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Water Mist Systems for Protection of Mass Timber Structures-Phase 2 Residential Fire Suppression Tests

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Water Mist Systems for Protection of Mass Timber Structures-Phase 2 Residential Fire Suppression Tests

Yoon J. Ko, Ph.D., Nour Elsagan, Ph.D. and Eric Gibbs

Executive Summary

As an alternative option to conventional sprinkler system, water mist systems are considered for the protection of timber buildings because they use much less amounts of water compared to sprinkler systems. The effectiveness of high pressure water mist (HPWM) and low pressure water mist (LPWM) systems was investigated in comparison to sprinkler systems for a residential fire scenario involving mass timber structures. The most distinct characteristic of the HPWM and LPWM systems was fine water droplets generated from the nozzles, which demonstrated effective smoke cooling in the room. Although the water spray rate of the HPWM was four times lower than that of the sprinkler system, the water mist systems effectively control the fire and maintained the room tenable. Most systems (HPWM, LPWM and sprinklers) tested in this study did not prevent fire damage on the CLT walls, but the HPWM system with a wide spray angle demonstrated rapid fire suppression and protection of the CLT walls. In all tests, a large water pool formed on the floor, which appeared proportional to the total water spray discharge in each test, and the moisture contents measured on the surface and bottom edges of the CLT panels indicated that water can penetrate into the interface between the floor and the wall in a typical CLT assembly.

1 Introduction

Current Canadian regulations allow the construction of wood frame buildings of up to six storeys in height. This height is expected to be increased in the 2020 version of the National Building Code (NBC) owing to the advancements in new technologies and mass timber products, such as Cross Laminated Timber (CLT). The International Building Codes (IBC) has recently accepted the proposed changes for IBC 2021, which allow the 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.

Sprinklers are the most commonly used fire suppression system in buildings due to their proven effectiveness in limiting the severity of fire and fire spread beyond the fire origin. In application to mass timber structures, however, there are concerns that sprinkler systems could create post-fire water damage and mold problems in mass timber structures.

1.1 Problems

As an alternative option to sprinkler system, water mist systems are considered for the protection of timber buildings because they use much less amounts of water (e.g. about 90-50% less water claimed by manufactures) compared to sprinkler systems. However, when it comes to the protection of residential and office buildings, water mist systems are still emerging technologies. In particular, there is currently no Canadian technical guide specifically addressing the design requirements for water mist systems in the protection of mid/high rise wood frame buildings, in terms of both protecting occupants as well as minimizing post-fire water damage of the wood structure. Research is needed to evaluate the performance of water mist systems in comparison to conventional sprinkler systems in mass timber building fire scenarios, and to substantiate potential benefits of water mist systems in minimizing post-fire water damage.

1.2 Background

NRC and NRCan initiated research on water mist system for the protection of mass timber buildings. In 2018-2019, Phase 1 identified regulatory gaps in guiding the use of fire suppression systems in application to mass timber buildings [1], [2]. Although several water mist standards provide test protocols for residential fires, none of these standards suggested specifics of water mist systems in protections of mass timber structures. It was also reported that experimental study is necessary to address important design parameters, such as fire scenarios, water spray characteristics and ventilation conditions, which affect the performance of the water mist system. In Phase 1, a numerical modelling study [3], [4] was conducted to design the test program for Phase 2. The numerical modelling study explored the impact of compartmentation, fuel package arrangements and the exposed mass timber wall and ceiling surfaces on the fire development as well as on the effectiveness of fire suppression.

In Phase 2, fire suppression tests using water mist and sprinkler systems were conducted to compare their relative fire protection performances in a compartment built with mass timber products. The results from the experiments were also compared with the numerical simulations conducted in Phase1. The expected outcomes from this research project is (1) to fill the knowledge gap in the use of water mist system for the protection of mass timber buildings and (2) to provide scientific data for the development of a technical guide (to be conducted in 2020-2021) for the use of water mist systems for the protection of mass timber buildings.

1.3 Scope and Objectives

The main objective of the testing program was to experimentally investigate the performance of water mist suppression systems in fire scenarios involving mass timber structures, with a focus on residential occupancies. A series of fire suppression tests was conducted using water mist and sprinkler systems.

More specifically, water mist and sprinkler system were tested for a residential fire scenario in a compartment built with exposed mass timber panels. The performance of the fire suppression systems was investigated in relation to:

- Controlling and suppressing the residential fire scenario
- Limiting fire severity in the room and maintaining tenable conditions
- Protecting mass timber structures by limiting fire spread to CLT panels
- Minimizing water and fire damage on the test assemblies

2 Test Descriptions

This section describes the residential fire scenario tested in this study and provides details of the test set-ups.

2.1 Test Method

In developing a test method for this testing program, the following issues were considered;

- Fire scenarios that represent the most severe fire cases in residential occupancies
- Repeatability of the test method
- Fire scenarios that enable investigation of the involvement of exposed mass timber structures in the fire
- Systematic test methods that allow investigation of the performance of water mist system in comparison to sprinkler systems

The most deadly residential fire scenarios involve upholstered furniture, mattresses or beddings. Kitchen fires are frequent but not as challenging as a living room fire scenario involving upholstered furniture, which is reported to have rapid initial fire development. Living room fires involving upholstered furniture are reported to reach room flashover within 3-5 minutes while flashover occurred at 11-13 minutes in the kitchen fire [5]. Thus, living room fire scenarios involving upholstered furniture were used in this testing program.

For repeatability, simulated upholstered chairs were used in this experimental program. The simulated upholstered chairs built with polyether foam sheets are reported to simulate comparable initial fire development to an actual upholstered chair fire. An upholstered chair fire is reported to release the peak heat release rate of 1.2-1.4 MW in 3-4 minutes; when placed in a room corner, the peak heat release rate is reported approximately 1.8 MW [6].

In this testing program, the simulated upholstered furniture fire was placed at a corner of a test compartment built with exposed mass timber walls and ceiling. This living room fire scenario allowed to observe how quickly the fire spread to the surrounding walls and ceiling; and to investigate the fire suppression performance of water mist system against this residential fire scenario with increased fire loads due to the exposed mass timber structures. Fire damages on the mass timber walls and ceiling were also investigated.

Details of the test set-ups were designed considering the current standard test methods of the water mist systems (e.g. UL 2167 [7] and BS 8458 [8]) and sprinkler systems (UL 1626 [9]) for residential applications. This approach allowed the comparison of the performance of water mist systems to that of sprinkler systems.

2.2 Test room set-up

The dimensions of the test room were similar to those used in the numerical model (approximately 8.53 m (L) × 4.27 m (W) × 2.4 m (H)) that was explored to obtain information necessary to verify fire suppression test plan in Phase 1. The walls and ceiling of the room were constructed from light-weight wood frames and sheathed with non-combustible materials (Densglas gold boards). The floor of the room was non-combustible concrete.

Ventilation was provided by 2 doors of 2.2 m height each. One of the doorways was 1.05 m wide and located at the corner opposite to the fuel package, and the other one was 0.9 m wide and located at the same side of the fuel package.

Figure 1 shows a schematic diagram of the test room with all dimensions, Figure 2 and Figure 3 show photos of inside and outside the test room.

