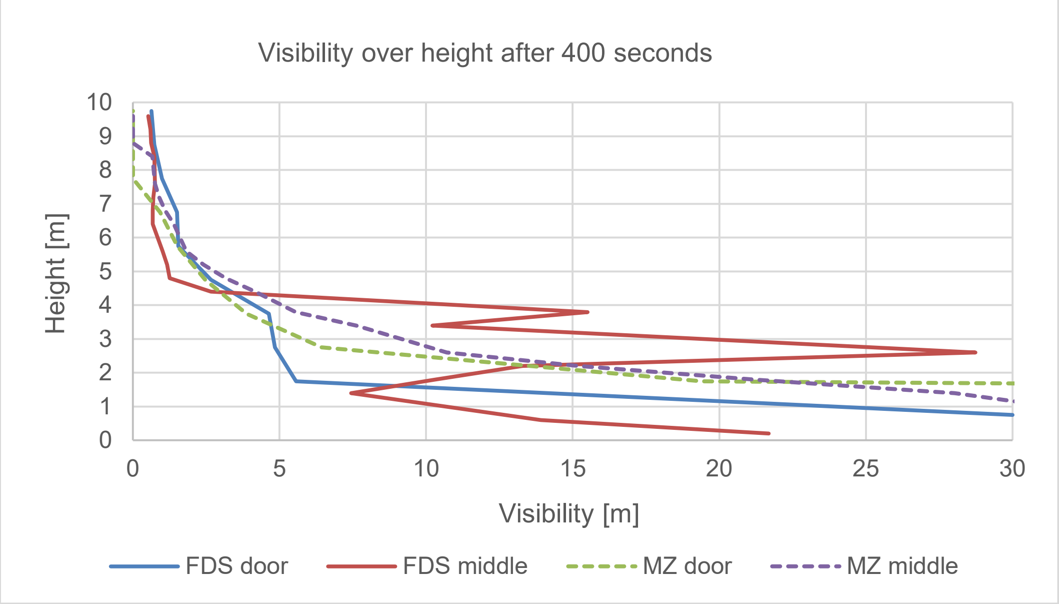

Figure B 4, Visibility over height, large enclosure with fast growth rate at 400 seconds

Large enclosure – medium growth rate

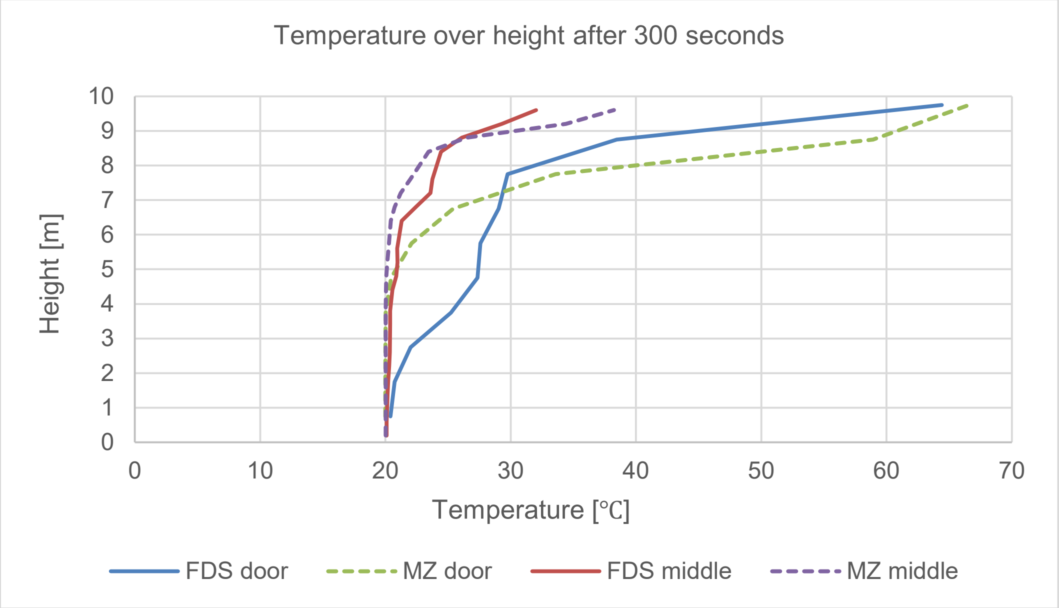

Figure B 5. Temperature over height, large enclosure with medium growth rate at 300 seconds

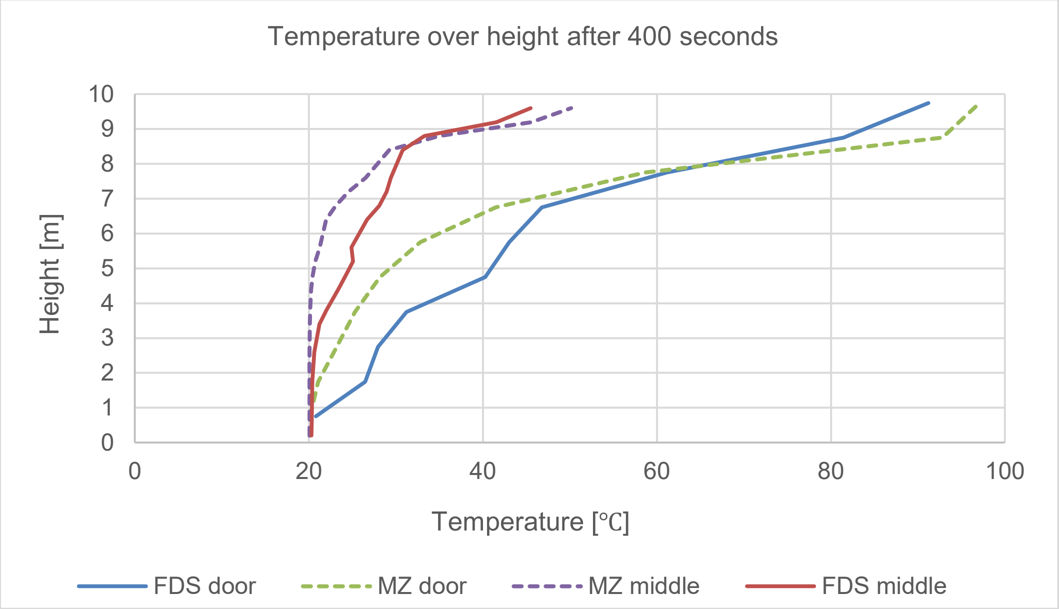

Figure B 6. Temperature over height, large enclosure with medium growth rate at 400 seconds

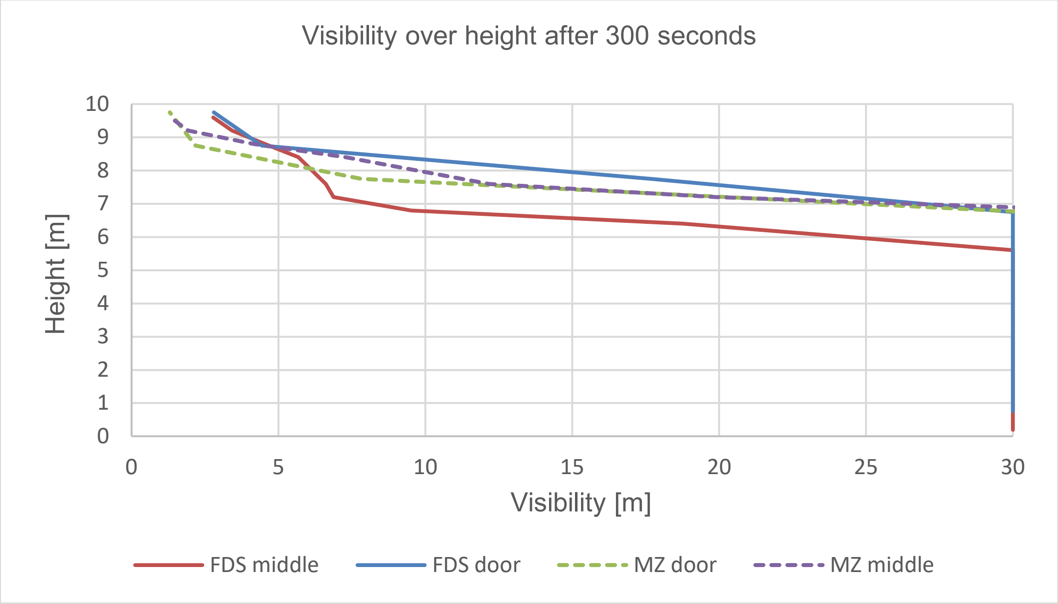

Figure B 7. Visibility over height, large enclosure with medium growth rate at 300 seconds

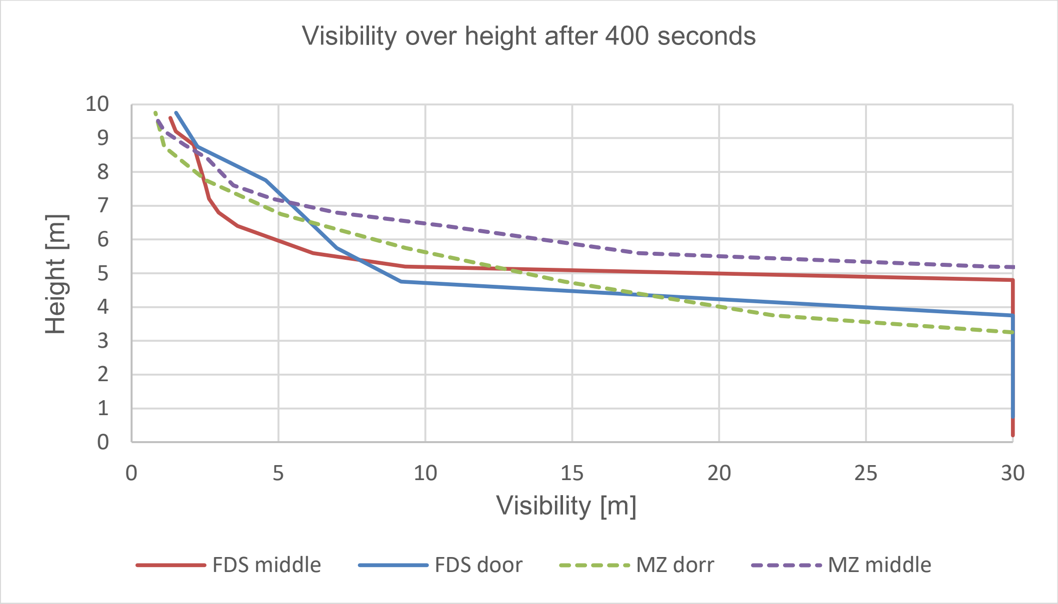

Figure B 8. Visibility over height, large enclosure with medium growth rate at 400 seconds

