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Numerical Modelling of Water Mist Systems in Protection of Mass Timber Residential Buildings

Author(s): Nour Elsagan, Ph.D. and Yoon Ko, Ph.D.

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Numerical Modelling of Water Mist Systems in Protection of Mass Timber Residential Buildings

Nour Elsagan, Ph.D. and Yoon Ko, Ph.D.

Executive Summary

This report presents the findings from a simulation parametric study to investigate the use of water mist systems for a residential compartment fire involving exposed mass timber structures. The fire and suppression models were first validated against experimental data obtained from the NRC fire tests that were conducted under the same project. Seventeen simulations were conducted using Fire Dynamic Simulator (FDS) software. The following parameters were investigated;

1- Effect of fuel arrangement and location on fire severity in exposed wood compartment
2- Effect of different finishing on fire severity in compartment
3- Fire and suppression in open space vs compartment
4- Effectiveness of water mist systems in fire suppression in compartments with different finishing.

The results show the effectiveness of the water mist system in suppressing the fire in exposed wood compartments where a high heat release is expected due to the high fuel load.

1 Introduction

The International Code Council (ICC) has recently accepted the proposed changes for its 2021 International Building Code (IBC) to allow a maximum of 9 storeys of exposed mass timber construction for residential and business occupancies with sprinkler protection. The proposed changes also allow exposed mass timber for all occupancies with varying height limitations as long as sprinkler protection is provided.

Water-based systems are the most commonly used suppression systems in buildings. They are classified as sprinklers and water mist systems according to the droplet size of the injected spray. According to NFPA 750 (National Fire Protection Association standard on Water Mist Fire Protection Systems), water mist systems discharge droplets less than a diameter of 1000 μm with Dv0.99 (i.e., 99% of the total volume of water being discharged is in drops with diameters less than 1000 μm), while the droplet size in the conventional sprinkler systems is around 5000 μm. Conventional fire sprinklers, which discharge a large volume of water, are the most commonly used systems in buildings due to their proven effectiveness in suppressing fire and preventing fire spread beyond the compartment of fire origin.

However, in application to mass timber buildings, there are concerns that conventional sprinkler systems could create post-discharge water damage including mold problems which is a major issue for the insurance industry [1,2]. As a potential alternative solution to sprinkler systems, the use of water mist systems is considered for the protection of timber buildings because they use significantly less amounts of water compared to sprinkler systems. Water mist systems are widely used in the fire protection of electronic equipment and machinery rooms in ships and industrial buildings applications. However, their use in the protection of residential and office buildings is still limited. Therefore, there is a research gap due to the limited data available on the performance of water mist systems in such buildings particularly those employing exposed timber structures.

Water mist system standards [NFPA 750 [3], FM 5560 [4], CEN 14972 [5]] require a water mist system to be evaluated through full-scale fire tests by qualified testing laboratories. Recently, timber buildings (both light timber and heavy timber buildings) have been studied widely through numerous fire tests to examine their fire performance and to develop design requirements. Although no test in the literature reports the effectiveness of water mist systems in heavy timber buildings, some water mist tests were conducted in residential fire scenarios.

The Swedish National Testing and Research Institute [6] tested high pressure water mist nozzles and three different types of residential sprinklers (a recessed pendent, concealed pendent and a horizontal wide wall, listed per NFPA 13R) for a living room fire scenario. It was observed that water mist systems drew a larger amount of fresh air to the fire, which resulted in more turbulent burning as compared to the sprinkler test. It was also concluded that high wall wetting is desirable for a water mist nozzle to minimize wall damage. In all the high ceiling living room tests, wall damage was observed and the fire redeveloped and burned continuously even with the mist system active. Consequently, the ceiling temperature in the living room and in the connected bedroom were high. The Research Institutes of Sweden (RISE) [7] investigated the benefits in using early activation of residential sprinklers with lower RTI (Response Time Index) and activation temperature ratings. The tests used either a simulated or authentic upholstered chair placed in a corner of the test compartment dimensioned with 3.66 m wide, 3.66 m long and 2.5 m high. Two low-pressure and two high pressure water mist systems were also tested for the same fire set-up for comparisons with sprinkler systems. It was reported that the performance of the water mist nozzles were comparable or better than the residential sprinkler system at approximately half the water flow rate for the tested fire scenarios. That was confirmed by measuring the ceiling temperature with sprinkler systems and water mist systems. The differences between the low and high pressure water mist systems were small. The smallest fire damages were observed in the tests with high water spray rates.

The current computational power coupled with advances in computational fluid dynamics (CFD) simulations and further understanding of fire dynamics and fire chemistry make CFD fire simulations a valuable tool. FDS [8] is an open source code that is widely used by the fire research community in modelling fire plume and thermal driven smoke flows. Several studies investigated water mist systems using FDS. Kim and Ryou [9] tested the fire extinguishing time and the temperature fields in the enclosed compartment for hexane and methanol pool fires. They simulated the experiments using FDS and found that the simulated ceiling temperature and oxygen mole fraction in the compartment comparable to the test results. Following that work, Ferng and Liu [10] numerically investigated the fire suppression mechanisms for the water mist with various droplet sizes. According to their simulations, they concluded that the O_2 displacement mechanism dominates the fire suppression for droplet sizes that were less than 500 μm, while the suppression mechanism using relatively larger-size droplets (>500 μm) was direct cooling.

Yang et al. [11] experimentally tested water mist suppression of a 6 MW fire in a room. They simulated the experiments using FDS and found that the model under-predicted the extinguishing time measured in the experiment by 12%. Similar experiments were conducted by Jenft et al. [12], where water mist was applied on pool fire in a room. Two scenarios were investigated; early application of water mist system on a developing fire (and ambient environment) and late application of water mist system on a developed fire (and high-temperature environment). The simulation results showed that the suppression model based on an exponential reduction of the fuel mass loss produced a sharp fire decrease, which did not exactly follow experimental observations for cases involving inerting effects. Both studies [11,12] recommended the development of enhanced numerical models to improve predictions of the fire extinguishment characteristics using water mist and conducting more experiments on fire extinguishment by water mist for the validation of the resulting numerical model.