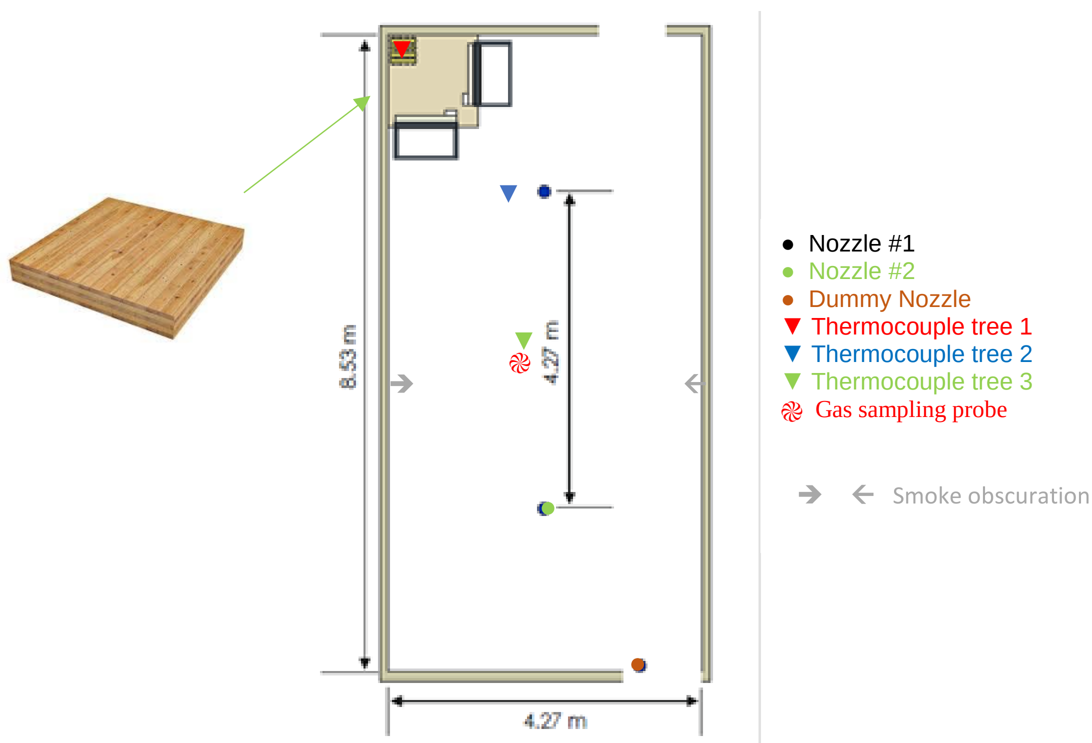


Figure 1 Test compartment with nozzle layouts and instrumentations

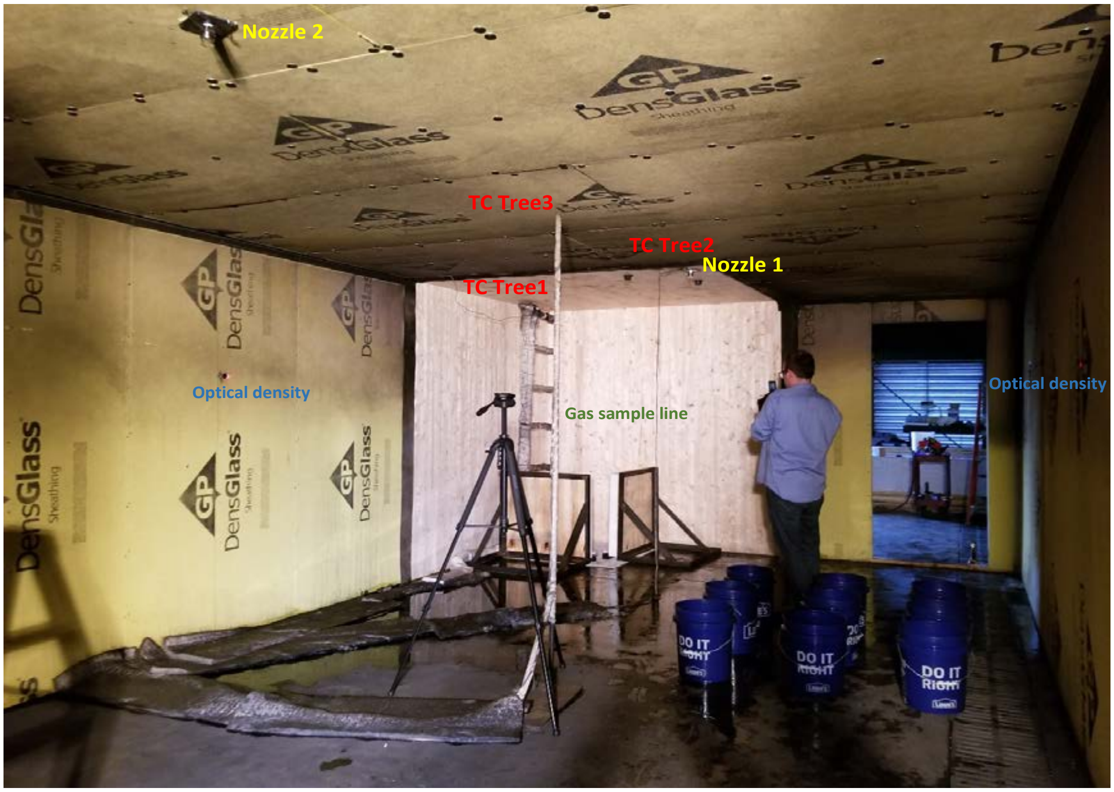


Figure 2 Test Compartment and instrumentation

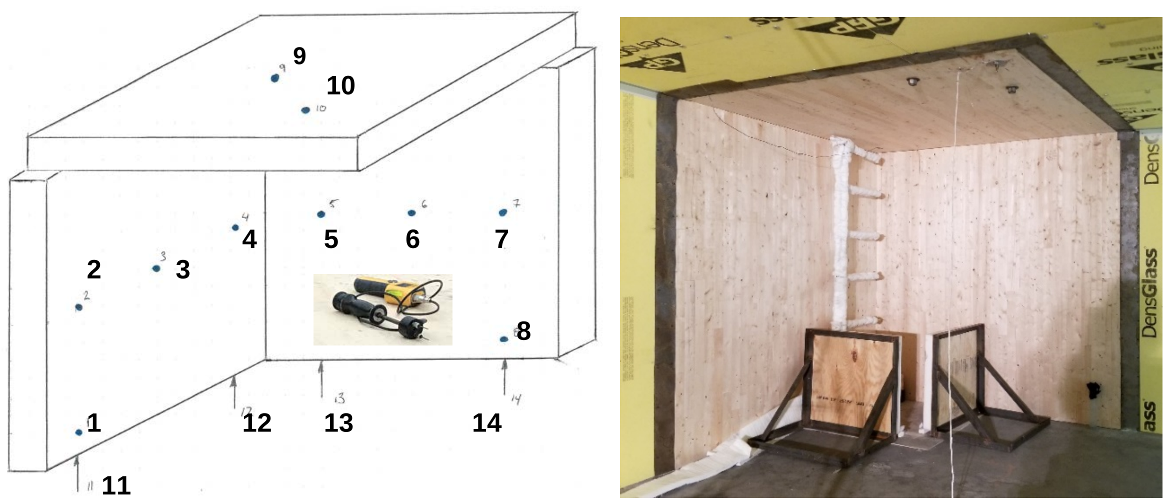
Figure 3 Outside view of the test compartment

2.2.1 CLT corner

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). To support the corner, the CLT panels were embraced using steel frames, and the ceiling CLT panel was bolted to the roof joists.

In each test, moisture contents of the CLT walls and ceiling were measured before the test. Using a pin-type moisture meter, measurements were made at the 14 measurement points shown in Figure 4. Post-test moisture contents were measured in selected tests at the same locations.

After each fire test, fire damages on the CLT surfaces were photographed and the damaged CLT panels were replaced with new ones for the next test.



a. 14 measurement points and pin-type moisture meter

b. CLT corner

Figure 4 Layout of the moisture measurement and the CLT corner

2.2.2 Fuel Package

A wood crib and simulated furniture were used as fuel for the fire, which is also employed in the standard test protocols of the water mist systems (e.g. UL 2167 [7], FM 5560 [10] and BS 8458 [8]) and sprinkler systems (UL 1626 [9]) for residential applications. The wood crib had a cross sectional area of 0.3×0.3 m^2 and 0.15 m thickness. The wood crib was placed on top of a heptane pan (0.3 m (W) × 0.3 m (L) × 0.1 m (H)). The wood crib was positioned 50 mm from each wall.

The simulated furniture was built with two foam (pure polypropylene oxide polyol, polyether) sheets with a thickness of 0.076 m, which were adhered to plywood panels (see Figure 4). The dimensions of the simulated furniture were 0.84 m width and 0.79 m height. The foam sheets used in the tests have the burning characteristic properties required by UL 2167 [7] (i.e. peak heat release rate of 230±50 kW/m^2 and heat of combustion of 22±3 kJ/g tested by ASTM E1354 at a 30 kW/m^2 heat flux exposure). The simulated furniture was ignited with two cotton wicks soaked in heptane.

2.3 Fire Suppression System

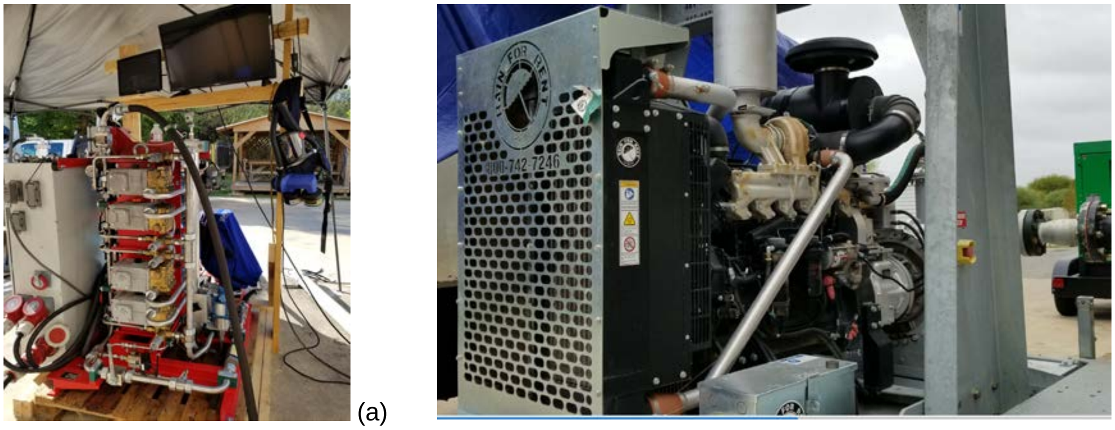
Water mist systems use water atomization technologies to produce fine water mist at high operating pressures through using specialized nozzles. In general, there are three types of water mist systems defined by the operating pressure: high pressure water mist (HPWM) system operates at pressure of 34.5 Bar (500 psi) or greater, intermediate pressure water mist system operates at pressure greater than 12.1 bar (175 psi) but less than 34.5 bar (500 psi); and low-pressure water mist (LPWM) system operates at pressure at 12.1 bar (175 psi) or less.

In this testing program, two high-pressure water mist (HPWM) nozzles, one low pressure water mist (LPWM) nozzle and one residential sprinkler nozzle were tested. Figure 5 shows the four pendent type nozzles tested, and Table 1 shows their specifications. Details of the nozzles are in Appendix A: Nozzle.

As indicated in Table 1, HPWM Type A and sprinkler Type D nozzles are approved for residential application by UL 2167 [7] for HPWM or UL 1626 [9] for sprinkler systems, and HPWM Type B and LPWM Type C nozzles are approved for Hazard Catergory-1 (HC-1) by FM 5560 [10]. Ko et.al [1] provides a review of these hazard classifications and their different design objectives. Due to the different design objectives for each hazard category, the expected performance level of the two groups of nozzles is different: the LH/HC-1 systems are expected to perform better than the residential systems as they are designed for property protection in addition to life safety. In the present study, the nozzles/systems in Table 1 are selected regardless of their approved types/ hazard categories and tested to evaluate their suitability to the mass timber building application, in which enhanced performance is required. Each nozzle contained an automatic fire detector (fusible glass link) and a water atomising/deflector component. The nozzle was connected to water supply and delivery components (such as water pipe lines and pumps). Figure 6 shows the water pump systems used for HPWM and LPWM and sprinkler systems.