Wide enclosure – fast growth rate

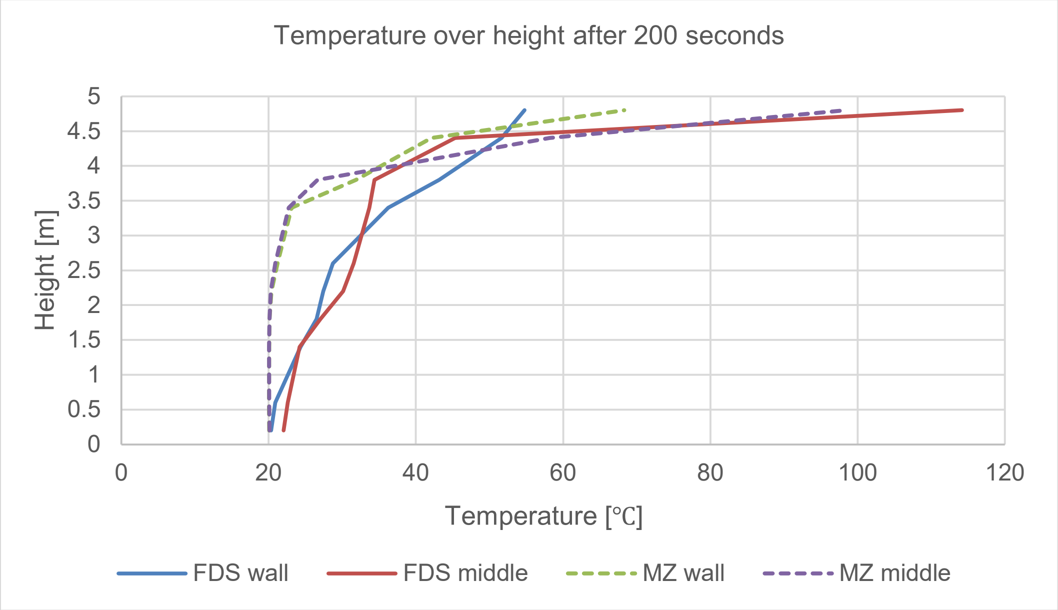

Figure B 9. Temperature over height, wide enclosure with fast growth rate at 200 seconds

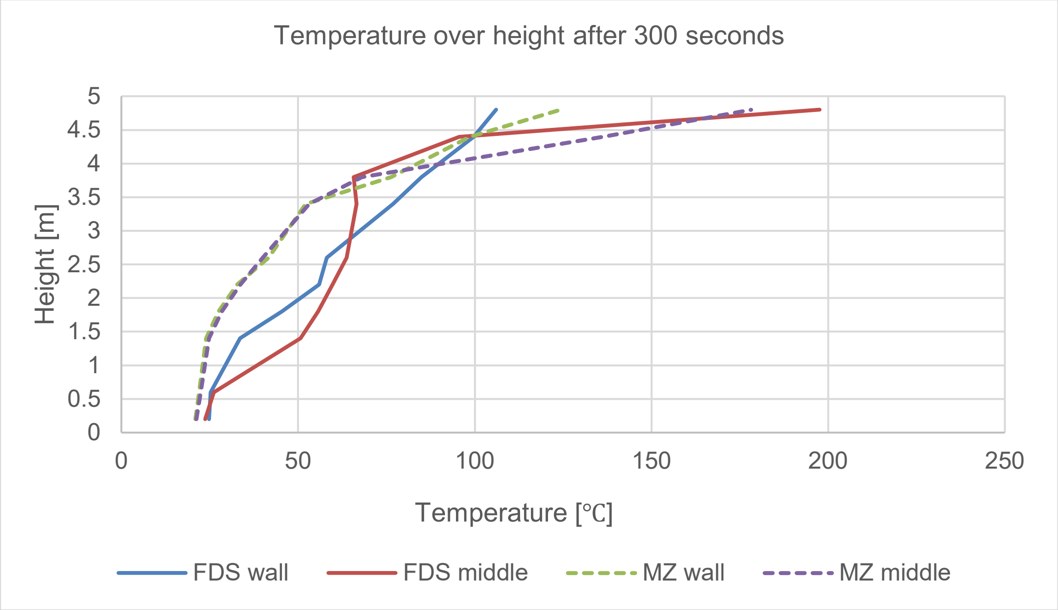

Figure B 10. Temperature over height, wide enclosure with fast growth rate at 300 seconds

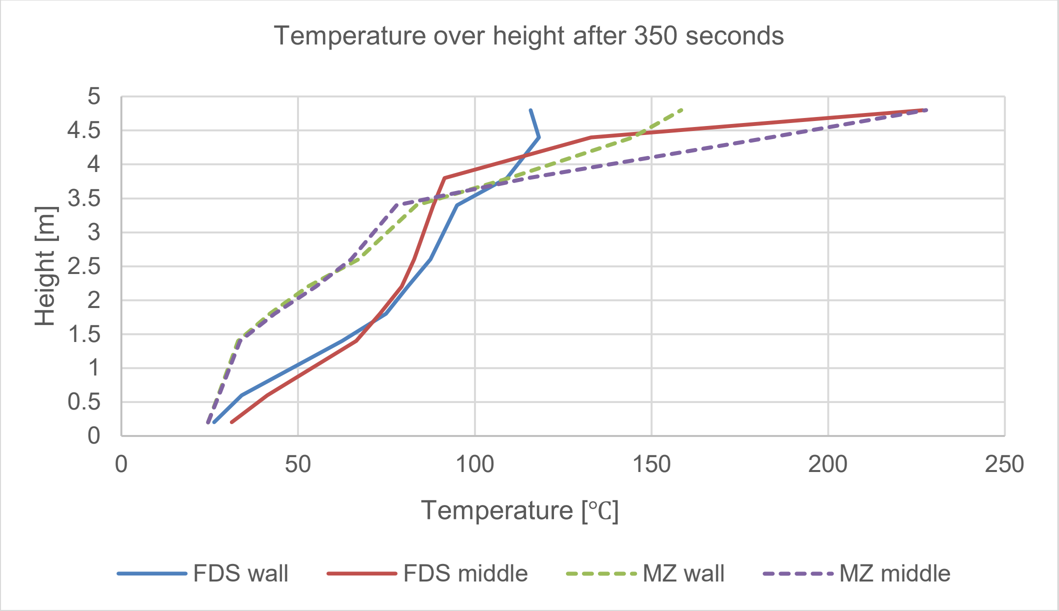

Figure B 11. Temperature over height, wide enclosure with fast growth rate at 350 seconds

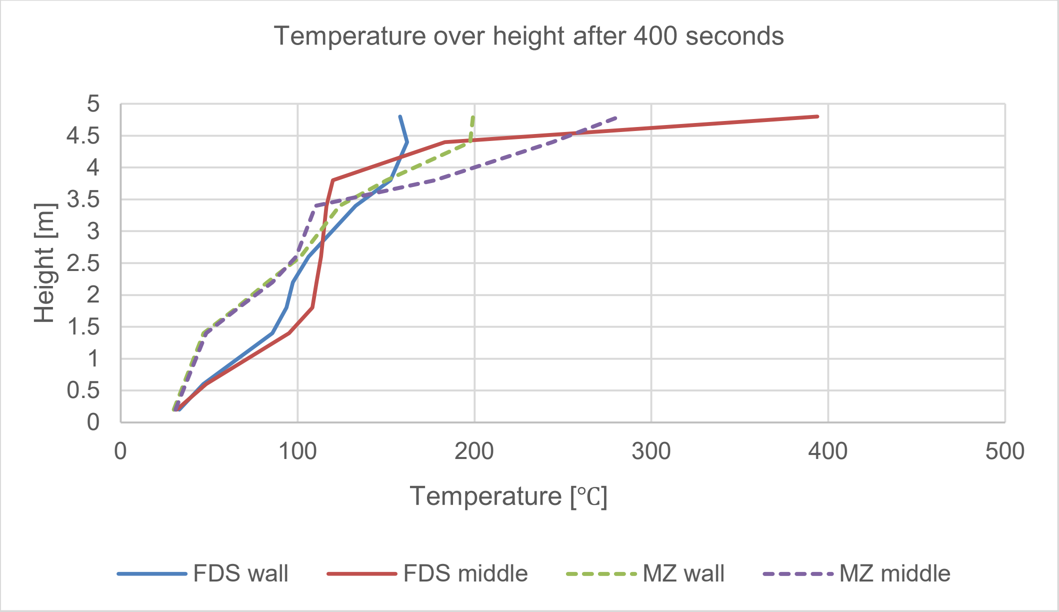

Figure B 12. Temperature over height, wide enclosure with fast growth rate at 400 seconds

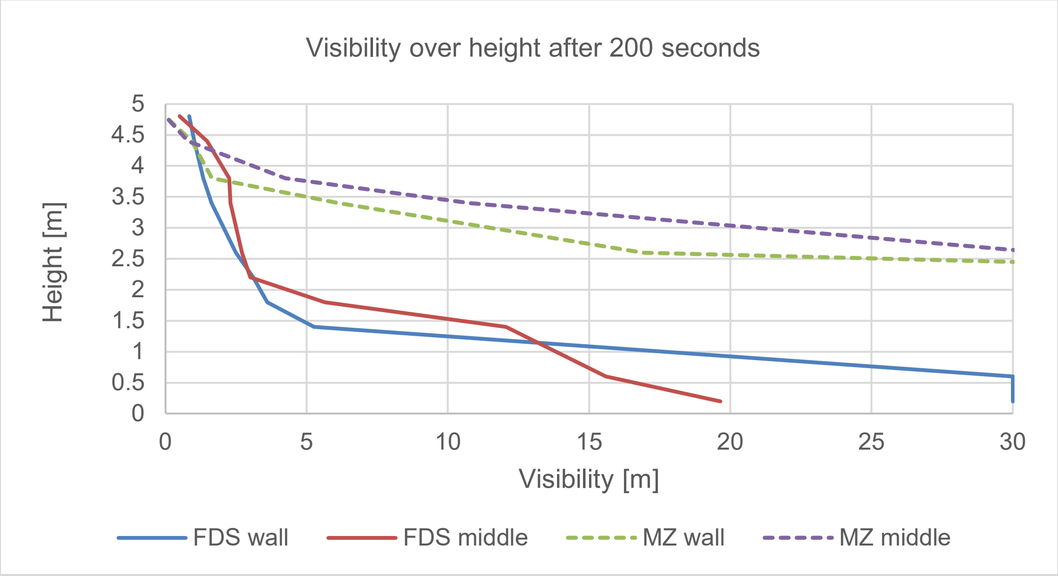

Figure B 13. Visibility over height, wide enclosure with fast growth rate at 200 seconds