Several research efforts have been undertaken by the Technical Research Centre of Finland (VTT) to validate and enhance the predictions of FDS in modeling water mist sprays. Hostikka et al. [13] modelled one industrial spray nozzle and three fire suppression nozzles in FDS and showed that the spray properties can be accurately predicted. The simulations were able to predict the spray diameter profiles of the nozzles. The effect of the water spray pressure on the air entrainment was also correctly predicted. The radiation attenuation results were within the experimental uncertainty when a relatively fine grid was used. In addition, they concluded that the spatial resolution should always be in balance with the statistical representation of the spray (number of droplets inserted per second) in order to better predict the radiation attenuation. VTT [14] reported the ability of FDS to accurately predict the activation of the nozzles. Simulations were compared against a set of experiments conducted in a 10 m x 20 m room at 2.5 m or 4 m height and with a 1.7 MW heptane pool as the fire source. A very good agreement was seen between experimental and simulation results. Cooling of fire plumes in FDS by water mist was also evaluated for heat release rates between 5–20 MW [14]. Moreover, an improved flame extinguishing model was implemented in FDS and validated against a number of experiments in the cup burner apparatus. This improved the capability of FDS to predict the performance of full-scale water mist fire suppression systems.

2 Objectives

In this work, a parametric study was conducted to numerically investigate the performance of water mist systems in residential compartments using FDS. First, the model was validated against data from experiments recently conducted by NRC. Then, several parameters were investigated;

- Open space vs closed compartment
- The arrangement of the components of the fuel package in the compartment
- The location of the fuel package in the compartment
- Different combination of finishing (exposed wood and gypsum board-protected) in the compartment

3 Investigated parameters

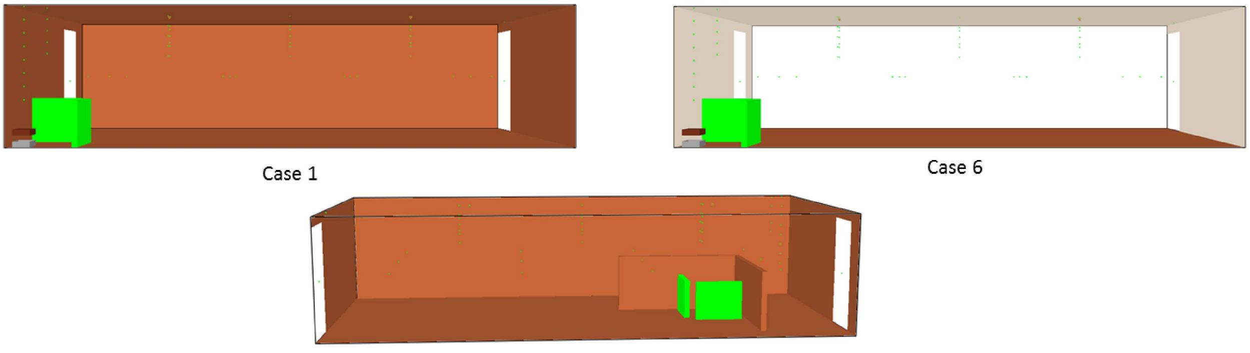
Table 1 shows the simulations conducted in this study. The simulations matrix was formulated to investigate the following;

1- Effect of fuel arrangement and location on fire severity in an exposed wood compartment
2- Effect of different finishings on fire severity in compartment
3- Fire and suppression in an open space vs compartment
4- Effectiveness of water mist systems in fire suppression in compartments with different finishing.

These parameters resulted in 12 fire simulations and 7 fire suppression simulations using water mist. The domains of cases 1, 5 and 6 are presented in Fig. 1 .

Table 1. Simulations matrix

Case no.	**Walls**	**Ceiling**	**Fuel package location**	**Fuel arrangement**	**Type of simulation**
1	Wood	Wood	Corner	Standard	Fired & suppression
2	Wood	Wood	Corner	Arrangement 2	Fired
3	Wood	Wood	Corner	Arrangement 3	Fired
4	Wood	Wood	Center	Standard	Fired
5	Wood	Wood	Under one nozzle	Standard	Fired
6	Gypsum board	Gypsum board	Corner	Standard	Fired & suppression
7	Wood	Gypsum board	Corner	Standard	Fired & suppression
8	Beside fuel package gypsum board, others wood (wall 1)	Wood	Corner	Standard	Fired
9	Beside fuel package gypsum board ,others wood (wall 2)	Wood	Corner	Standard	Fired
10	One of the walls away from fuel package wood, others gypsum board (wall 3)	Wood	Corner	Standard	Fired
11	One of the walls away from fuel package wood, others gypsum board (wall 4)	Wood	Corner	Standard	Fired
12	Open space	Wood	-	Standard	Fired & suppression


Case 1

Case 6

Case 5

Fig. 1. Domains of some of the investigated cases

4 Model description

A domain of dimensions 9.6 m (L) × 4.8 m (W) × 2.4 m (H) was built in FDS. The length and width were based on the coverage area of the nozzle, as recommended by UL 2167 [1]; where the length and width are equal to double the nozzle spacing and the nozzle spacing; respectively. In case of closed compartment simulations, ventilation was provided by 2 doors of 2.2 m height each. One of the doors was 1.05 m wide and located at the corner opposite to the fuel, and the other one was 0.9 m wide and located at the same side of the fuel and 0.5 m from the corner. Fig. 2 shows a schematic diagram of the domain with all dimensions. The computational grid size was 0.1 m (L) × 0.1 m (W) × 0.1 m (H). This resulted in 110,592 cells that were divided into 12 meshes to decrease the computational time.

One simulation was conducted without the compartment wall to investigate the impact of compartmentation on the performance of fire suppression systems. In this simulation, the boundaries of the domain were set as "open".

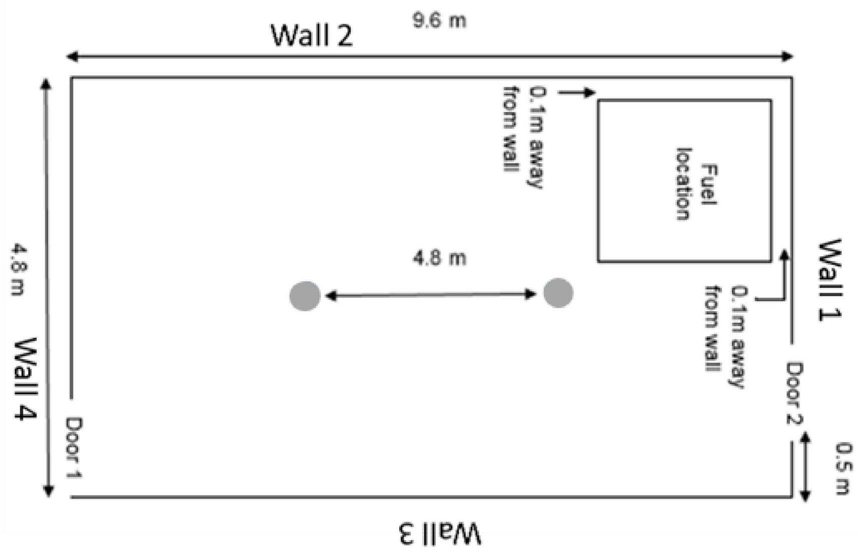


Fig. 2. Schematic diagram showing the dimensions of the enclosed compartment domain and location of nozzles (grey circles).