HPWM Type A Type B LPWM Type C Sprinkler Type D

Figure 5 Nozzles tested



(a) (b)

Figure 6 Water pump systems used for (a) HPWM and (b) LPWM and Sprinkler systems

Table 1. Fire suppression systems tested

Type	Description	K factor [lpm/bar$^{1/2}$]	Max. Spacing [m]	Temperature rating [°C]	operating pressure [bar]
A	HPWM Marioff Hi-Fog (C40 Residential)	2.4	4.27	79*	50 or70
B	HPWM Marioff Hi-Fog (C10 Light hazards)	4.1	5	79*	80
C	LPWM VID (OH-VOS Light hazards)	16.5	4.5	79	8
D	Sprinkler Tyco (TY123 Residential)	43.2	5.5	79	0.92 bar for spacing 4.3 m

* It should be noted that in real installations, Type B and C nozzles would apply the temperature rating of 57°C or 68°C as per its UL Listing, For traditional sprinklers (Type D) the most common temperature rating is 68°C. The temperature rating of 79°C applied in this study represents an activation with a built in safety factor in the tests.

The nozzles tested in this study have the K-factor in the range of 2.4 and 43.2 lpm/bar$^{1/2}$. The K-factor is the discharge coefficient of a nozzle, which relates the amount of water (*Q*) and the pressure (*P*) discharged through the nozzle (see Eq. 1). In general, the larger a K-factor is, the more amount of water is permitted through the nozzle like sprinkler. The amount of water (*Q*) sprayed through a nozzle can be calculated based on Eq. 1.

$$K = Q/\sqrt{P} \qquad \text{Eq. 1}$$

The nozzles tested in this study had the same temperature rating of 79°C. The temperature rating of fusible glass links governs the nozzle response time. With the rating of 79°C, the fusible link will break when the link temperature reaches the rating value, yet the smoke temperature is usually significantly higher than the rating value as there will a thermal lag in the convective heat transfer from the smoke to the fusible link. For residential sprinklers, ordinary (57°C -77°C) or intermediate (79°C -107°C) temperature–rated sprinklers are required by NFPA 13 [11], 13R [12], and 13D [13], unless ambient temperatures can exceed 37.8°C. Each nozzle was installed in the test as specified in the manufactures' installation instructions.

2.3.1 HPWM

A high-pressure water mist system (HPWM) was installed in the test set-ups using two different types of nozzles with various operating pressures. Type A nozzle (refer to Table 1) is approved for residential application as per UL 2167 and has a K factor of 2.4 lpm/bar$^{1/2}$. Type B nozzle (refer to Table 1) is approved for light hazards applications as per FM 5560 and has a K factor of 4.1 lpm/bar$^{1/2}$. Both types have a maximum spacing greater than 4.27 m.

2.3.2 LPWM

Type C nozzle (refer to Table 1) was used for Low pressure water mist system (LPWM) tests. Type C nozzle was approved for light hazards applications as per FM 5560 and has a K-factor of 16.5 lpm/bar$^{1/2}$. The maximum spacing is 4.5 m.

2.3.3 Sprinkler

Type D residential sprinkler nozzle with K-factor of 43.2 lpm/bar$^{1/2}$ was used in the tests.

2.3.4 Nozzle layout

In each test, two nozzles were installed on the ceiling as shown in Figure 1 and Figure 2, and one dummy nozzle was also installed near the door far side from the fire. Nozzle #1 was installed on the ceiling at a radial distance of 3 m from the fire corner. Nozzle #2 was installed at 4.27 m away from Nozzle #1, and an unpressurized, dummy nozzle (Nozzle #3) was also installed near the doorway. For each test, the 3 nozzles had the same temperature rating.

At each installation location, the nozzle was installed in accordance with the manufacture's design and installation instruction (i.e installed to flush with the ceiling as much as possible). The dummy nozzle (Nozzle #3) was installed on the ceiling such that the heat response elements were located 51 mm below the ceiling, following UL 2167 test protocols.

2.4 Instrumentation

Instrumentation of the test room is shown in Figures 1 and 2. The test room was instrumented with the following;

- Three thermocouple trees (each with 6 thermocouples at 0.4 m spacing) above the wood crib, beside nozzle #1 and at the center of the room
- One thermocouple at each nozzle
- Water supply line pressure sensor for the HPWM, LPWM and sprinkler systems
- Pressure sensor at the water supply pumps
- Pressure sensor at the dummy nozzle
- Smoke density measurement across the room at a height of 1.6 m
- Oxygen, carbon monoxide and carbon dioxide concentration measurements at the center of the room at a height of 1.6 m
- Buckets to measure water spray density on the floor
- Cameras

2.5 Test Matrix

HPWM, LPWM and sprinkler systems were tested in this study. The water spray density designed was in the rage of 0.9- 2.7 l/min·m^2. For sprinkler systems, the minimum required water spray density is 2.0 l/min·m^2 for residential buildings [13] and 4.1 l/min·m^2 for residential buildings in mixed use [11] . While the sprinkler system has the required design spray densities based on the area/density curve developed for different hazard classifications in NFPA 13 [11], water mist systems do not have generic design methods. Water mist systems are required to be designed based on verifications through full-scale fire tests due to their complex technical features, such as water droplet atomization, spray cone angle, spray velocity and mixing ability driven by the operating pressure. To study the suitability of the selected systems to mass timber building applications and also to investigate how the technical features would affect the performance of water mist systems in protection of residential mass timber buildings, a series of tests were conducted. Ten tests were conducted, and Table 2 shows the test matrix.

Table 2. Test matrix

Test ID	Suppression System	Nozzle type	Operating pressure (bar)	**T**emperature Rating (°C)	Water spray density (l/min·m^2)	Note
1	HPWM	A	51.7	79	0.9	minimum protection designed for life safety
2	HPWM	A	72	79	1.1	maximum protection designed for life safety
3	HPWM	B	80.3	79	2.0	designed for property protection
4	HPWM	B	80	N/A	2.0	designed for property protection delayed manual activation approx.1 minute
5	HPWM	A	52	N/A	0.9	designed for life safety delayed manual activation approx.1 minute
6	LPWM	C	8.6	79	2.7	designed for property protection
7	LPWM	C	8.6	N/A	2.7	designed for property protection delayed manual activation approx.1 minute
8	Sprinkler	D	0.94	79	2.3	After 2nd sprinkler head activated, Water supply system failed
9	Sprinkler	D	0.94	79	2.3	After 2nd sprinkler head activated, Water supply system failed
10	Sprinkler	D	0.94	Simulated 79	2.3	Sprinkler activations simulated

3 Test Results

3.1 Spray Characterization

The spray characteristics of fire suppression systems are key factors affecting their performance in controlling the fire and limiting the severity of the fire. The three systems tested in this study had distinct spray angles, spray patterns and water spray densities, which brought up varying degrees of protection for the test room. To capture the spray characteristics, water spray tests were conducted without fire for the four types of nozzles.

3.1.1 HPWM Type A

Type A nozzles used in Test 1 and 2 had a mean droplet size of approximately 100 microns, and the K-factor is 2.4 lpm/bar$^{1/2}$, as per the manufacture's specification. The estimated water spray densities based on the K-factor and the operating pressures were 0.9 and 1.1 l/min·m^2, respectively in Test 1 and 2, which were similar to the average water spray densities of 0.94 l/min·m^2 measured by the bucket tests. Type A nozzle sprayed fine water mist with a spray angle of approximately 90°, as shown in Figure 7 – (1). To clearly identify the spray angle, the photo was taken immediately after the opening of the nozzle before the fine mist filled up the test room. Although the fine water droplets did not directly hit and wet the walls and ceiling, the fine droplets filled up the test room.

3.1.2 HPWM Type B

As shown in Figure 7 – (2), the spray angle of Type B nozzle was much greater than Type A, and so was the water spray rate. Type B nozzles used in Test 3 have the K-factor of 4.1 lpm/bar$^{1/2}$, as per the manufacture's specification. The estimated water spray density based on the K-factor and the operating pressure was 2.0 l/min·m^2. The average water spray density measured by the bucket tests was, however, much lower (1.1 l/min m^2) than the estimated value, which showed that a significant amount of water sprayed to the walls rather than falling onto the floor.

3.1.3 LPWM Type C

The spray angle of Type C nozzles was as wide as that of Type B nozzles as shown in Figure 7 – (3), while the Type C nozzle was operated with a much lower pressure of 8.6 bar than Type B (i.e. 11% of the operating pressure of Type B). Type C nozzle has the K-factor of 16.5 lpm/bar$^{1/2}$, as per the manufacture's specification. The estimated water spray density based on the K-factor and the operating pressure of Type C nozzles was 2.7 l/min m^2, which was 35% higher than that of Type B nozzle. Both Type B and C nozzles were approved for light hazard application. The average water spray density measured on the floor by the bucket tests was 1.5 l/min m^2, which indicated that a portion of water sprayed through the wide spray angle of Type C nozzles was discharged to the walls as well as the ceiling. Compared to other types of nozzles, Type C nozzles left the largest wetting pattern on the celling (the celling height was 2.4 m) since the nozzle also spray water partially upward toward the ceiling.

3.1.4 Sprinkler Type D

Type D nozzle has the K-factor of 43.2 lpm/bar$^{1/2}$ and was operated at 0.9 bar to match the coverage area of 4.3 m by 4.3 m as per the manufacture's specification. The estimated water spray density based on the K-factor and the operating pressure of Type D nozzles was 2.3 l/min m^2, which was two times higher than that of Type A nozzle. Both Type D and A nozzles were approved for residential application. As shown in Figure 7 – (4), the spray angle of Type D was much wider than that of Type A so that the sprinkler system effectively wetted the walls including the corner built with the CLT panels.

Sprinkler systems standards require a water distribution test that checks the wetting pattern up to a height not less than 0.7 m on the walls of a test enclosure, with a minimum of 5% percent of the sprinkler spay rate [14]. UL 1626 [9] and FM 2030 [15] include sprinkler system test methods for checking the spray pattern in the vertical and horizontal planes.