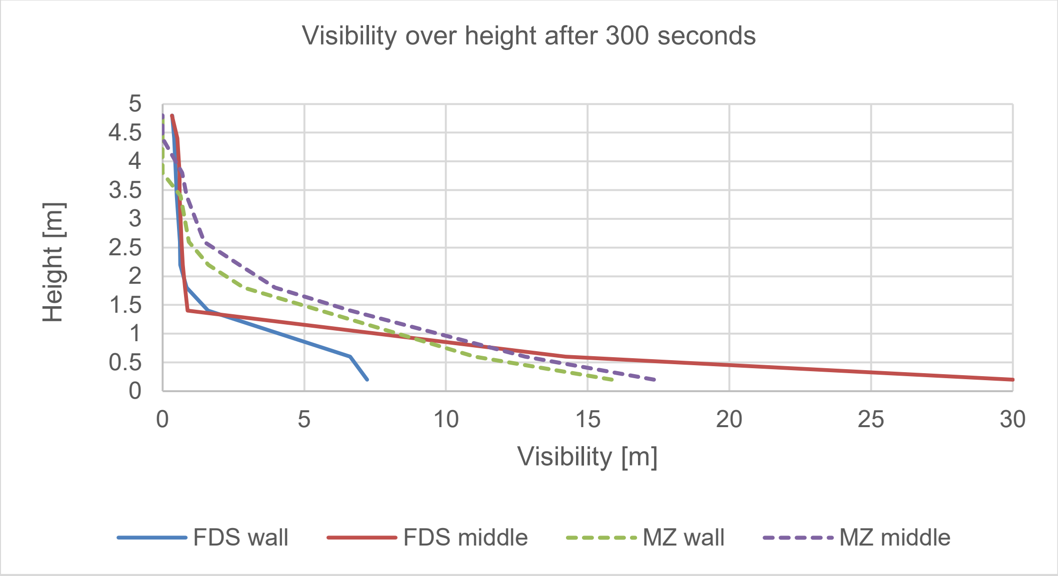

Figure B 14. Visibility over height, wide enclosure with fast growth rate at 300 seconds

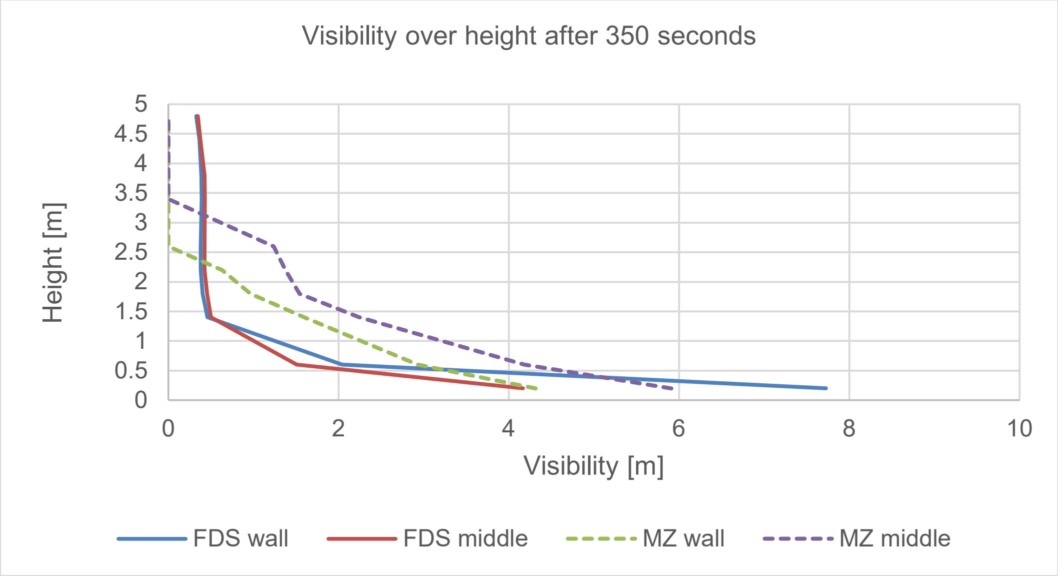

Figure B 15. Visibility over height, wide enclosure with fast growth rate at 350 seconds

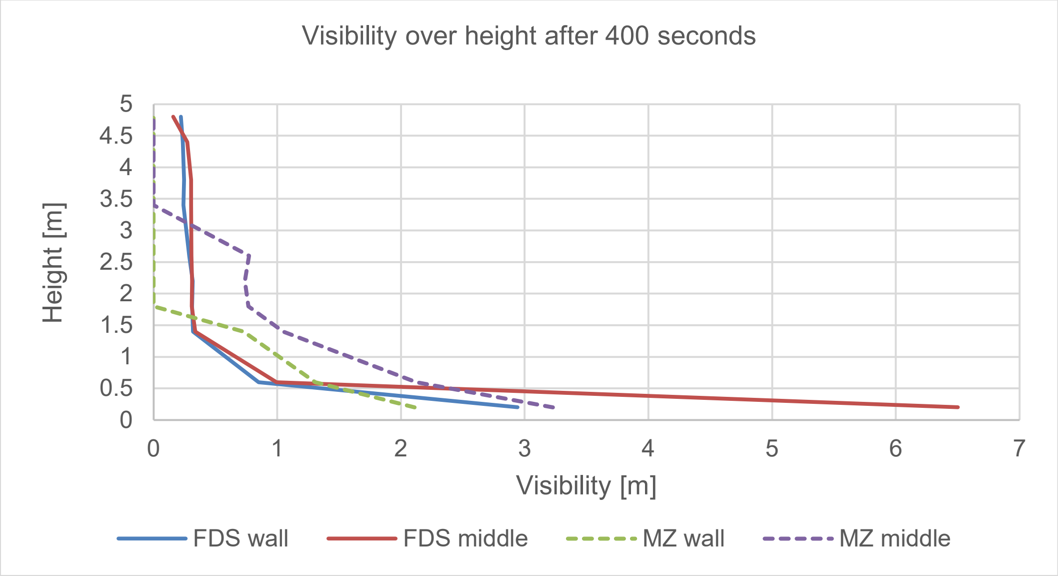

Figure B 16. Visibility over height, wide enclosure with fast growth rate at 400 seconds

Wide enclosure – medium growth rate

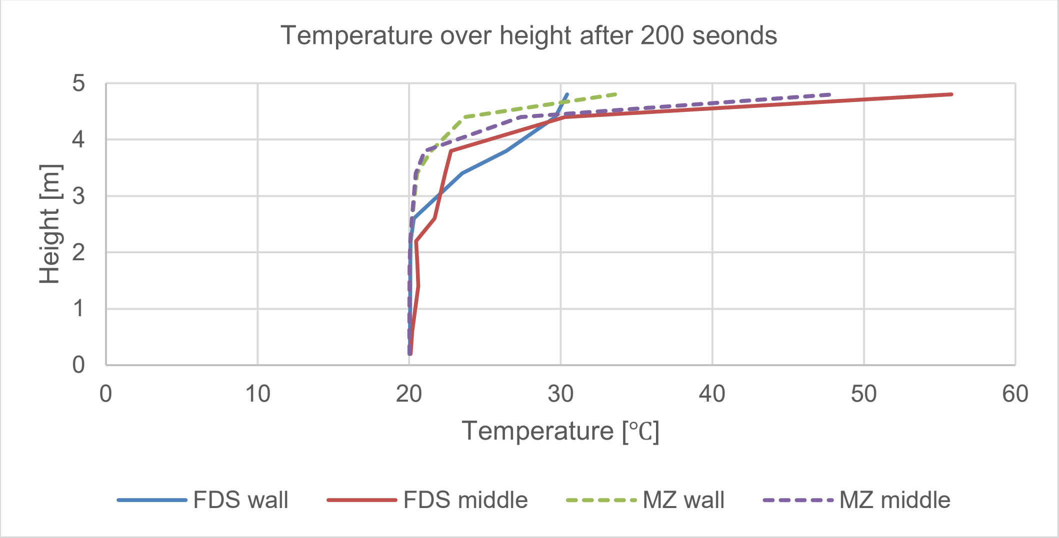

Figure B 17. Temperature over height, wide enclosure with medium growth rate at 200 seconds

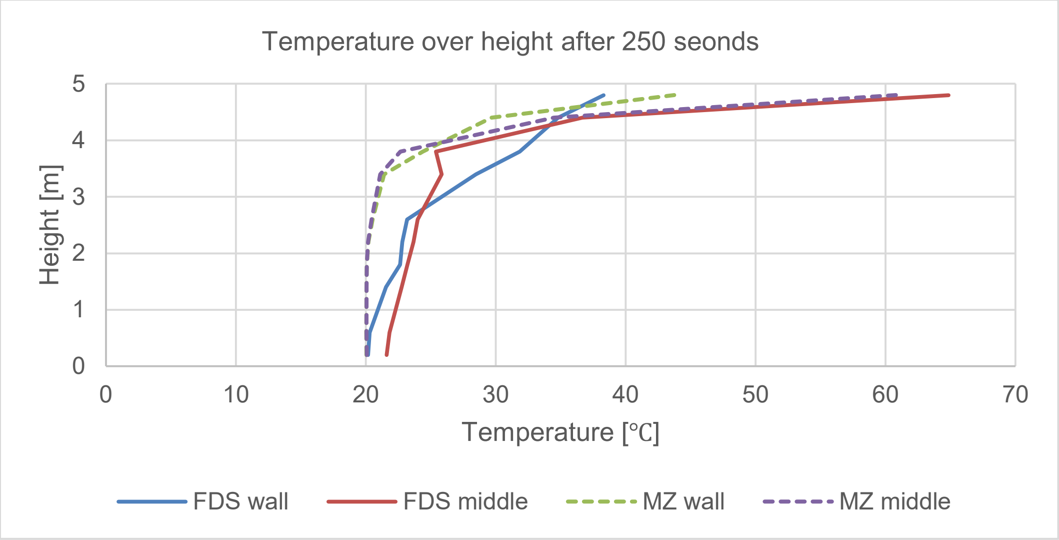

Figure B 18. Temperature over height, wide enclosure with medium growth rate at 250 seconds