Two types of wall finishing were implemented in the simulations; exposed wood and gypsum-board protected. The model developed by Gomaa and Elsagan [2] was used for simulating the ignition of wood. The dehydration of Gypsum-board was adopted from Thomas [3]. In all simulations, the floor was made up of wood to replicate a hardwood floor.

Based on the standard test protocols from UL 2167 [1] , BS 8458 [4] and FM 5560 [5], a wood crib and simulated furniture were used as fuel for the fire. The crib had cross sectional area of $0.3 \times 0.3\ m^2$ and 0.15 m thickness and placed at 0.15 m from the ground. The mass of the crib was 6.156 kg and can release energy with a total of 107 MJ. Two polyurethane foam (PUF) sheets were used to simulate the furniture. The dimensions of the sheet were 0.865 m width, 0.075 m thick and 0.775 m high. The mass of the PUF sheets was 2.5 kg and can release energy with a total of 58.75 MJ. The ignition of PUF was simulated using the model by Bilbao et al. [6].

The PUF is ignited in the simulation using hot particles. A burner is used for igniting the wood crib. The heat release rate per unit area (HRRPUA) from the burner follows a profile to match the experimental results. The HRRPUA profile is shown in Fig. 3. The burner is placed on the ground in a steel pan beneath the crib.

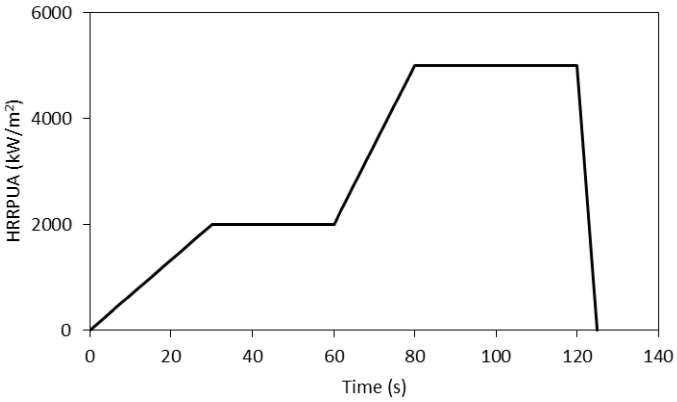


Fig. 3. HRRPUA of the burner igniting the wood crib

The PUF and wood crib fire were simulated in 3 different arrangements to investigate how these fuel arrangements affect fire spread to the adjacent walls and ceiling. As shown in Fig. 4, the three arrangements were simulated in the wood compartment. The standard arrangement is presented in Fig. 4-1, where the crib was placed at the corner at 10 cm away from the walls and the PUF sheets were placed opposite to the crib.

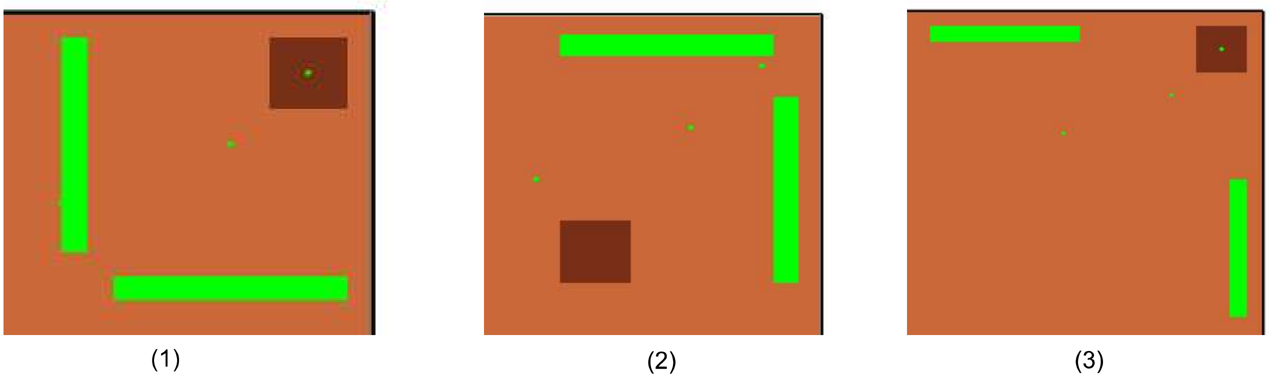

(1) (2) (3)

Fig. 4. Different fuel arrangements used in the simulations for wood enclosure.

In arrangement 2 shown in Fig. 4-2, the two PUF sheets were placed next to the wall at a distance of 10 cm, and the crib was placed opposite to the PUF sheets. The third arrangement is shown in Fig. 4-3, where the three fuel components (2 PUF sheets and crib) were placed at 10 cm next to the wall. The arrangement resulting in the most severe fire scenario was selected and used in all simulations and the NRC suppression tests.

In most simulations, the fuel packages were placed at the fuel corner as shown in Fig. 2, yet other locations were also explored; at the centre of the room (between the two nozzles) and under one nozzle. When the fuel package was placed at the center of the compartment or under one nozzle, two wood partition walls of dimensions 1.2 m height and 1.2 m length were placed at 10 cm from the crib (see Fig. 1 case 5).

For simulating the fire suppression scenarios using the water mist system, two pendant-type nozzles were placed at the centerline of the room and at distance 2.4 m from the wall (refer to fig. 2). The specifications of the water mist nozzles used in the simulations were based on those of the experimental ones. Some details about the experiments and the specifications of the nozzles are provided in the next section.