(1) HPWM Type A at 52 bar

(2) HPWM Type B at 80 bar

(3) LPWM Type C at 8.6 bar

(4) Sprinkler Type D at 0.94 bar

Figure 7 Water sprays

3.2 Suppression tests

Each test was started by igniting heptane in the pan below the wood crib located at the fire corner. The simulated furniture was also ignited with two cotton wicks soaked in heptane. After the ignition, the fire developed quickly over the simulated furniture and wood crib. Within about 1 minute, the smoke filled the upper part of the room, yet the flame did not reach the ceiling. The room temperature measured at the centre at 1.6 m height was about 50-60˚C, when Nozzle #1 was triggered. The activation time of Nozzle #1 (i.e. installed close to the fire corner, see Figure 2) was approximately 1.2-1.8 minutes with automatic activation of the nozzle, which has the temperature rating of 79˚C. Only Nozzle #1 was activated in the HPWM and LPWM tests. Whereas for all sprinkler system tests both Nozzles #1 and #2 were activated with Nozzle #2 activated after approx. 1 minute from the activation of Nozzle #1. Each test was conducted for 30 minutes, but the operation of the suppression system was terminated after 10 minute from activation when all combustibles were extinguished or only the wood crib sustained combustion (i.e. following the current standard test methods of UL 2167 [7], BS 8458 [8] and UL 1626 [9]).

3.2.1 High Pressure water mist tests

Five tests were conducted to investigate the performance of HPWM in application to a residential fire scenario involving mass timber structures. Two different types of HPWM nozzles were tested with various operating pressures. In Tests 1 and 2, Type A nozzle was tested with automatic activations. Type B was also tested in Test 3 with automatic operation. In Test 4 and 5, Type B and A nozzles, respectively, were tested with delayed activations.

In Test 1, Type A nozzle was tested with an operating pressure of 52 bar. The water spray rate, which was calculated based on the K factor of 2.4 lpm/bar$^{1/2}$and the measured operating pressure of 52 bar, was 17.3 l/min.

The fire developed quickly at the corner over the simulated furniture and wood crib fire. Figure 8 shows the test room conditions before and after the activation of the nozzle. As shown in the photo (Figure 8-a) taken at 1.1 minutes from the ignition, the smoke filled the upper part of the room, and the flame height was about 1 m at the fire corner.

Nozzle #1 with the temperature rating of 79˚C activated after 1.17 minutes from the ignition. Immediately prior to the activation of the suppression system, the temperatures measured at the fire corner were 750˚C and 450˚C at 0.4 m and 0.8 m, respectively (see Figure 9). After the nozzle activation, the flame temperature measured at the fire corner did not increase but plateaued for 2-3 minutes. Thereafter, the systems using Type A nozzle allowed the fire grow back, resulting in the second temperature peaks at approximately 10 minutes from the ignition(while the system was operating). Subsequently, however, the systems successfully suppressed the fire after 30 minutes of operation of the systems.

Figure 10 shows the ceiling gas temperature at the fire corner measured in the HPWM tests. Similarly, the ceiling gas temperature measured at the fire corner (thermocouple tree1) was also decreased with the HPWM system activation, yet the gas temperature at the fire corner grew back slightly resulting in the second temperature peak at approximately 10 minutes. In Test 1, the systems successfully controlled the fire and extinguished the fire after 30 minutes of operation of the systems (i.e. only small flame was remained in the wood crib fire after the termination of the test).

In Test 1, Nozzle #2 and #3 (dummy nozzle) were not activated because the temperature in the test room was well controlled by the operation of Nozzle #1. Figure 11 shows the ceiling gas temperature at the room centre, which was lower than 100°C throughout the test.

(a) prior to the activation of HPWM

(b) after 30 seconds from the activation of HPWM

Figure 8 Condition in the test room (Test 1)

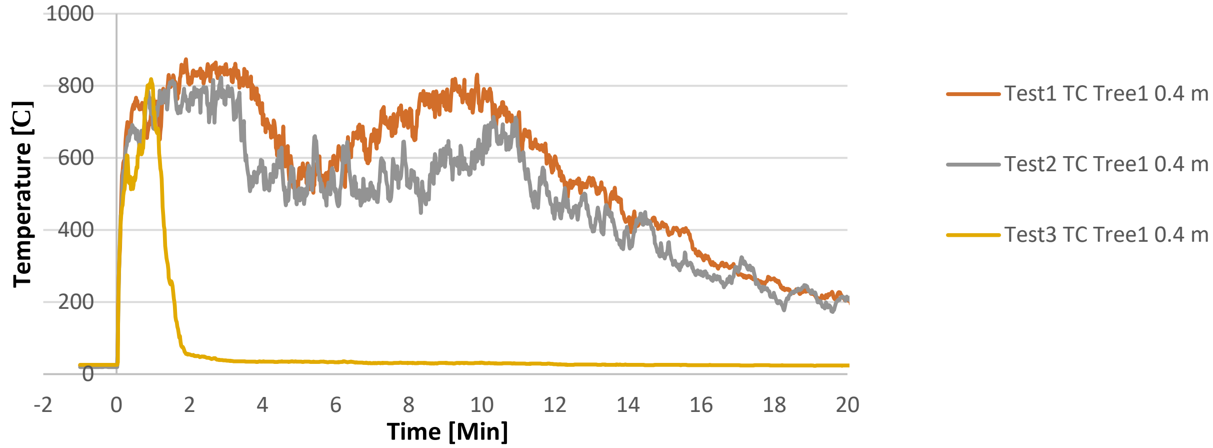


Figure 9 Flame temperature measured in HPWM Test 1-3

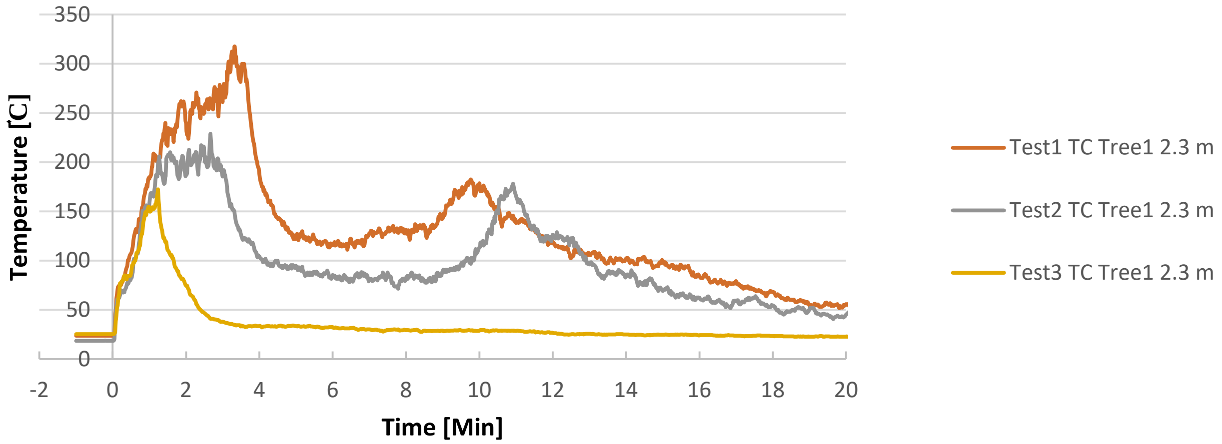


Figure 10 Ceiling gas temperature at the fire corner (thermocouple tree 1) measured in HPWM Tests 1-3

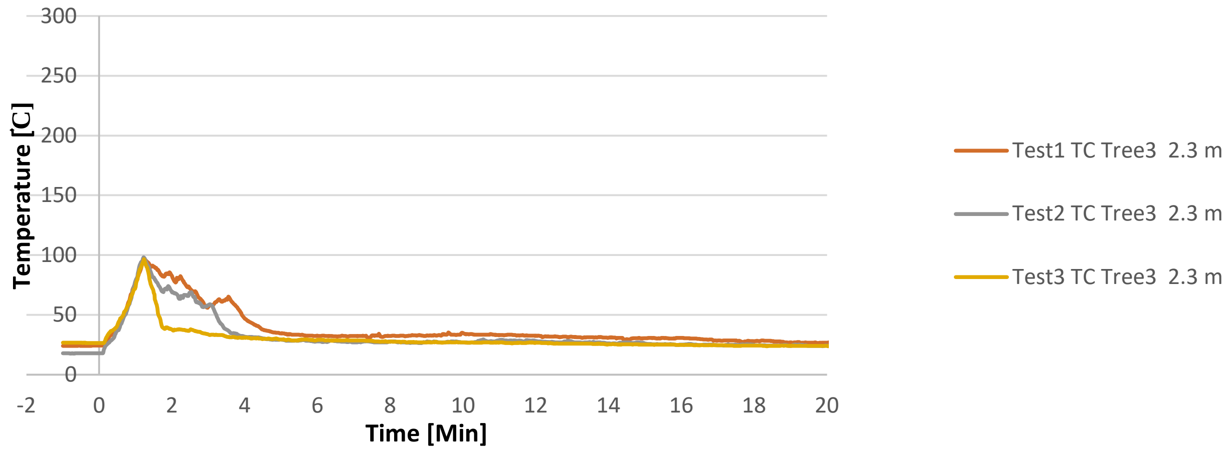


Figure 11 Ceiling gas temperature at the room centre measured in HPWM tests

In Test 2, the same type of nozzles (Type A) used in Test 1 was tested with a higher operating pressure of 72 bar to investigate the effect of operating pressures in controlling fire and cooling smoke. The water spray rate, which was calculated based on the K-factor and the measured operating pressure, was 20.4 l/min.

The fire development prior to the activation of Nozzle #1 in Test 2 was very similar to that in Test 1, which triggered Nozzle #1 with the temperature rating of 79˚C at 1.27 minutes. At the activation of Nozzle #1, the temperature measured at the fire corner in Test 2 was similar to that in Test 1 (see Figure 9).

The temperature data from Test 2 and Test 1 were similar such that the second peak was observed at approximately 10 minutes, as seen in the flame temperature at the corner (Figure 9) and ceiling gas temperature at the room centre (Figure 11). The effect of operating pressure was marginal on cooling smoke and suppressing fire.

As shown in Figure 11, the ceiling gas temperatures at the centre of the room were below 100˚C in Test 2, after the activation of Nozzle #1. Thus, Nozzle #2 and #3 (dummy nozzle) were also not activated in Test 2.

In Test 3, Type B nozzle was tested with an operating pressure of 80 bar. The water spray rate, which was calculated based on the K factor (4.1 lpm/bar$^{1/2}$) and the measured operating pressure, was 36.7 l/min. Figure 12 shows the test room before and after the activation of the system.