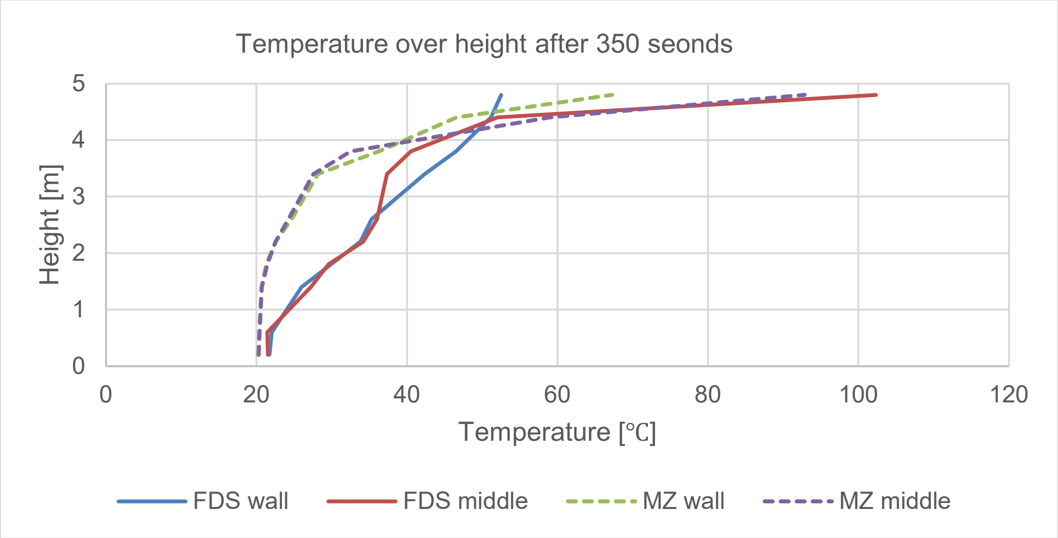

Figure B 19. Temperature over height, wide enclosure with medium growth rate at 350 seconds

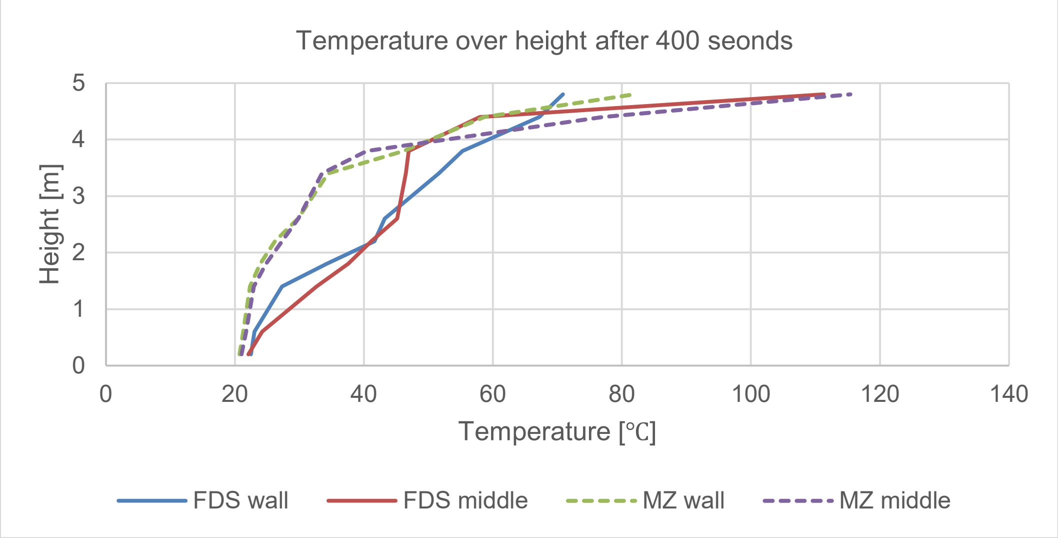

Figure B 20. Temperature over height, wide enclosure with medium growth rate at 400 seconds

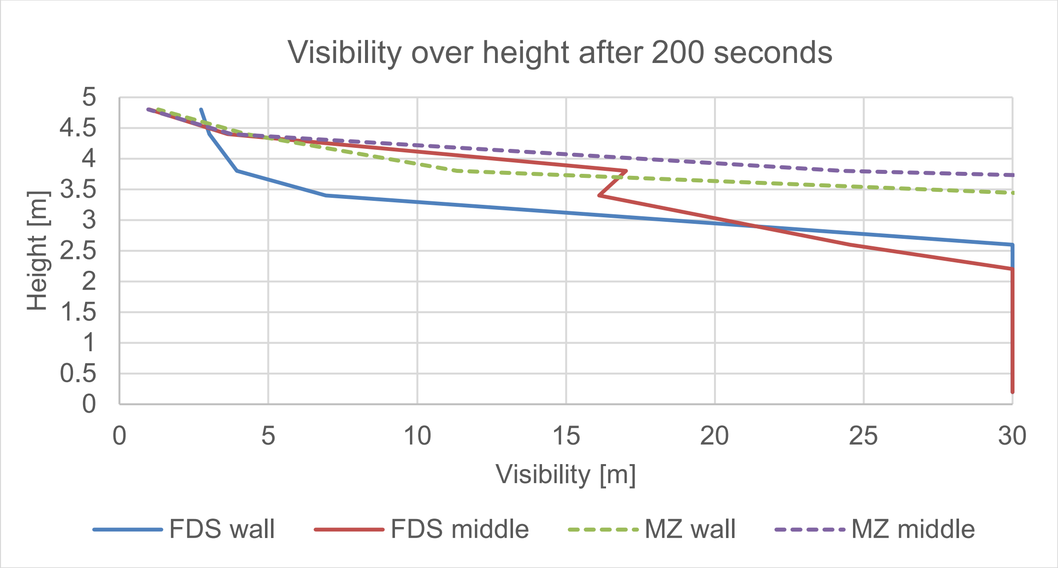

Figure B 21. Visibility over height, wide enclosure with medium growth rate at 200 seconds

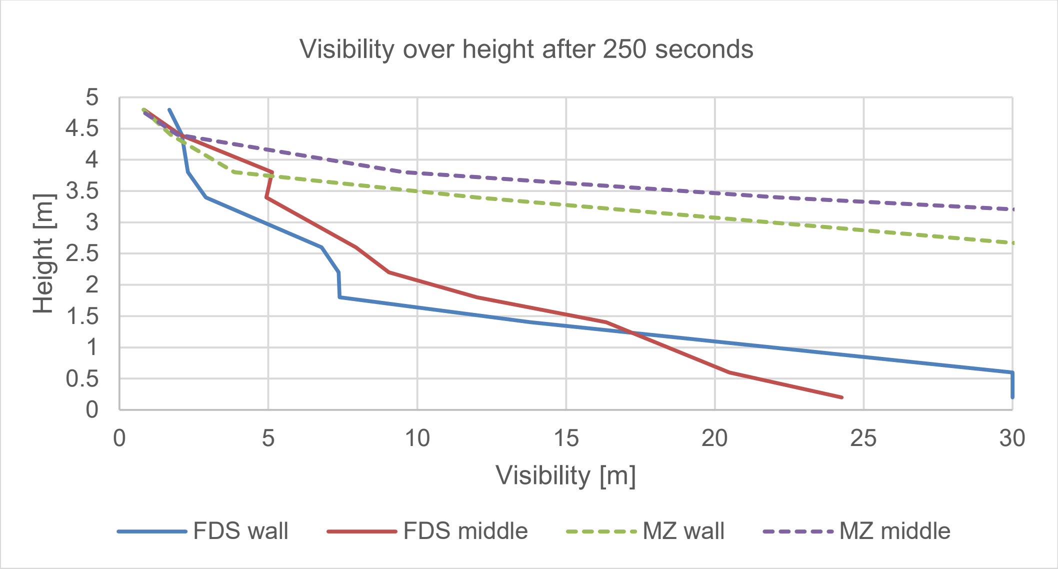

Figure B 22. Visibility over height, wide enclosure with medium growth rate at 250 seconds

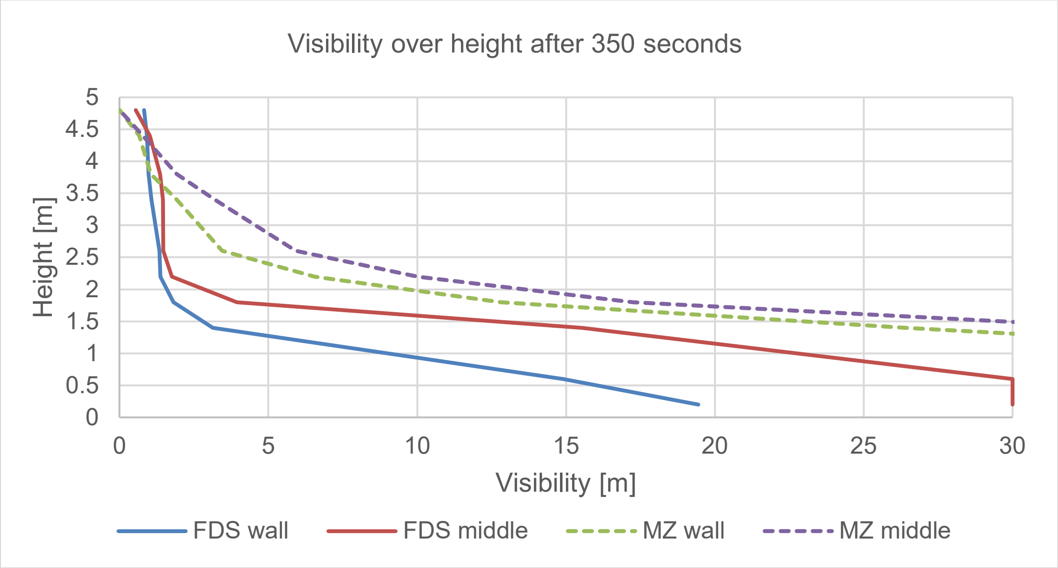

Figure B 23. Visibility over height, wide enclosure with medium growth rate at 350 seconds