In FDS, the water droplets are introduced into the domain and transported as lagrangian particles. When a droplet falls on a solid surface, it sticks and is reassigned a new speed and direction. If the surface is horizontal, the direction is randomly chosen, whereas the direction is downwards for vertical surfaces. The mass and energy transfers between water droplets and the surrounding gases (or solid surfaces) are computed for each droplet. The temperature of each droplet is computed at each time step and the appropriate amount of water vapor is produced within the cell, which decreases the oxygen mass fraction. In addition, the cell gas temperature is reduced slightly based on the energy lost to the droplet. The temperature of the droplet and the surrounding gases are calculated using the following formulae [7];

$$\frac{dT_p}{dt} = \frac{1}{m_p c_p}\left[\dot{q}_r + A_{p,s} h\left(T_g - T_p\right) + \frac{dm_p}{dt} h_v\right] \qquad (1)$$

$$\frac{dT_g}{dt} = \frac{1}{m_g c_g}\left[A_{p,s} h\left(T_p - T_g\right) + \frac{dm_p}{dt}\left(h_v + h_l\right)\right] \qquad (2)$$

Where the subscripts p and g represent the particle and gases; respectively. T, m and c are temperature, mass and specific heat. $A_{s,p}$ is the surface area of the droplet. h_l is the liquid specific enthalpy and h_v is the latent heat of vaporization of the liquid.

Both the reduction in temperature and oxygen mass fraction reduce the rates of pyrolysis and combustion and hence reduce the burning rate of the fuel. This eventually results in fire suppression or control.

However, FDS doesn't account for the fire suppression effect of wetting and water cascading on the combustible surface. This limits proper simulations of fire suppression, for instance, by sprinklers system of which the main mode of suppression is wetting of the fuel. However, fire suppression by water mist systems is achieved mainly by heat transfer from the combustible surface (i.e., fuel) to the water droplets. Modelling of heat transfer is very well established in FDS.

5 Experimental

A series of experiments was conducted by NRC to investigate the performance of water mist systems in fire scenarios involving mass timber structures, with a focus on residential occupancies. Details about the experiments will be provided in another report, only data used in model validation is briefly presented here.

The experiments were conducted in a compartment setup similar to the one used in the simulations. The walls and ceiling of the room were constructed with light-weight wood frames and sheathed with non-combustible materials (Densglas gold boards). The floor of the room was non-combustible concrete. At the corner where the fuel package was placed, the walls and ceiling were built with CLT panels (made from Canadian spruce/pine/fir, produced by Nordic Structures) with dimensions approximately 2.4 m (L) × 2.4 m (W).

Four different water mist systems were used in the experiments. The specifications of the nozzles are shown in Table 2 and were used as input to the simulations. It is worth-noting that, no data for particle diameter was available from manufacturer and a median particle diameter of 100 μm was assumed for all cases. Thermocouple trees were placed in the experiment to measure temperatures at the room center, above crib and beside the nozzle closer to the fuel package. Temperature measurements from the experiments were compared against the suppression simulation results. Moreover, the suppression was manually delayed to 2.133 min in one of the tests. Data from that test were used to validate the fired simulation in wood compartment.

Table 2. Specifications of water mist nozzles used in the simulations

Specification	**T1**	**T2**	**T3**	**T6**
Median particle diameter (μm)	100	100	100	100
Operating pressure (bar)	52	72	80	8
K-factor (l/min/bar$^{0.5}$)	2.4	2.4	4.1	16.5
Activation temperature (°C)	79	79	79	79

6 Results and Discussion

First, temperature measurements from the simulations were compared against the experimental ones. Once a reasonable agreement was achieved, the model was further used to investigate the parameters presented in section 3.

6.1 Model Validation

Temperature measurements from fired simulation of wood compartment using the standard fuel package at room corner (case 1) were compared against the experimental measurements from the manually delayed suppression test (test 4 in the experiments). Figures 5-7 show the temperature from the simulation and experiment until 2 min 6 sec (suppression timing in the experiment) at different heights and locations (room center, above crib and beside nozzle). A reasonable agreement can be seen. The discrepancy might be attributed to:

1- A wood combustion model was used in the simulations, however the experiments involved CLT panels which probably have different combustion behaviour.
2- Difficulty in simulating the ignition and initial fire development which are sensitive to the fuel conditions (e.g. material properties and moisture contents), the ignition source and the test room conditions. It should be noted that he HRR from the ignition source (heptane burner) was not experimentally measured.

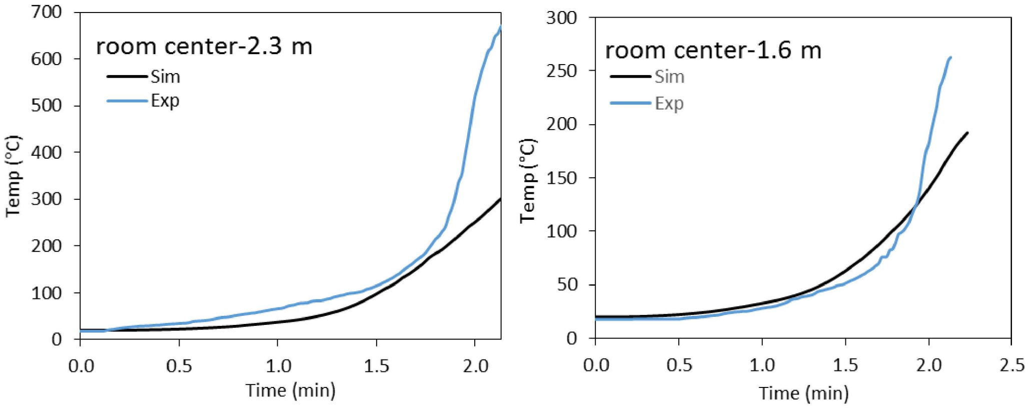


Fig. 5. Simulation and experimental temperature at room center at 1.6 m and 2.3 m height (without suppression)

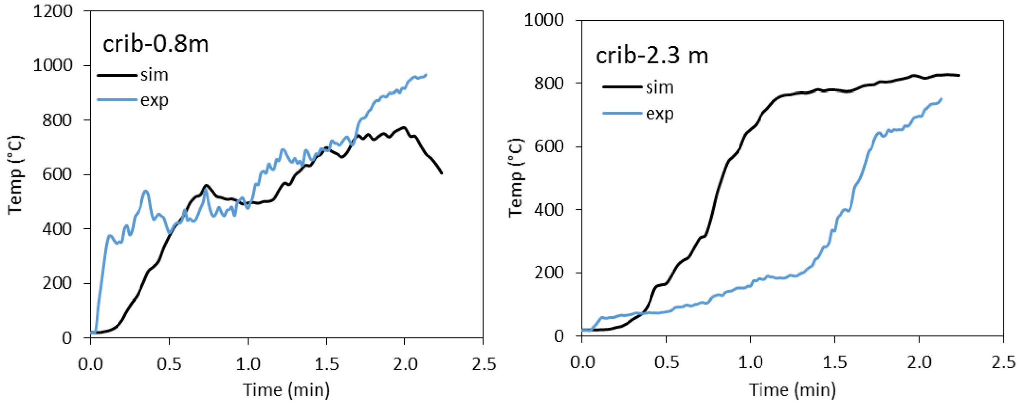


Fig. 6. Simulation and experimental temperature at 0.8 m and 2.3 m above the crib (without suppression)