Nozzle #1 activated at 1.18 minutes from the ignition, approximately at the same times as in Tests 1 and 2, which is because of the relatively consistent initial fire development achieved over the fuel packages. The flame temperature (Figure 9) and ceiling gas temperature (Figure 10 and Figure 11) measured in Test 3 were also similar to Test 1 and 2 until the activation of Nozzle #1; however, Type B nozzle resulted in more effective fire control and smoke cooling than Type A nozzles tested in Tests 1-2. Within 1 minute from the activation of Nozzle #1, the ceiling gas temperature at the fire corner decreased to the ambient level, and the system extinguished the fire within approximately 1 minute from the activation (see Figure 9). Consequently, Nozzle #2 and #3 (dummy nozzle) were not activated in Test 3 because of the rapid suppression and cooling by the operation of Nozzle #1.

The system was operated for 20 minutes, and during and after the operation time, the fire did not grow back.

When compared with Type A nozzle, Type B nozzle demonstrated more effective fire suppression and smoke cooling due to the nozzle design since Type B is designed for property protection, which is a more sever requirement than life safety only, for which Type A is designed. As shown in Figure 9 and Figure 10, the flame temperature and ceiling gas temperature decreased immediately with the activation of the nozzle (Type B).

(a) prior to the activation of HPWM (b) after 30 seconds from the activation of HPWM

Figure 12 Condition in the test room (Test 3)

3.2.2 Delayed activation of HPWM

In Tests 4 and 5, Type B nozzles and Type A nozzles, respectively, were tested by delaying the activation manually. The response time of the nozzle with a temperature rating of 79°C was detected by monitoring the pressure changes in the water supply pipeline caused by the breakage of the fusible glass link at the nozzle. However, in these tests the water supply was manually held closed for approximately 1 minute from the breakage of the fusible glass link. These tests enabled the investigation of fire spread to the CLT wall and ceiling panels due to mainly the manually delayed intervention of the suppression system.

In Test 4, for the duration of 2 minutes from the ignition, the fire developed very quickly by involving the entire CLT wall and ceiling panels installed at the fire corner. The flame started to come out through the doorway close to the fire corner, which indicated that the room was about to flashover. The flame was also observed outside the test room, along the edges of the wall and ceiling. To protect the test room, water was applied outside the test room to extinguish the flame penetrated through the joints and gaps.

With the fire development in the room, Nozzle #2 and #3 (dummy), following the delayed activation of Nozzle #1, also responded to the fire. The times at which the fusible glass links broke were monitored, but the water supply was delayed as the water supply valve was hold closed. The response times were 1.45 and 1.68 minutes, respectively for Nozzle #2 and #3. Figure 13 shows the test room before and after the activation of the system in Test 4. The maximum ceiling gas temperatures measured were 800°C and 660°C at the fire corner and the room centre, respectively. In Figure 15, the impact of the delayed activation on the ceiling gas temperature observed in Test 4 is compared with that in Test 3.

At approximately 2.1 minutes from the ignition, the water supply line was manually opened in Test 4, and water was discharged in the test room through the two nozzles, Nozzle #1 and #2. The HPWM reached an operational pressure of 50 bar at 2.5 minutes due to a malfunction of the pump, and then the operating pressure became the correct 80 bar in 2-3 minutes. The HPWM system using Type B nozzle effectively extinguished the fire within 2 minutes.

The rate of water sprayed through the two nozzles, calculated based on the K factor and the measured operating pressure, was 73.3 l/min.

In Test 5, the Type A nozzle was tested with a delayed activation. The fusible glass links at the three nozzles broke at 1.1, 1.6 and 2.1 minutes, respectively for Nozzle #1, #2 and #3. Similarly to Test 4, the water line was manually opened after 56 seconds from the response time of Nozzle #1. After 2.1 minutes from the ignition, the fire in this test also developed quickly, but slightly slower than Test 4. Figure 16 compares the ceiling gas temperature in the delayed activation against the automatic activation of the system. It can be seen that, the maximum ceiling temperatures at the fire corner measured in Test 5 (delayed activation) and Test 1 (automatic activation) were 780°C and 300°C; respectively.

In Test 5, water was sprayed in the test room through Nozzle #1 and #2, with an operating pressure of 52 bar. The rate of water sprayed through the two nozzles, which was calculated based on the K factor and the measured operating pressure, was 34.6 l/m. The HPWM system using Type A nozzle effectively controlled the fire although the activation was delayed by approximately 1 minute. Figure 14 shows the test room before and after the activation of the HPWM system in Test 5.

As demonstrated in Test 4 and 5, the suppression effectiveness of water mist system systems generally becomes more distinctive with large fires in a compartment unless the fire size does not overpower the water mist systems. The larger the fire size in a compartment, the more the heat transfer would occur between the fine water mist and the fire plume, which would maximize the evaporation of the fine water droplets and eventually suffocate the fire effectively.

(a) prior to the activation of HPWM (b) after 20 seconds from the activation of HPWM

Figure 13 Condition in the test room (Test 4)

(a) after 5 seconds from the activation of HPWM (b) after 20 seconds from the activation of HPWM

Figure 14 Condition in the test room (Test 5)

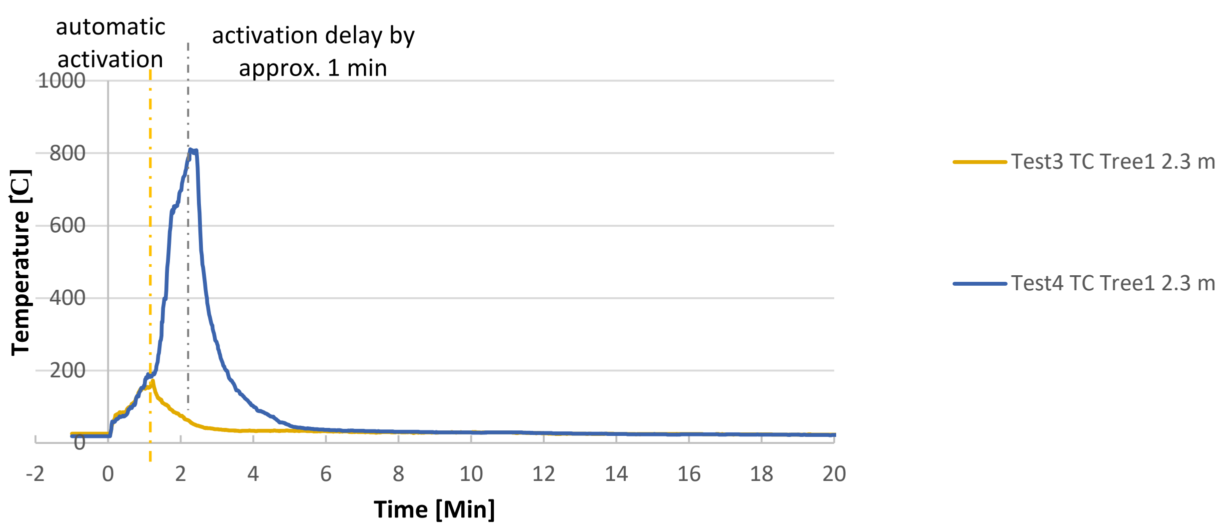


Figure 15 Ceiling gas temperature at the fire corner (thermocouple tree 1) measured in HPWM Test 3 and 4

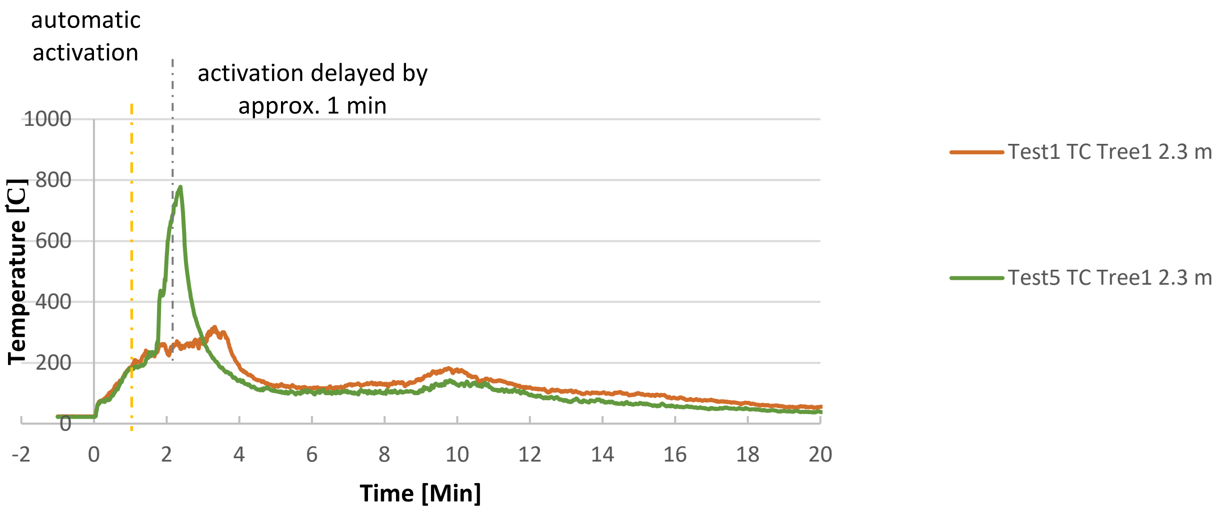
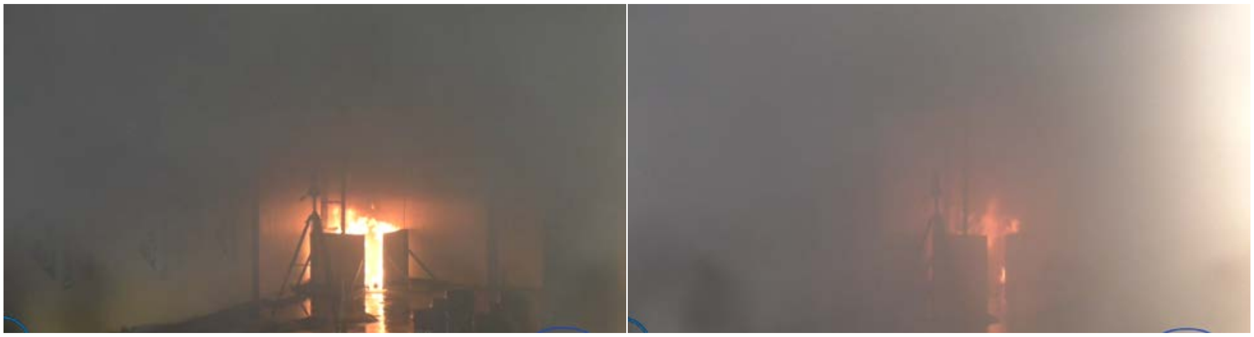


Figure 16 Ceiling gas temperature at the fire corner (thermocouple tree 1) measured in HPWM Test 1 and 5

3.2.3 Low pressure water mist tests

Two tests were conducted using the LPWM system using Type C nozzle. To provide the required operating pressure of 8 bar, a pump system was installed on the water supply line to the two nozzles installed on the ceiling. A dummy nozzle was also installed near the doorway. The three nozzles had a temperature rating of 79°C.