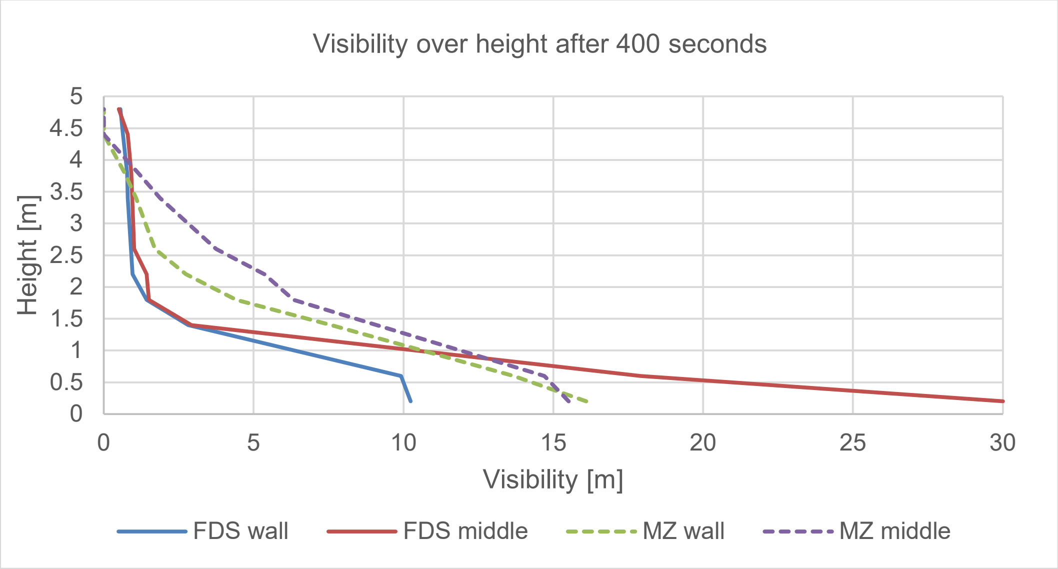

Figure B 24. Visibility over height, wide enclosure with medium growth rate at 400 seconds

Corridor – fast growth rate

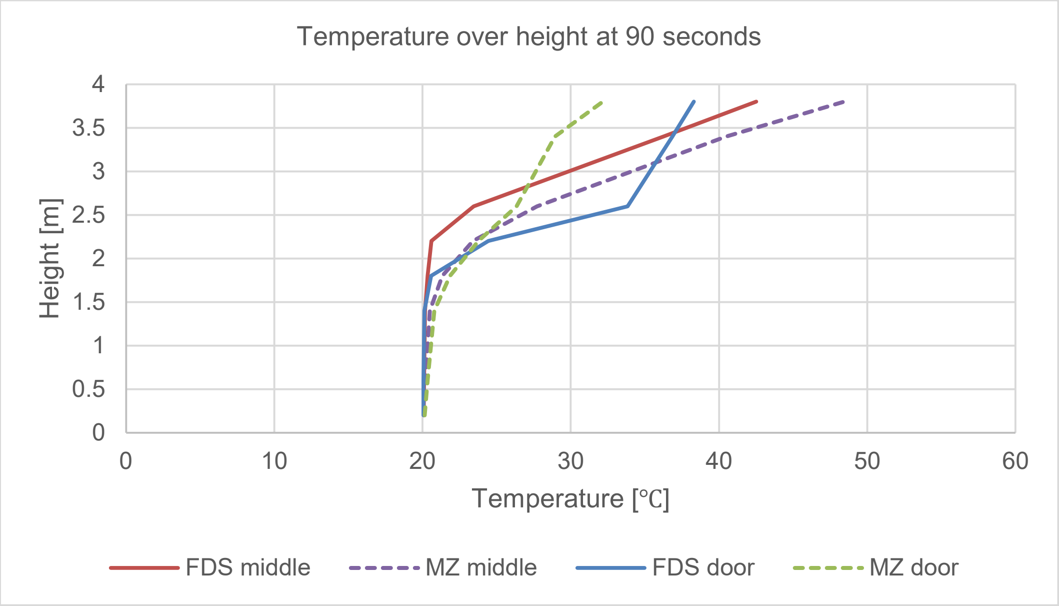

Figure B 25. Temperature over height, Corridor with fast growth rate at 90 seconds

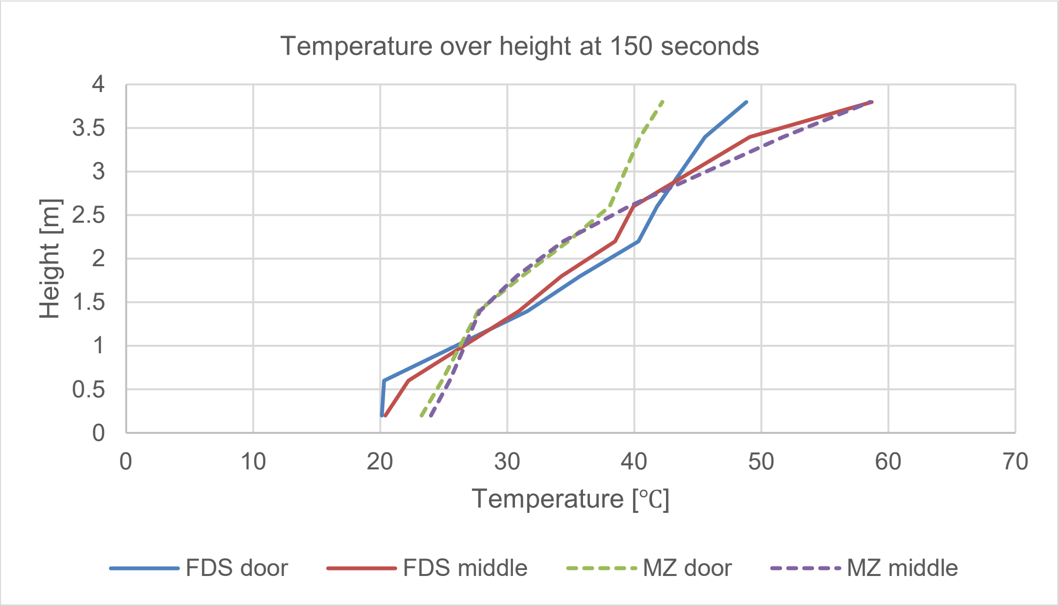

Figure B 26. Temperature over height, Corridor with fast growth rate at 150 seconds

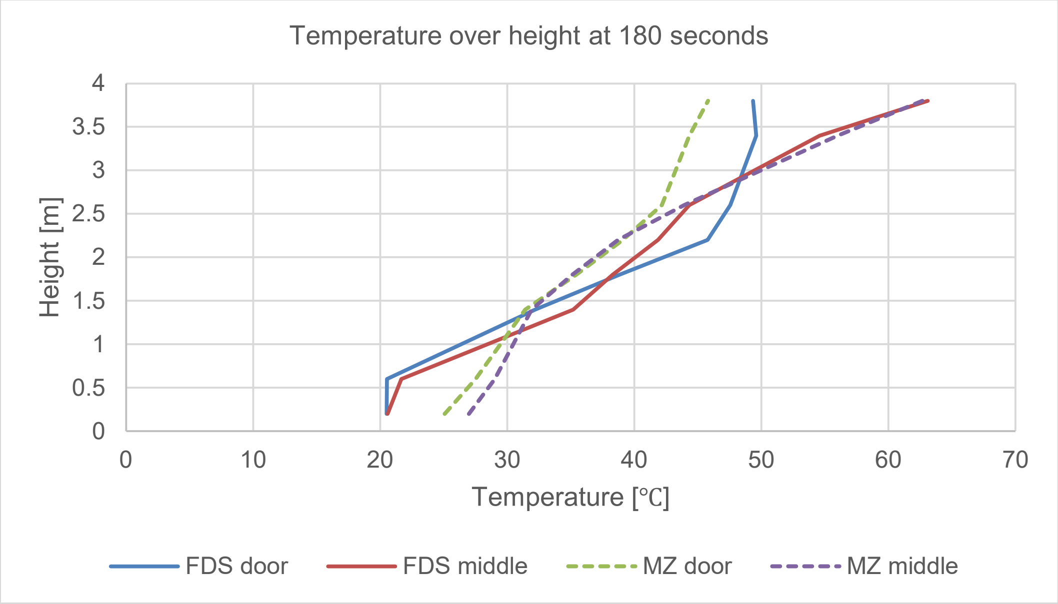

Figure B 27. Temperature over height, Corridor with fast growth rate at 180 seconds

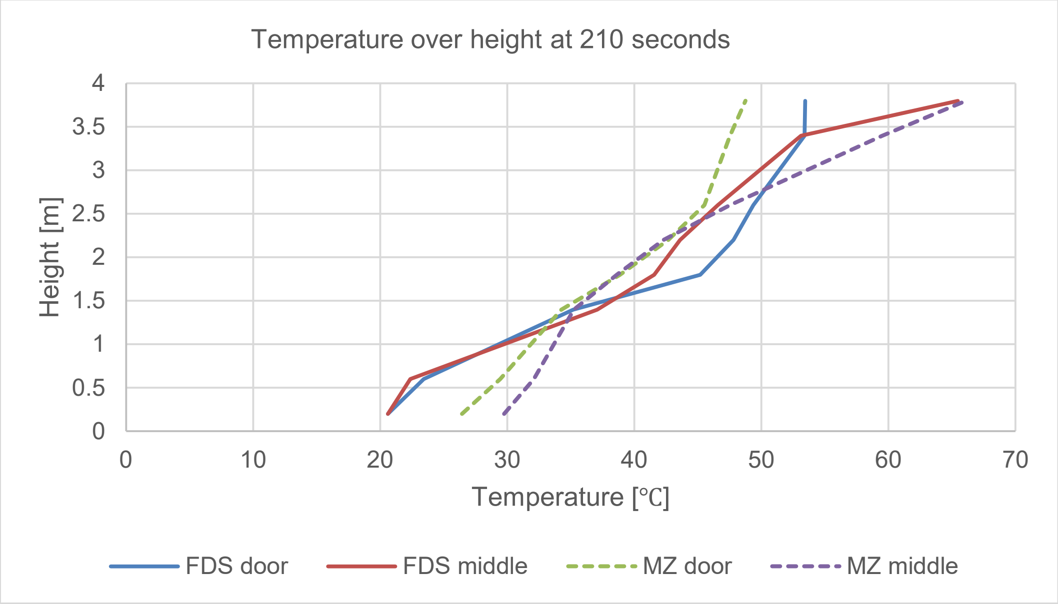

Figure B 28. Temperature over height, Corridor with fast growth rate at 210 seconds