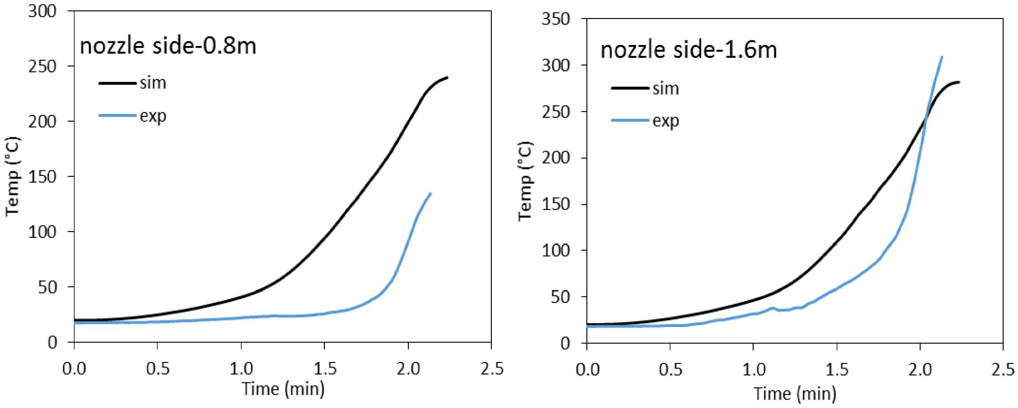


Fig. 7. Simulation and experimental temperature beside the nozzle at 0.8 m and 1.6 m height (without suppression)

Figures 8 and 9 compare the experimental and simulation temperatures at 1.6 m height at room center and beside nozzle under suppression scenarios using nozzles T1 and T6 (refer to Table 2). Generally, simulations are over-predicting the temperature, even though they were able to reasonably predict the initial rate of growth of the fire. In addition, nozzles in the simulations were activated earlier than the experiments. For example, the experimental nozzle activation in T1 was 1.17 min while the simulated value was 0.9 min. Again this might be due to simulating the CLT panels as wood which might have increased the rate of fire spread in the compartment resulting in faster activation of the nozzles.

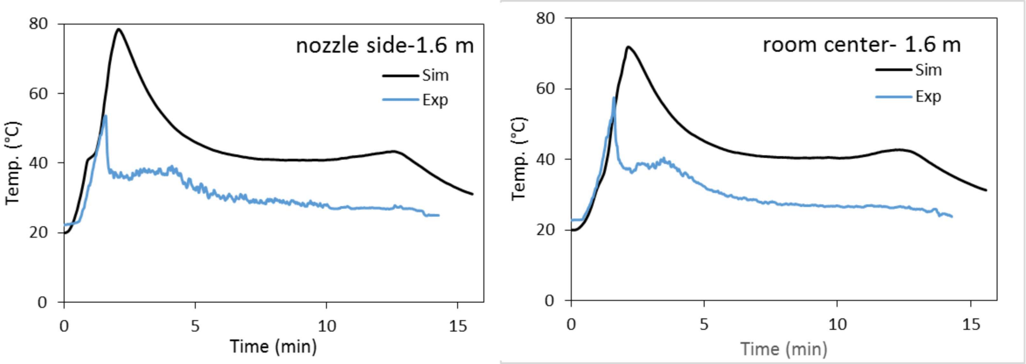


Fig. 8. Simulation and experimental temperature beside the nozzle and at room center at 1.6 m height for suppression using nozzle T6

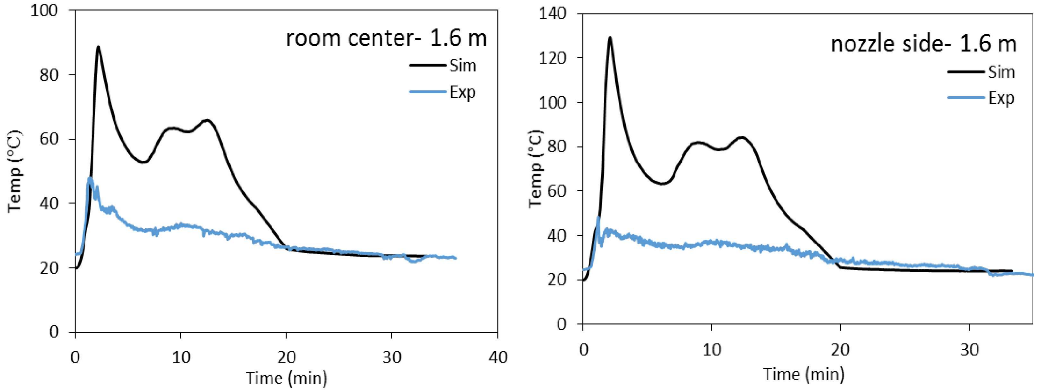


Fig. 9. Simulation and experimental temperature beside the nozzle and at room center at 1.6 m height for suppression using nozzle T1

6.2 Effect of fuel arrangement and location on fire severity in exposed wood compartment

The three different fuel arrangements presented in Fig. 4 were first investigated to find the arrangement of the fuels that would result in the most significant fire involvement of the walls and ceiling adjacent to the fuels. The heat release rate (HRR) profiles from the simulations are presented in Fig. 10. Only the standard arrangement and arrangement 3 resulted in fire spread to the wooden walls and ceiling adjacent to the fuel packages. In these arrangements (standard and 3), the wood crib was adjacent to the walls. The figure also shows that, the fastest flash-over in the room was exhibited by the standard fuel arrangement, where flashover occurred around 6 min. Therefore, the standard fuel arrangement was applied in all simulations.