In Test 6, Nozzle #1 was activated at 1.38 minutes, and the system reached the full operating pressure of 8 bar at 1.57 minutes. At the time of activation, the fire fully developed over the simulated furniture and wood crib at the corner. The LPWM system sprayed an amount of 48.4 l/min, which was calculated based on the operating pressure and the K-factors of 16.5 lpm/bar$^{1/2}$. The LPWM system limited the fire spread to the CLT panels and suppressed the fire within 4 minutes from the activation. The ceiling gas temperature measured at the room centre also decreased to the ambient level within 4 minutes from the activation. Similar to HPWM systems, when tested for automatic activation with no delay, activation of Nozzle #2 and #3 (dummy) didn't occur. The LPWM system was shut off at 10 minutes. Figure 18 and Figure 19 show the flame temperature measured at the fire corner and the ceiling gas temperature measured at the room centre, respectively. It should be noted that a small flame grew back at the fire corner at about 11 minutes (after 1 min from shutting off the system) but self-extinguished soon after.



(a) Prior to the activation of LPWM (b) after 20 seconds from the activation of LPWM

Figure 17 Condition in the test room (Test 6)

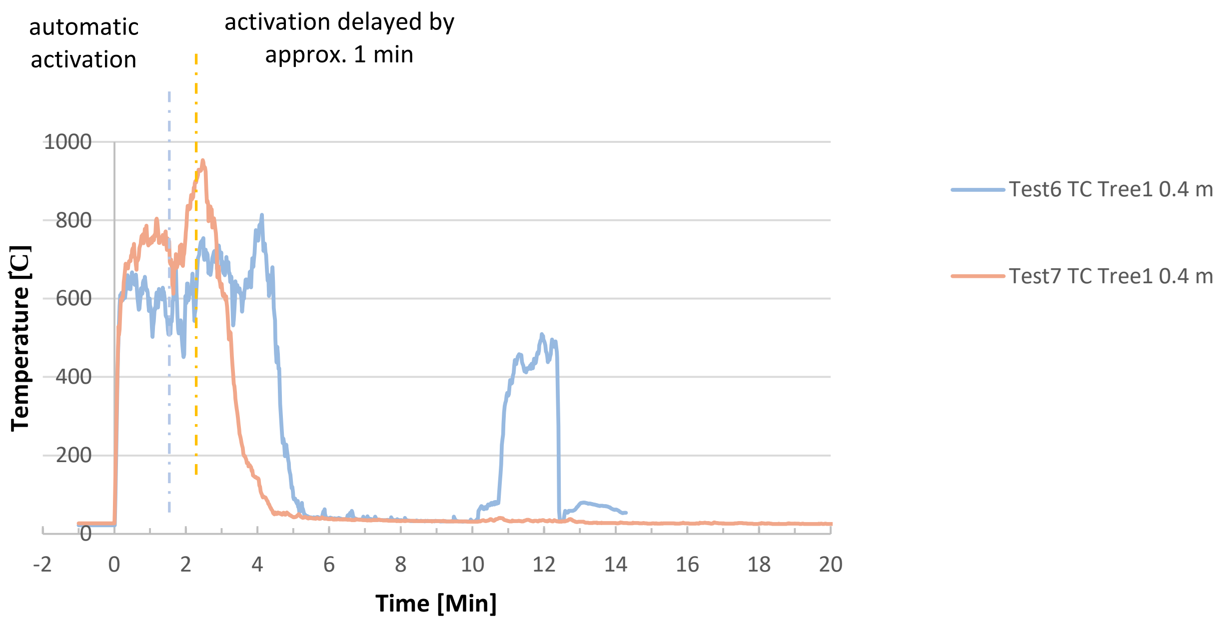


Figure 18 Flame temperature measured in LPWM Test 6 and 7

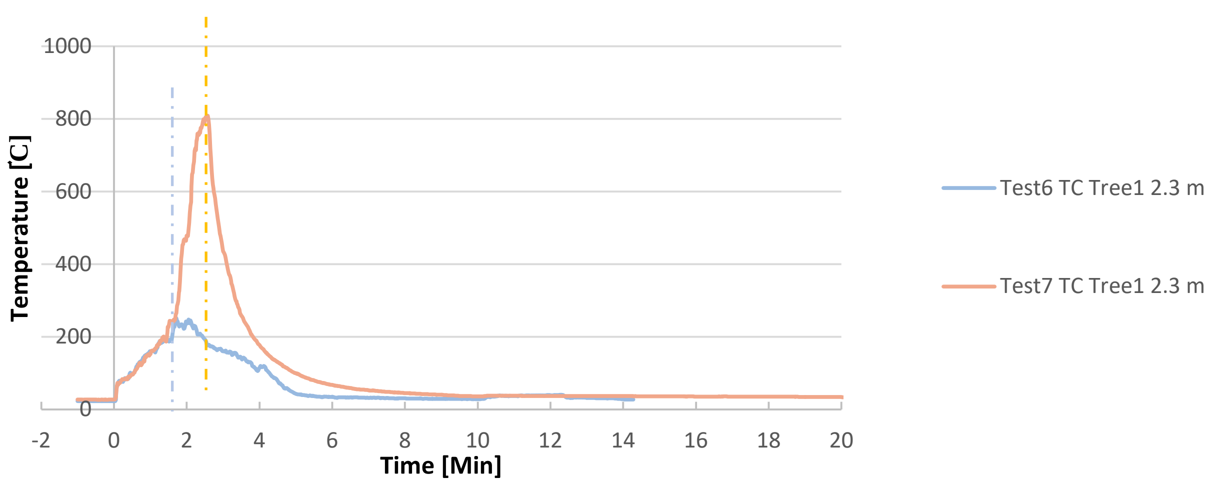


Figure 19 Ceiling gas temperature at the fire corner (thermocouple tree 1) measured in LPWM Test 6 and 7

3.2.4 Delayed activation of LPWM

In Test 7, the same LPWM system using the Type C nozzle was tested with a delayed activation. The response time of Nozzle #1 was 1.1 minutes, yet the water supply line was delayed by 1.3 minutes and manually opened at 2.5 minutes from the ignition. The delayed activation resulted in fire spread to the entire CLT ceiling panel, and the ceiling gas temperature measured at the centre of the room was 800˚C immediately prior to the start of water spray (at 2.5 minutes). Figure 18 and Figure 19 show the impact of the delayed activation of the LPWM on the flame temperature and the ceiling gas temperature at the fire corner in comparison to Test 6 (automatic activation). The high temperature in the room broke the fusible glass links of Nozzle #2 and #3. The response time of Nozzle #2 was at approximately 1 minute after the activation of Nozzle #1, and almost at the same time the dummy nozzle also responded (at 2.0 minutes from the ignition). When the water line was opened manually, the LPWM system effectively controlled the fire and decreased the temperature in the room by spraying water through the two nozzles. The water spray rate through the two nozzles was 96.8 l/min, which was calculated based on the operating pressure of 8 bar and the K-factors of 16.5 lpm/bar$^{1/2}$. As shown in Figure 18, the LPWM system with the delayed activation demonstrated effective control of the flame temperature in Test 7, which was more effective than with the automatic activation in Test 6.

(a) Prior to the activation of LPWM (b) after 10 seconds from the activation of LPWM

Figure 20 Condition in the test room (Test 7)

3.2.5 Sprinkler tests

To compare with the HPWM and LPWM systems, the sprinkler system using Type D nozzles approved for residential application were tested with automatic activations with a temperature rating of 79˚C.

In Test 8, Nozzle #1 was operated with the required pressure of 0.94 bar and was activated at 1.7 minutes from the ignition. The sprinkler system was effective on the wood crib fire but not on the simulated furniture fire, which contributed to the subsequent activation of Nozzle #2 at 2.7 minutes. The ceiling temperatures at the room centre were 92°C and 128°C at the activation time of Nozzle #1 and #2, respectively. After the activation of Nozzle #2, the pump pressure accidently dropped, and the operating pressure decreased to 0.3 bar. The low operating pressure resulted in increasing the ceiling temperature at the centre of the room to 180°C. The dummy nozzle (#3) was also activated at 3.9 minutes when the gas temperature at the location became 126°C. After 2 minutes, the sprinkler systems gained the pressure loss, and the operating pressure became normal at 5 minutes. With the required pressure of 0.9 bar, the ceiling temperature at the room centre also decreased to 50°C at 6 minutes.

Due to the pressure problem, the sprinkler system test was repeated in Test 9. Nozzle #1 was activated at 1.6 minutes with the required operating pressure of 0.9 bar. Nozzle #2 was also activated at 2.7 minutes, about the same time as in Test 8. With the activation of Nozzle #2, the operating pressure again dropped to 0.4 bar. The test data from Test 9 are very similar to those from Test 8, in which the system with the low pressure allowed the increase of the celling gas temperature at the room centre and the fire prolonged by approximately for 2 minutes. The dummy nozzle (#3) was also activated at 3.2 minutes when the gas temperature at the location became 122°C.