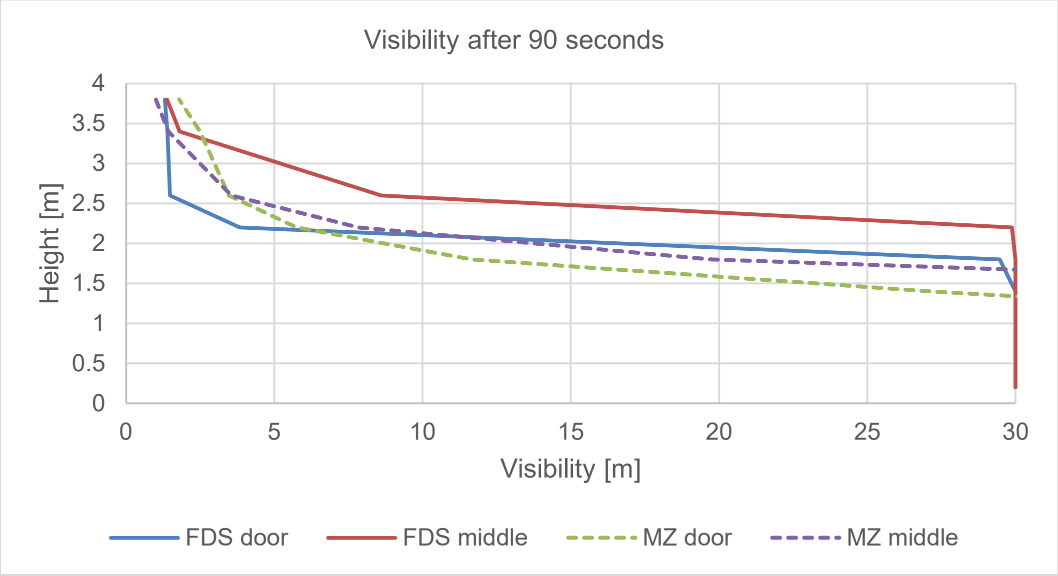

Figure B 29. Visibility over height, Corridor with fast growth rate at 90 seconds

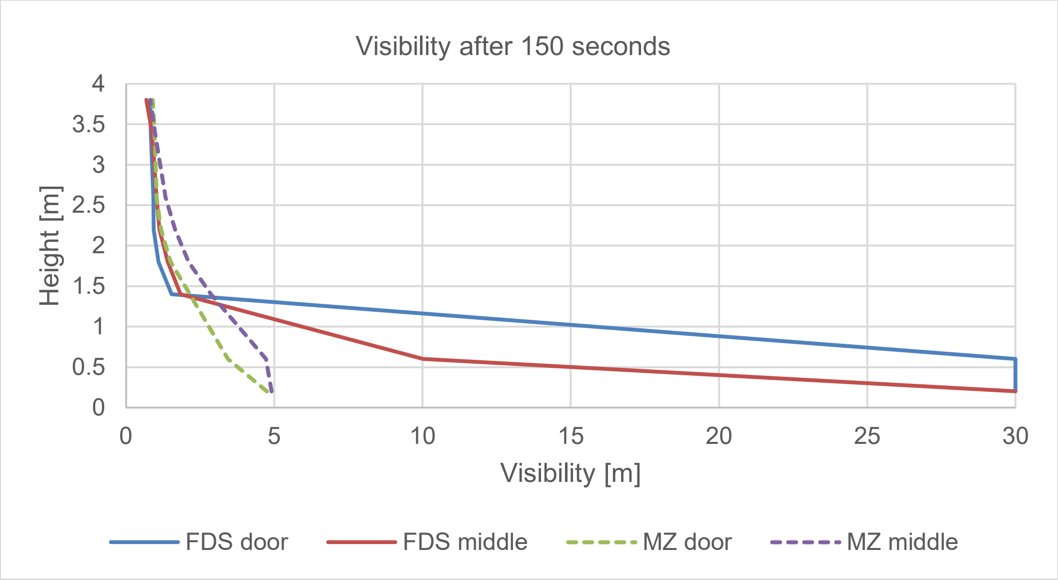

Figure B 30. Visibility over height, Corridor with fast growth rate at 120 seconds

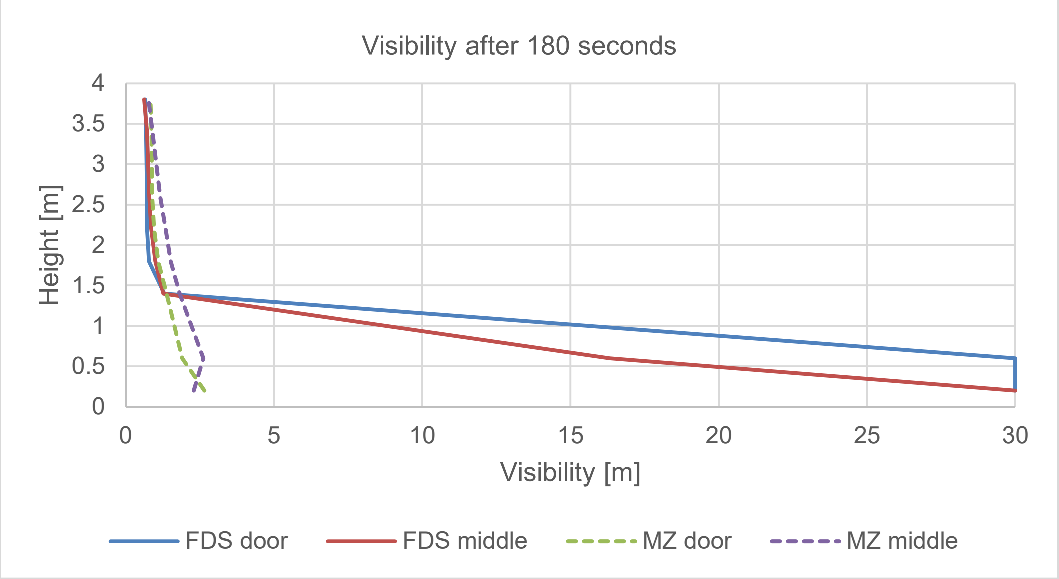

Figure B 31. Visibility over height, Corridor with fast growth rate at 180 seconds

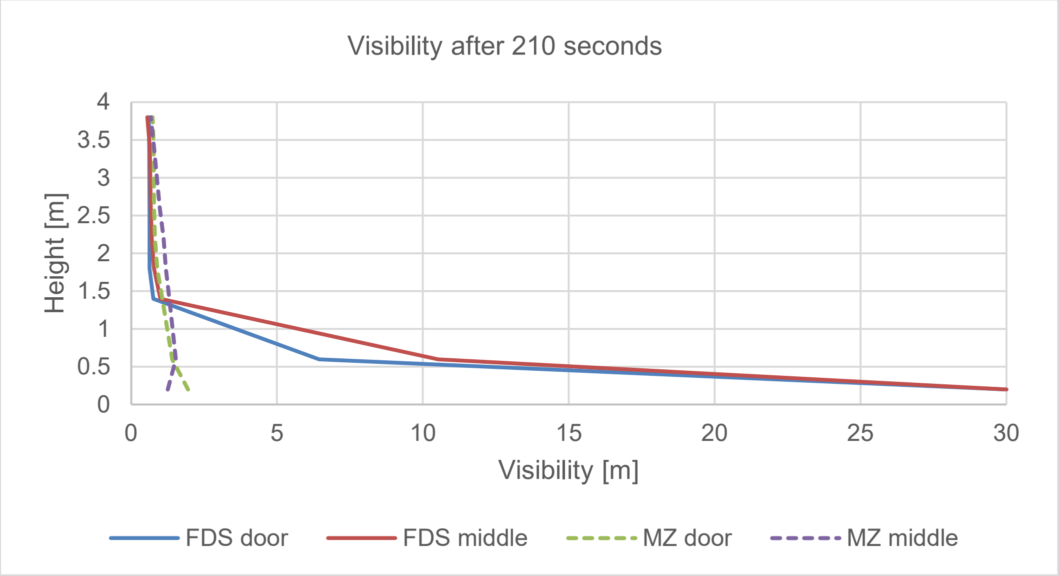

Figure B 32. Visibility over height, Corridor with fast growth rate at 210 seconds

Corridor – medium growth rate

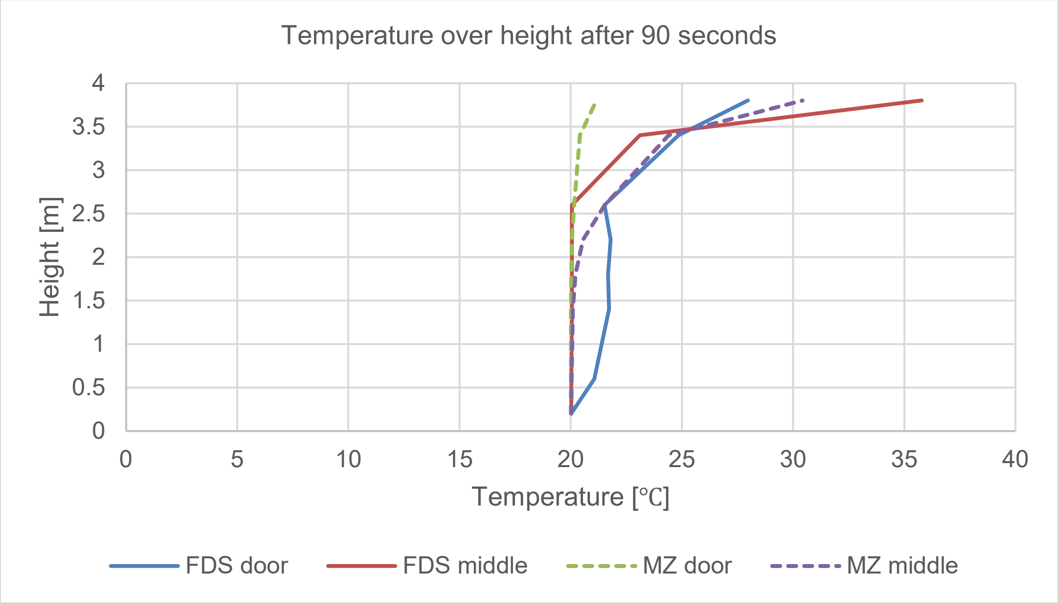

Figure B 33. Temperature over height, Corridor with medium growth rate at 90 seconds