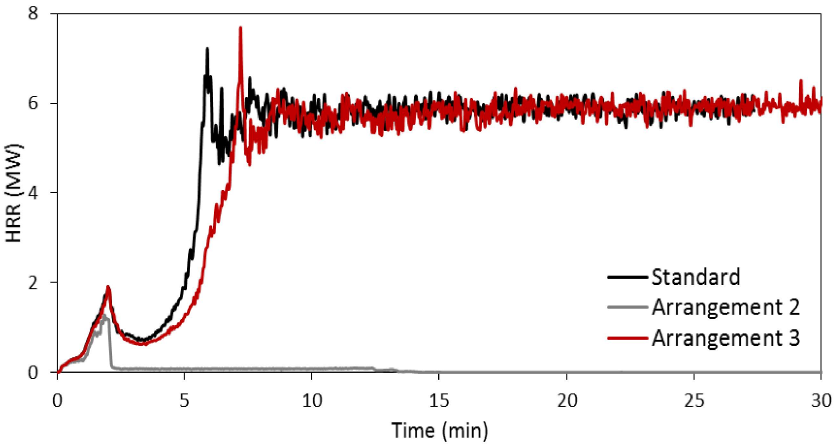


Fig. 10. HRR of fire (no suppression intervention) simulations in wood compartment for three arrangements.

The effect of the location of the fuel package was also investigated. Fig. 11 compares the HRR in exposed wood compartment with the fuel package placed at a corner of the room (case 1), center of the room (case 4) and under one nozzle (case 5). The figure shows that, flashover only occurred with the fuel package at the corner of the room. The small distance between the fuel package and the adjacent walls in case 1 resulted in fast heat transfer from the fire to the walls of the compartment. In addition, the fire effectively received heat feedback from the surrounding walls and ceiling. This highlights the contribution of the walls to the fire development in the compartment.

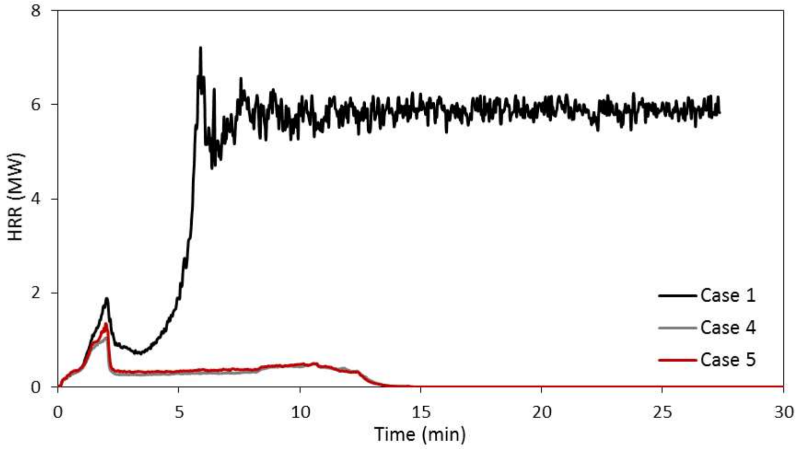


Fig. 11. HRR simulations in exposed wood compartment with different fuel locations.

6.3 Effect of different finishing on fire severity in compartment

Fig. 12 shows the HRR of the fire in compartments with different finishing. In all cases, the standard fuel package was placed at the corner of the compartment. It can be clearly seen that, less heat was released in the fully gypsum-board protected (case 6) compartment compared to all the other scenarios in which all walls and ceiling were exposed wood (case 1), or only one wall (cases 8-11) or the ceiling (case 7) were protected by gypsum-board. This is attributed to the fire spread from the fuel package to the exposed wooden walls and ceiling. It is worth-noting that the HRR of cases 8 and 9 were similar.

The HRR of the fuel package, excluding the involvement of adjacent walls and ceiling, was well captured in the simulation of fully gypsum-board protected compartment (case 6). The initial fire development of the PUF is consistent with the fire growth rate for PUF as reported by SP 2017 (Technical Research Institute of Sweden) [8].

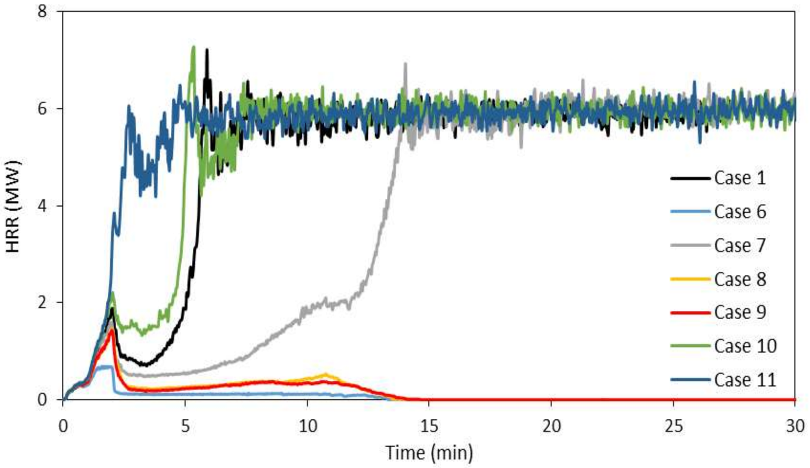


Fig. 12. HRR of fire simulations in compartments with different finishing. Refer to table 2 for cases number.

When the fire scenario involved exposed wood walls and/or ceiling, the fire spread from the fuel package quickly to the adjacent walls and ceiling, which resulted in rapid increase in HRR, as illustrated in Fig. 12. In case 1 (fully exposed wood and ceiling), the onset of the fire spread to the wooden walls and ceiling took place at about 1.3 min at which the heat release rate was approximately 1 MW. Spreading quickly to the wooden walls and ceiling, flashover occurred in the compartment at about 6 min. Thereafter, the whole compartment was involved in the fire, and the HRR curve plateaued at 6 MW. The HRR did not increase further due to the limitation of air within the room (ventilation-controlled fire- A HRR of 6 MW was the maximum fire size that can be achieved given the sizes of the two doors).

The contribution of the walls and ceiling to flashover in the compartment can be seen by comparing the time to flashover of the different cases. When the walls beside the fuel package were gypsum board (cases 8 and 9), flashover didn't occur. It can be concluded that, fire starts to spread from the fuel package to the compartment through the walls. This was further confirmed by the experiments that showed more damage to the CLT walls when the suppression system was automatically operated (more discussion and figures are presented in the experimental report). The protected ceiling (Case 7) delayed the flashover by approximately 8.5 minutes (compared to fully exposed wood compartment), where flashover occurred at 14.5 min. This reflects the contribution of the combustible ceiling (e.g. exposed wood) to the fire spread and fast flashover within the compartment which is attributed to the effective heat transfer from the upper smoke layer to the ceiling. Surprisingly, faster flashover can be seen in cases 10 and 11, where one of walls opposite to the fire location was protected by gypsum board. This might be due to the higher emissivity of gypsum board ($\varepsilon = 0.9$) compared to wood ($\varepsilon = 0.76$) in the simulations. The higher emissivity probably increased the radiation feedback which increased the fire intensity. This requires further investigation.