Test 8 and Test 9 verified the interaction of the sprinkler system with the fire for the initial stage of 2.7 minutes, and in particular, the sequence of the nozzle activations was well captured in these tests. However, it was necessary to carry out one more test to properly investigate the performance of the sprinkler system for the entire spray duration without any loss in the operating pressure.

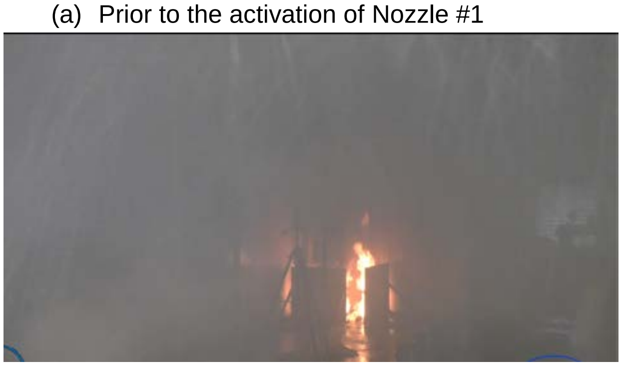
To avoid the subsequent pressure drops following the automatic activation of Nozzle #2, the sprinkler system test was repeated again with a fixed operating pressure (the required value of 0.9 bar) in Test 10. To maintain the operating pressure during the test, the activations of the nozzles were manually controlled following the sequence that were verified in Test 8 and 9.

The fire developed similarly in Test 10, and the nozzles were opened simulating the actual sequences observed in Test 8 and 9. The Nozzles were opened at 1.3 minutes (Nozzle #1) and 2.3 minutes (Nozzle #2), at which the ceiling gas temperature reached 101°C and 128°C, respectively. Figure 22, Figure 23 and Figure 24 show flame temperatures at the fire corner, ceiling gas temperature at the fire corner and ceiling gas temperature a t the centre of the room, respectively. The measurements in Tests 8-10 are similar until the activation of Nozzle #2 (2.3 minutes), where the measurements after that time in Tests 8 and 9 were affected by the dropped operating pressures. With the continuous operating pressure of 0.9 bar, there was no significant increase in the ceiling gas temperature at the centre of the room. Although there was a small visible flame over the simulated furniture, the temperature of the room decreased to the ambient level at 8 minutes, and the sprinkler system was turned off at 10 minutes.

The sprinkler system sprayed an amount of 83.8 l/min through the two nozzles installed in the room, which was calculated based on the K-factors of 43.2 lpm/bar$^{1/2}$ and the operating pressure of 0.94 bar.

(a) Prior to the activation of Nozzle #1

(b) Prior to the activation of Nozzle #2



(c) After 1 min after the activation of Nozzle #2

Figure 21 Condition in the test room (Test 10)

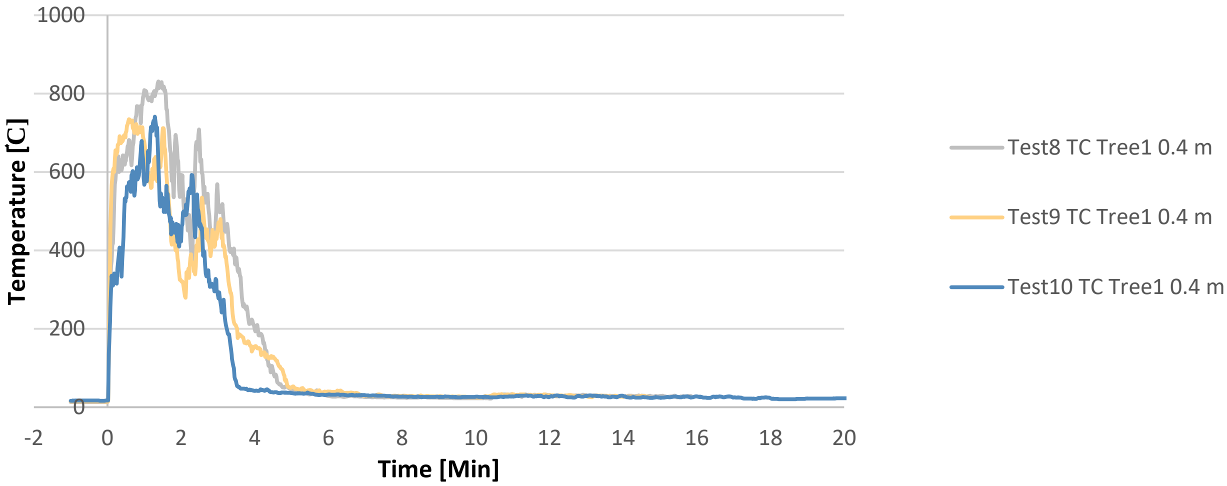


Figure 22 Flame temperature measured in sprinkler Test 8, 9 and 10

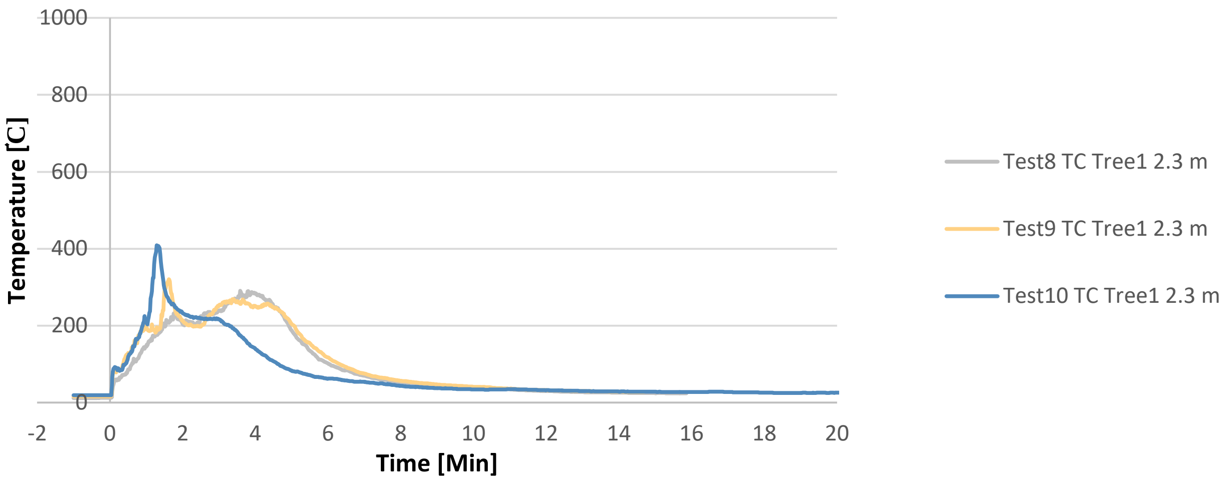


Figure 23 Ceiling gas temperature at the fire corner (thermocouple tree 1) measured in sprinkler Test 8, 9 and 10

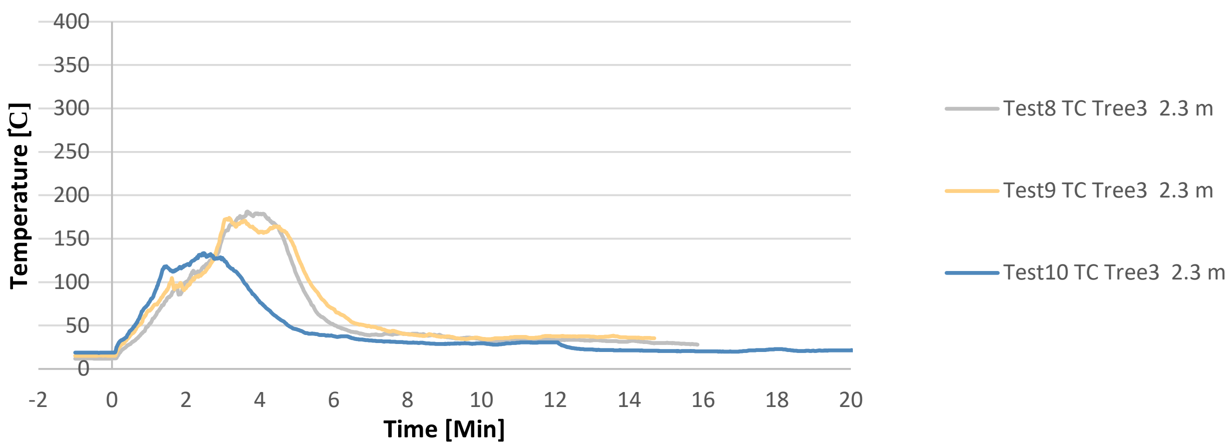


Figure 24 Ceiling gas temperature at the room centre (thermocouple tree 3) measured in sprinkler Test 8, 9 and 10

4 Discussion

This section compares the performance of the three investigated systems (HPWM, LPWM and sprinkler) in suppressing a residential fire involving exposed mass timber structures. Different perspectives are considered in the comparison to fairly assess the 3 systems.

4.1 Water spray rate

In each test of the HPWM system, only one nozzle was activated in the test room, and the HPWM system used the lowest water spray rates among the systems tested. The water spray rates, which were calculated based on the K factor and the measured operating pressure, was 17.3 l/min and 36.7 l/min for Type A nozzle with the K-factor of 2.4 lpm/bar$^{1/2}$ (Test 1) and Type B nozzle with K-factor of 4.1 lpm/bar$^{1/2}$ (Test 3), respectively.

The LPWM and sprinkler systems sprayed a comparable amount of 48.4 l/min and 42.0 l/min per a nozzle, respectively. However, the total water spray rate of the sprinkler system was two times larger than that of the LPWM system since the two nozzles installed in the room were activated in the sprinkler test while only one nozzle was activated in the LPWM test (when tested for automatic activation without delay of activation). The LPWM system was operated at a pressure 8 times higher than the sprinkler system. The K-factors of the LPWM and sprinkler systems were 16.5 lpm/bar$^{1/2}$ and 43.2 lpm/bar$^{1/2}$, respectively.