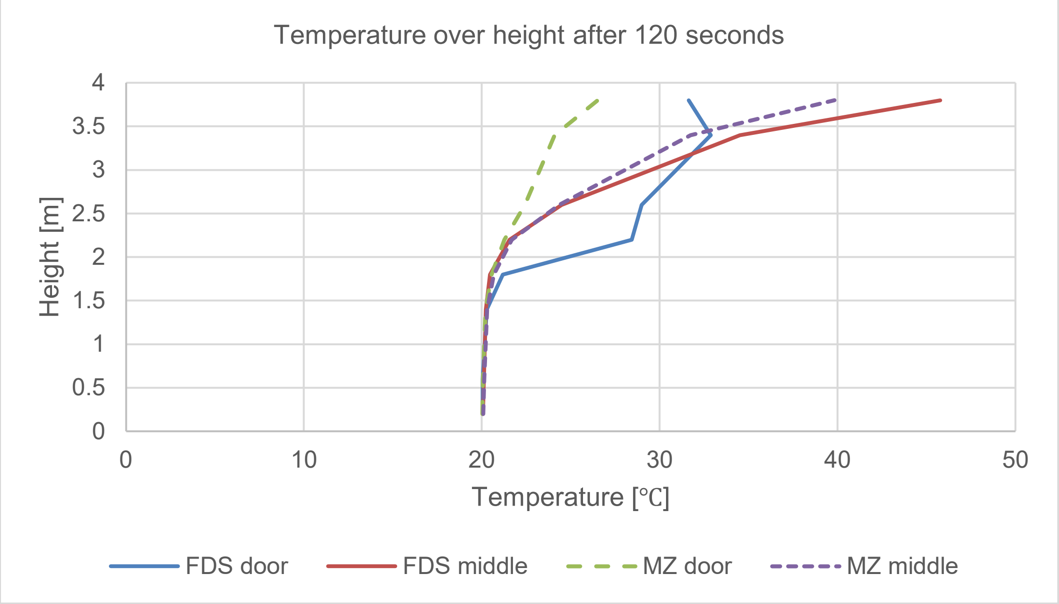

Figure B 34. Temperature over height, Corridor with medium growth rate at 120 seconds

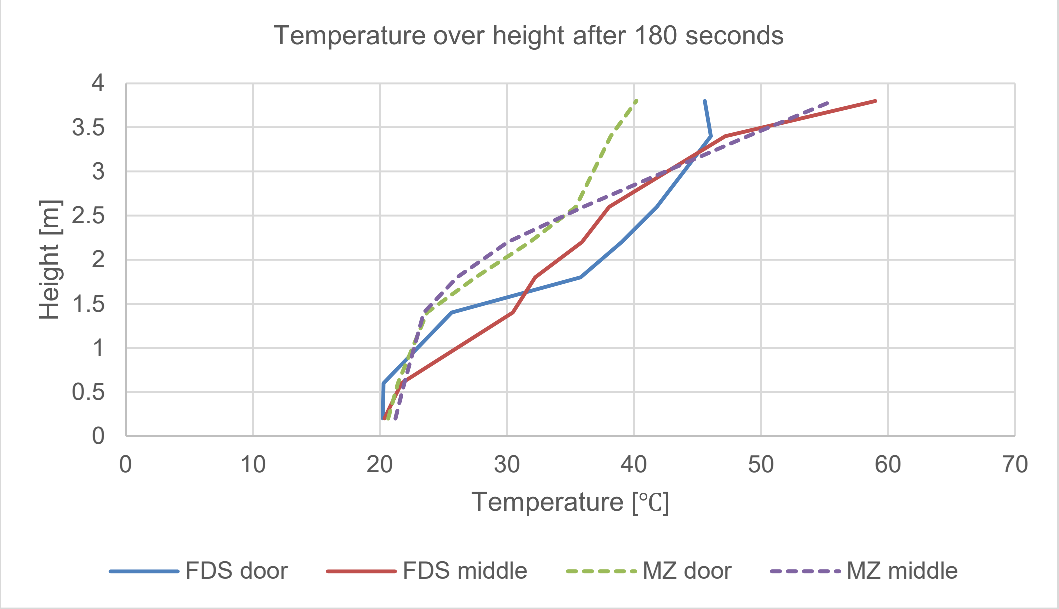

Figure B 35. Temperature over height, Corridor with medium growth rate at 180 seconds

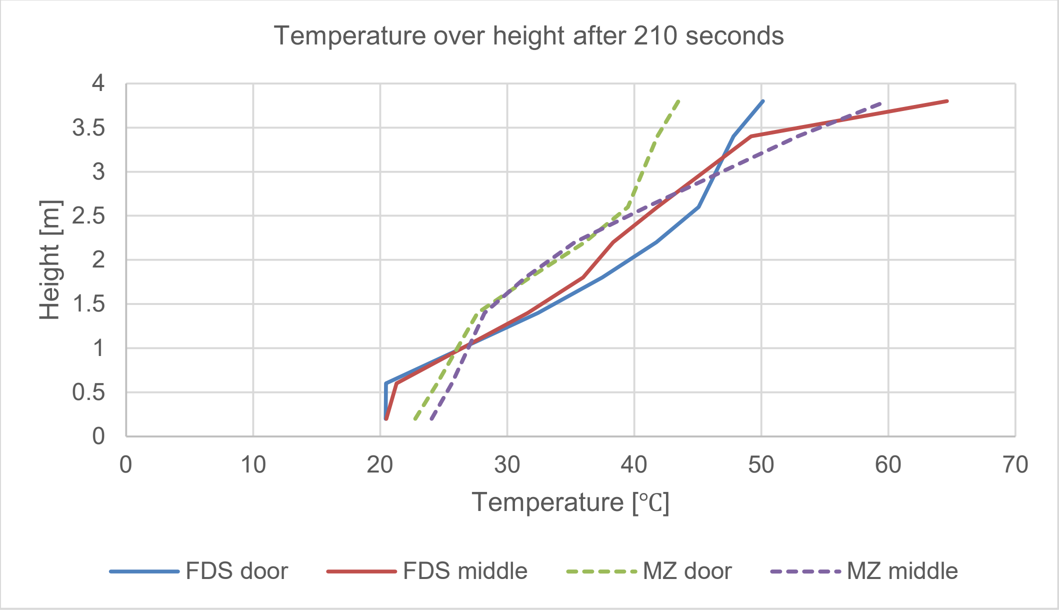

Figure B 36. Temperature over height, Corridor with medium growth rate at 210 seconds

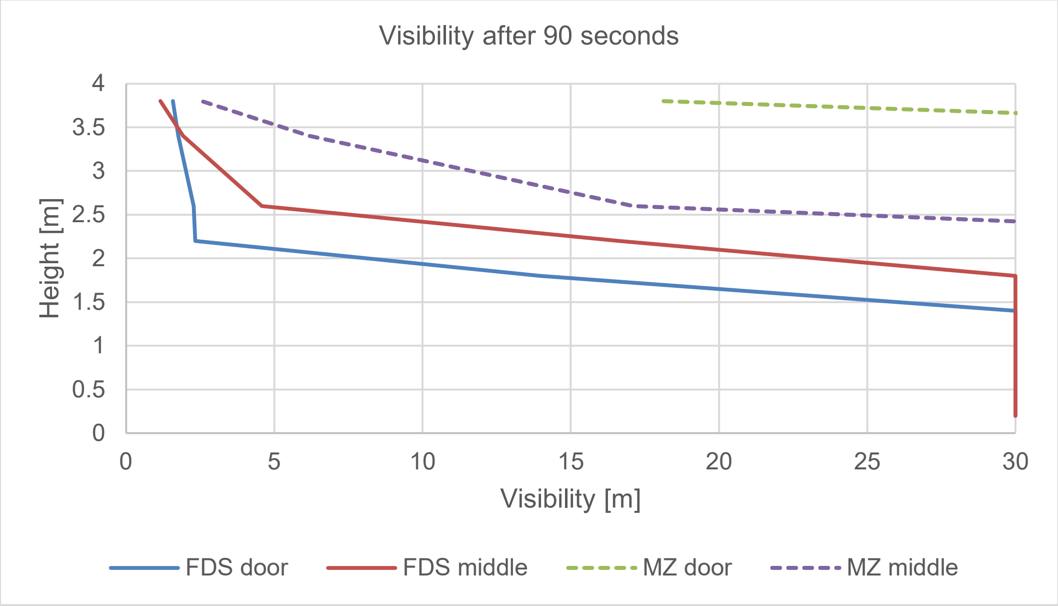

Figure B 37. Visibility over height, Corridor with medium growth rate at 90 seconds

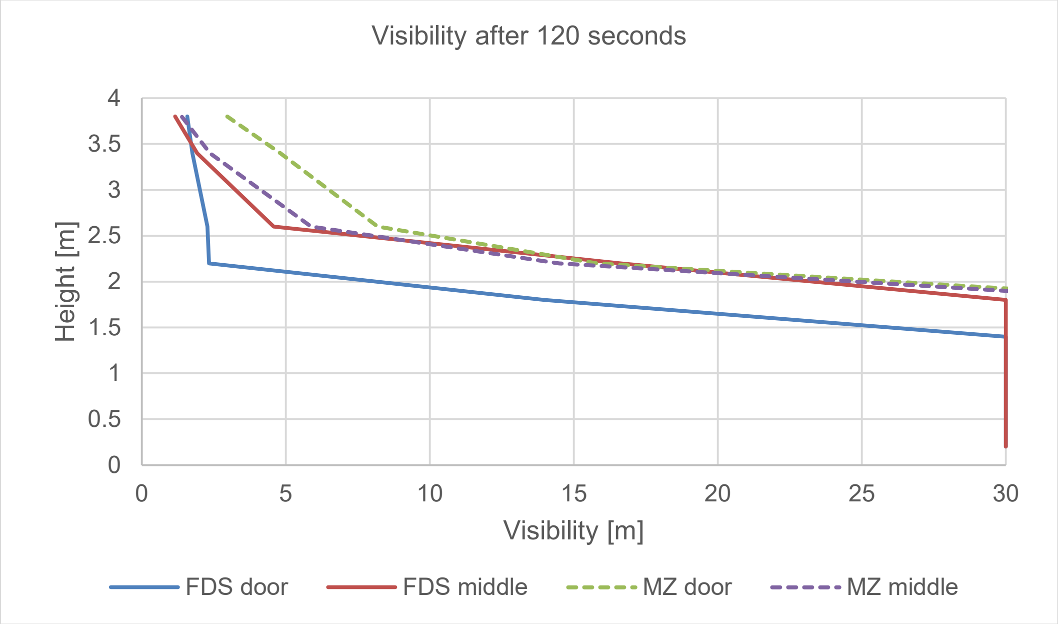

Figure B 38. Visibility over height, Corridor with medium growth rate at 120 seconds