6.4 Fire and Suppression in open space and compartment

Fig. 13 shows the HRR of open space and all exposed wood compartment, both under fire conditions and suppression using water mist (specifications of the nozzle used in T2 were applied). Flashover didn't occur in the open space due to the continuous air flow into the open space which prevents hot smoke layer build-up, which would normally occur in an enclosed compartment and cause flashover. The figure also shows that the water mist system effectively suppressed the fire and prevented flashover in the all exposed wood compartment. The fire was suppressed in 2 mins and extinguished in 13 mins. In the case of the suppression in the open space, there was not much decrease in the HRR while using the water mist system. However, Fig. 14 shows the decrease of the temperature at 1.6 m height above the fuel package and beside the nozzle with the use of the water mist. Thus, the water mist system was able to control the fire and lower the temperatures in the open space.

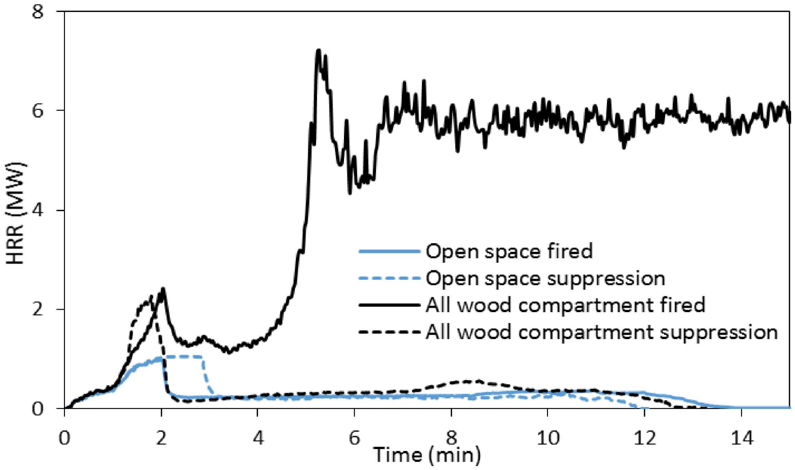


Fig. 13. HRR of fired –no suppression intervention- (straight lines) and suppression (dashed lines) simulations in exposed wood compartment and open space

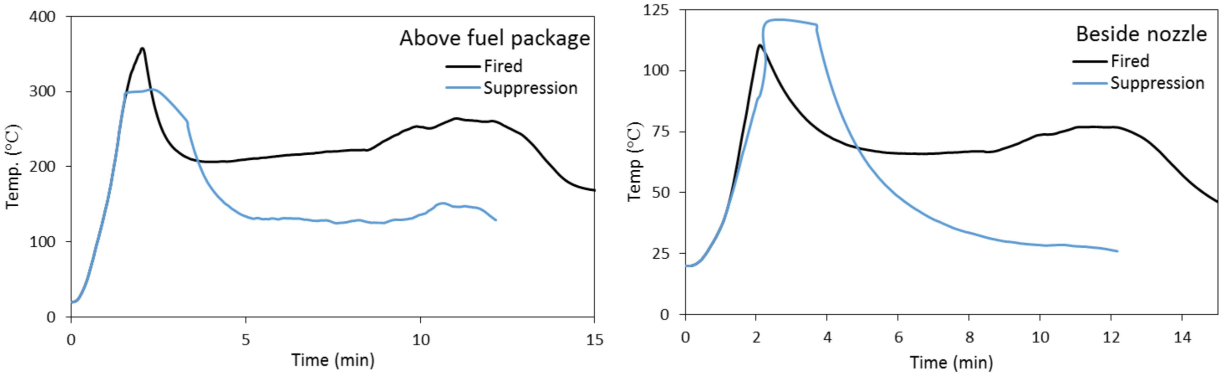


Fig. 14. Temperature profiles at 1.6 m height above fuel package and beside the nozzle in fired (no suppression intervention) and suppression simulations of open space.

6.5 Effectiveness of water mist systems in fire suppression in compartments with different finishing

Fig. 15 shows the impact of water mist system on HRR profiles in the simulation of a fully exposed wood compartment (case 1), a fully protected gypsum-board compartment (case 6) and a compartment with only a gypsum-board protected ceiling (case 7). The specification of the water mist system in T2 were used in those simulations.

The nozzles were activated in all the suppression simulations. Fig. 15 shows that the water mist system suppressed the fire in cases 1 and 7 at around 2 min (corresponding to 2.5 MW) by minimizing fire spread to the adjacent walls/ceiling and completely extinguished the fire at 13 min. This reduction in HRR compared to no-suppression scenario and effective fire suppression are attributed to the effective cooling by the water mist system. In addition, the evaporation of water mist and oxygen displacement through the interaction between the droplets and hot smoke resulted in fire suffocation and complete extinguishment.

On the other hand, the water mist system did not affect the HRR in the case of gypsum-board protected compartment (case 6). This is because in general the effectiveness of water mist system in fire suppression and extinguishment is affected by relative fire size to the volume of the compartment. It can be inferred that the evaporation of water mist and oxygen displacement became substantial from the time HRR reached 2.5 MW as shown in the suppression simulation of case 1, whereas maximum HRR was around 1 MW in the gypsum-board compartment.

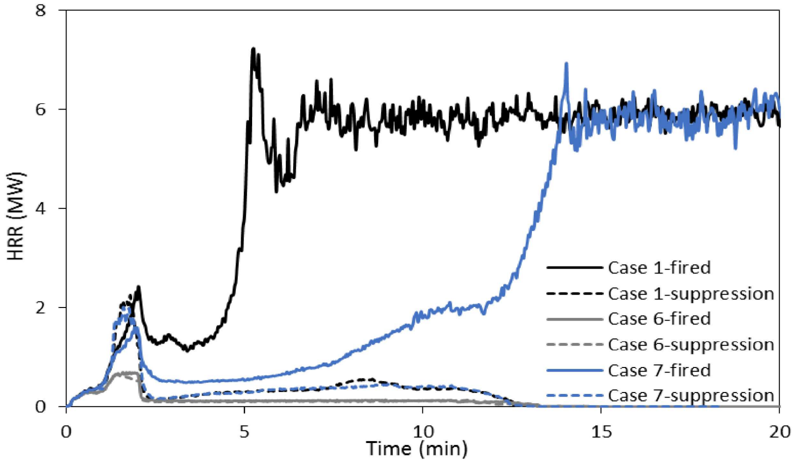


Fig. 15. HRR of fired –no suppression intervention- (straight lines) and suppression (dashed lines) simulations in all exposed wood (case 1), all gypsum-board protected (case 6) and only gypsum-board protected ceiling (case 7) compartments.