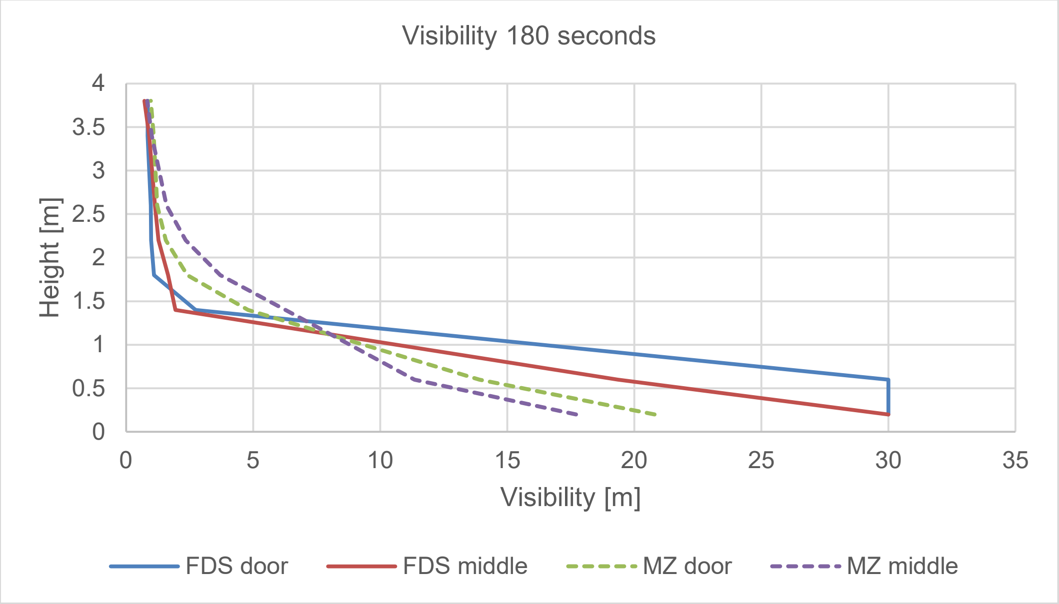

Figure B 39. Visibility over height, Corridor with medium growth rate at 180 seconds

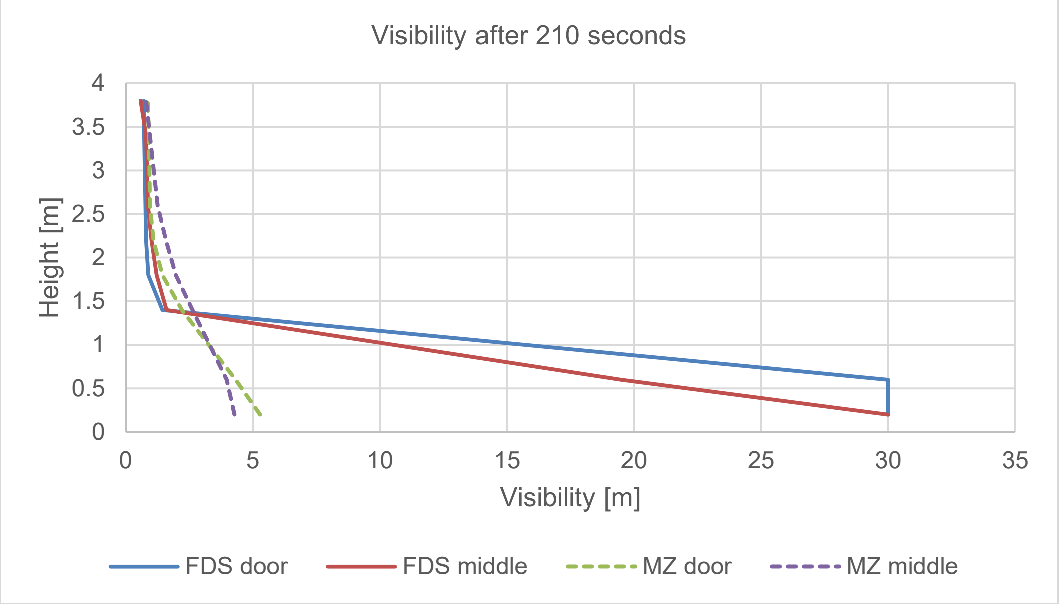

Figure B 40. Visibility over height, Corridor with medium growth rate at 210 seconds

Appendix C

Code for both models for the scenario of the corridor with fast growth rate is presented as an example.

FDS:

```
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&MESH IJK=64, 52, 100, XB=-1.0,2.2, 2.0,4.6, -0.4,4.6/ 2
&MESH IJK=64, 52, 100, XB=2.2,5.4,  -0.6,2.0,         -0.4,4.6/ 3
&MESH IJK=64, 52, 100, XB=2.2,5.4,  2.0,4.6, -0.4,4.6/ 4
&MESH IJK=64, 52, 100, XB=5.4,8.6,  -0.6,2.0,         -0.4,4.6/ 5
&MESH IJK=64, 52, 100, XB=5.4,8.6,  2.0,4.6, -0.4,4.6/ 6
&MESH IJK=64, 52, 100, XB=8.6,11.8,-0.6,2.0,          -0.4,4.6/ 7
&MESH IJK=64, 52, 100, XB=8.6,11.8,2.0,4.6, -0.4,4.6/ 8
&MESH IJK=64, 52, 100, XB=11.8,15.0,        -0.6,2.0,          -0.4,4.6/ 9
&MESH IJK=64, 52, 100, XB=11.8,15.0,        2.0,4.6, -0.4,4.6/ 10
&MESH IJK=64, 52, 100, XB=15.0,18.2,        -0.6,2.0,          -0.4,4.6/ 11
&MESH IJK=64, 52, 100, XB=15.0,18.2,        2.0,4.6, -0.4,4.6/ 12
&MESH IJK=64, 52, 100, XB=18.2,21.4,        -0.6,2.0,          -0.4,4.6/ 13
&MESH IJK=64, 52, 100, XB=18.2,21.4,        2.0,4.6, -0.4,4.6/ 14
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&MESH IJK=64, 52, 100, XB=24.6,27.8,        2.0,4.6, -0.4,4.6/ 18
&MESH IJK=64, 52, 100, XB=27.8,31.0,        -0.6,2.0,          -0.4,4.6/ 19
&MESH IJK=64, 52, 100, XB=27.8,31.0,        2.0,4.6, -0.4,4.6/ 20

&VENT XB=-1.0,31.0,  -1.0,-1.0,   -1.0,5.0,      SURF_ID='OPEN'/
&VENT XB=-1.0,31.0,  5.0,5.0, -1.0,5.0,      SURF_ID='OPEN'/
&VENT XB=-1.0,-1.0,  -1.0,5.0,  -1.0,5.0,      SURF_ID='OPEN'/
```

```
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&VENT XB=-1.0,31.0,  -1.0,5.0,  5.0,5.0,       SURF_ID='OPEN'/


&TIME T_END=600 /


&MISC TMPA=20.0 /


&DUMP NFRAMES=900 /


&DUMP DT_DEVC=1.0,DT_SLCF=5.0,DT_BNDF=1.0/


&SURF ID='WALL', COLOR='GRAY', BACKING='EXPOSED', MATL_ID='CONCRETE',
MATL_MASS_FRACTION=1.0, THICKNESS=0.2/
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MATL_MASS_FRACTION=1.0, THICKNESS=0.2/
&SURF ID='FLOOR', COLOR='GRAY', BACKING='EXPOSED', MATL_ID='CONCRETE',
MATL_MASS_FRACTION=1.0, THICKNESS=0.2/
&SURF ID='ROOF', COLOR='INVISIBLE', BACKING='EXPOSED', MATL_ID='CONCRETE',
MATL_MASS_FRACTION=1.0, THICKNESS=0.2/


&OBST XB=-0.2,30.2, -0.2,0.0, -0.2,4.2, SURF_ID='WALL2' /
&OBST XB=-0.2,0.0, -0.2,4.2, -0.2,4.2, SURF_ID='WALL' /
&OBST XB=-0.2,30.2, 4.0,4.2, -0.2,4.2, SURF_ID='WALL' /
&OBST XB=30.0,30.2, -0.2,4.2, -0.2,4.2, SURF_ID='WALL' /
&OBST XB=-0.2,30.2, -0.2,4.2, -0.2,0.0, SURF_ID='FLOOR' /
&OBST XB=-0.2,30.2, -0.2,4.2, 4.0,4.2, SURF_ID='ROOF' /


&HOLE XB=-0.4,0.2, 2.0,3.0, 0.0,2.0 /
&HOLE XB=29.8,30.4, 2.0,3.0, 0.0,2.0 /


&REAC ID='BBRAD_1', FYI='BBRAD_1MJ/kg, Wood', C=3.4, H=6.2, O=2.5, N=0.0,
HEAT_OF_COMBUSTION=1.6E4, SOOT_YIELD=0.1 /
```

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&RAMP ID='FIRE_RAMP_Q', T=5, F=0.006/
&RAMP ID='FIRE_RAMP_Q', T=10, F=0.0235/
&RAMP ID='FIRE_RAMP_Q', T=15, F=0.0528/
&RAMP ID='FIRE_RAMP_Q', T=20, F=0.094/
&RAMP ID='FIRE_RAMP_Q', T=25, F=0.1469/
&RAMP ID='FIRE_RAMP_Q', T=30, F=0.2115/
&RAMP ID='FIRE_RAMP_Q', T=35, F=0.2879/
&RAMP ID='FIRE_RAMP_Q', T=40, F=0.376/
&RAMP ID='FIRE_RAMP_Q', T=45, F=0.4759/
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