The temperature profiles shown in Fig. 16 demonstrate the capability of the water mist system in lowering the temperature in the room (at 1.6 m height along the center of the room), in all exposed wood, only gypsum-board protected ceiling and all gypsum-board protected compartments. This verified that the water mist system had excellent gas phase cooling effects, which controlled fire and limited fire spread beyond the fire origin although it may not be able to completely suppress or extinguish the fire in some circumstances.

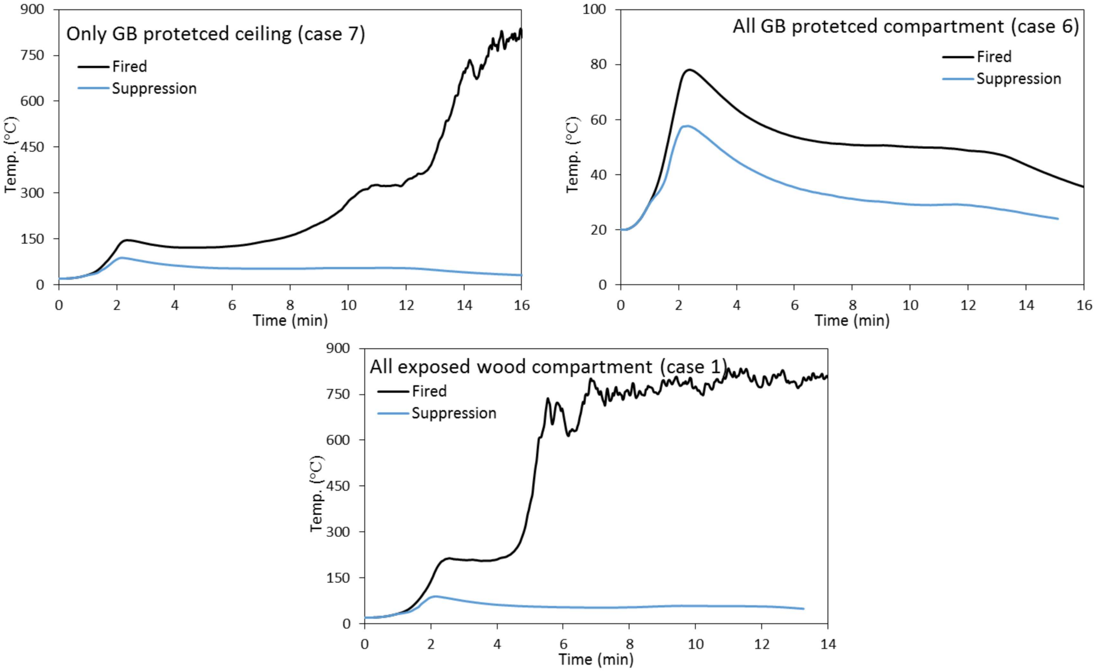


Fig. 16. Temperature profiles at the center of the room and 1.6 m height in fired (no suppression intervention) and suppression simulations of different compartments

7 Conclusions

The effectiveness of water mist systems in suppressing fires was numerically investigated using FDS. The model was first validated against experimental data from the testing conducted by NRC. The model showed qualitatively reasonable agreement with the experiments. Then the model was used to investigate different parameters. Nineteen simulations including 7 water mist simulations were conducted. It was concluded that;

Fired simulations

1- The standard arrangement of the fuel packages of the wood crib and PUF sheets that is suggested in UL 2167 resulted in the highest rate of fire spread in the fully exposed wood compartment.
2- Flashover in the all exposed wood compartment only occurred when the fuel package was placed at the corner of the room.
3- Protecting the walls of the fire corner by gypsum-board prevented the flashover. This shows that the fire spread from the fuel package to the compartment was first through the walls. This was also observed in the fire suppression experiments, where more damage was seen for the walls and not the ceiling due to the timely activation of the suppression system.
4- Protecting the ceiling with gypsum-board delayed the flashover in the compartment.

Suppression simulations

5- In cases of all exposed wood and only gypsum-board protected ceiling compartments, the water mist system completely extinguished the fire and prevented its spread to the walls of the compartment
6- In cases of all gypsum-board and gypsum-board protected walls compartments, and open space, the water mist system controlled the fire and lowered the temperature within the compartment.

These findings show the effectiveness of the water mist system in suppressing the fire in exposed wood compartments where a high heat release is expected due to the high fuel load. The results from these simulations are qualitatively reliable since the model was validated against experimental data. However, some of the findings require further investigation.

One of the main advantages of using water mist systems over sprinklers is the less volume of water expelled, which reduces the damage to wood structure. However, such assessment can't be done based on the simulation results, since FDS was not able to simulate the suppression by sprinklers system.

References

[1] UL, Standard for Water Mist Nozzles for Fire Protection Service, 2017.

[2] I. Gomaa, N. Elsagan, EFFECT OF CHAR BURNING MECHANISM ON WOOD COMBUSTION, in: Proceedings of the 3rd International Fire Safety Symposium IFireSS 2019, Ottawa-Canada, 2019: pp. 471–481.

[3] G. Thomas, Thermal properties of gypsum plasterboard at high temperatures, Fire and Materials. 26 (2002) 37–45. https://doi.org/10.1002/fam.786.

[4] BS 8458 : Fixed fire protection systems – Residential and domestic watermist systems – Code of practice for design and installation, (2015). https://global.ihs.com/doc_detail.cfm?document_name=BS%208458&item_s_key=00665388&item_key_date=840101.

[5] FM global, ANSI/FM Approvals 5560-2017 Americal national standard for water mist systems FM Approvals., 2017.

[6] R. Bilbao, J.F. Mastral, J. Ceamanos, M.E. Aldea, Kinetics of the thermal decomposition of polyurethane foams in nitrogen and air atmospheres, Journal of Analytical and Applied Pyrolysis. 37 (1996) 69–82. https://doi.org/10.1016/0165-2370(96)00936-9.

[7] K.B. McGrattan, R.J. McDermott, C.G. Weinschenk, G.P. Forney, Fire dynamics simulator, technical reference guide, 2013.

[8] M. Arvidson, An evaluation of residential sprinklers and water mist nozzles in a residential area fire scenario, 2017. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-32868.