The water spray density was 0.9-1.1, 2.0, 2.7 and 2.3 l/min·m^2 for the HPWM system with Type A nozzles, the HPWM system with Type B nozzle, the LPWM with Type C and the sprinkler system with Type D nozzle, respectively. For sprinkler systems, the minimum required water spray density is 2.0 l/min·m^2 for residential buildings [12], [13] and 4.1 l/min·m^2 for residential buildings in mixed use [11] . Unlike the sprinkler system, water mist systems do not have generic design methods, and they are required to be designed based on verifications through full-scale fire tests due to the complex technical features.

The effectiveness of a fire suppression system depends on not only the water spray density but also on the spray duration and the total water discharge. The time required to decrease the ceiling temperature at the fire corner to 50˚C was approximately 19, 2, 4 and 7 minutes (from the system activation), and the total amount of water discharge until the time was approximately 340 l, 50 l, 170 l and 480 l for the HPWM Type A nozzle (Test 1 and 2), HPWM Type B nozzle (Test 3), LPWM Type C nozzle (Test 6) and sprinkler Type D nozzle (Test 10). When compared relative to the total amount of water discharge, the HPWM Type B nozzle required only 10% of the total water used by the sprinkler Type D nozzle to demonstrate the comparable effectiveness. Consequently, potential water damage on mass timber structures, which is assumed to be proportional to the total water discharge, could be minimized with a HPWM properly designed with a right type of nozzle.

4.2 Fire control

Initial fire development after the ignition was relatively consistent in each test by growing quickly over the standard fuel package (i.e. the simulated furniture and wood crib fire), which allowed to compare the performance of the suppression systems. In Figure 25, plotted are the flame temperatures measured above the wood crib at 0.4 m height in the HPWM (Test 1 and Test 3), LPWM (Test 6) and sprinkler system (Test 10) tests to compare the performance of each suppression system in controlling fires.

The flame temperatures were similar in all tests until the activation of the first nozzle (#1) installed close to the fire corner. Nozzle #1 was activated at 1.2, 1.2, 1.57 and 1.3 minutes, respectively in Test 1 (HPWM Type A nozzle), Test 3 (HPWM Type B nozzle), Test 6 (LPWM Type C nozzle) and Test 10 (Sprinkler Type D nozzle). It should be noted that the temperature rating of each nozzle was 79 ˚C, and each nozzle was installed as specified in the manufactures' installation instructions. Nozzle #2 was activated only in the sprinkler tests (when tested for automatic activation), and the time of activation was 2.3 minutes in Test 10.

After the activation of Nozzle #1, the flame temperatures varied depending on the fire suppression system used in each test. The longest time required to control the flame temperature at this measurement location below 300˚C was 17 minutes resulted from Test 1 with HPWM Type A nozzle, and the shortest time required was 1.5 minutes in Test 3 with Type B nozzle.

In Test 1, the activation of the HPWM system initially decreased the flame temperature, but the flame temperature increased again starting in approximately 5 minutes from ignition, which resulted in the second peak temperature at about 9 minutes. However, Nozzle #2 was not activated in Test 1 due to the relatively low temperature maintained in the test room by the operation of Nozzle #1. In Test 3, the HPWM designed for light hazard applications demonstrated rapid control of the fire by extinguishing the fire within 1 minute from the activation of the system, which saved a portion of the wood crib and the PU slabs remained unburned.

The sprinkler system also rapidly suppressed the wood crib fire, but the system did not immediately suppress the simulated furniture fire (PUF fire) since the fire was not directly facing Nozzle #1 and partially shielded from the water sprays. Consequently, Nozzle #2 was activated, and the sprinkler system suppressed the fire within 4 minutes from the ignition.

The LPWM system using Type C nozzle also suppressed the fire within approximately 5 minutes from the ignition, but a small flame grew back when the suppression system was closed at 10 minutes.

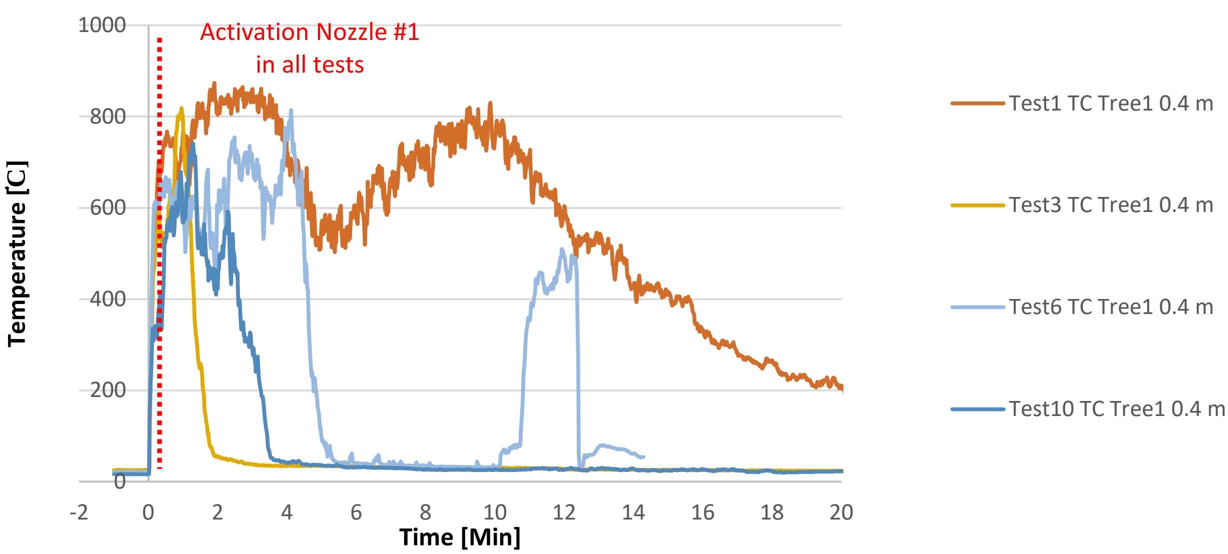


Figure 25 Flame temperature measured above the wood crib at 0.4 m height

In Figure 26, the total water spray rate is plotted against the time to lower the flame temperature (measured above the wood crib at 0.4 m height) to 300°C. The HPWM with Type B nozzle demonstrated rapid fire suppression within 1 minute from the activation of the system (Test 3 and Test 4) even when the activation was delayed by approximately 1 minute (Test 4). Comparably, the sprinkler system and the LPWM system suppressed the fire within about 3 minutes from the activation. With the HPWM system using Type A nozzles, however, the flame remained for 12-16 minutes after the activation. The HPWM system using Type A nozzle was operated for 30 minutes, but the operation of other suppression systems was terminated after 10 minutes when all combustibles were extinguished or only the wood crib sustained combustion. It should be noted that when the spray duration was too short (approx. 10 minutes), the fire grew back after shutting off the system. Thus, the effectives of a fire suppression system depends on not only the water spray rate and spray characteristics but also the spray duration. The minimum water supply duration currently required by NFPA 750 [16] is 10 minutes and 30 minutes for residential one-and-two family dwellings and residential up to 4 stories, respectively. NFPA 13 D [13] and NFPA 13 R [12] require a duration of 10 minutes and 30 minutes of water supply for one-and-two family dwellings and low-rise residential occupancies, respectively.

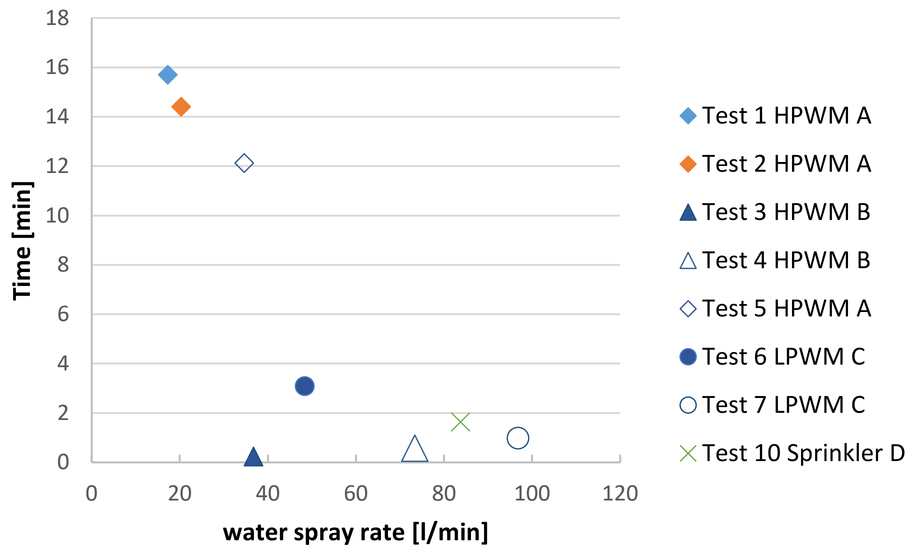


Figure 26 Total water spray rate against the time to lower the flame temperature (measured above the wood crib at 0.4 m height) to 300℃

4.3 Cooling effect

To compare the cooling effect of the HPWM, LPWM and sprinkler system, the ceiling gas temperature measured at 75 mm below the ceiling at Nozzle #1 and at the room centre were compared in Figure 27 and Figure 28, respectively. A maximum ceiling gas temperature criterion of 316˚C is required by UL2167 [5]and UL1626 [9] at these locations, and Cote [17] suggested a limit of 260˚C for gas temperature beneath the ceiling near the centre of a room. As shown in Figure 27 and Figure 28, the measured temperature data were below the required temperature because of the timely activation of Nozzle #1 occurred when the ceiling gas temperature at Nozzle #1 reached 110˚C-120˚C (The temperature ratings of the four nozzles were 79˚C). In addition, in the sprinkler systems tests, Nozzle #2 was also activated, which contributed to the cooling of smoke temperature in the test room.

The ceiling smoke temperature at the room centre (Figure 28) allowed to observe the cooling effect of the systems since the measurement at this location had less interference from water sprays than at the thermocouple tree #2 (Figure 27). The cooling effect of the HPWM and LPWM systems tested in Test 1, 3 and 6 were comparable, as shown in Figure 28. However, the sprinkler system resulted in slightly higher ceiling temperature than the water mist systems although the system sprayed water at the rate of 83.8 l/min, which is four times larger than the rate of 17.3 l/min by the HPWM using Type A nozzle.

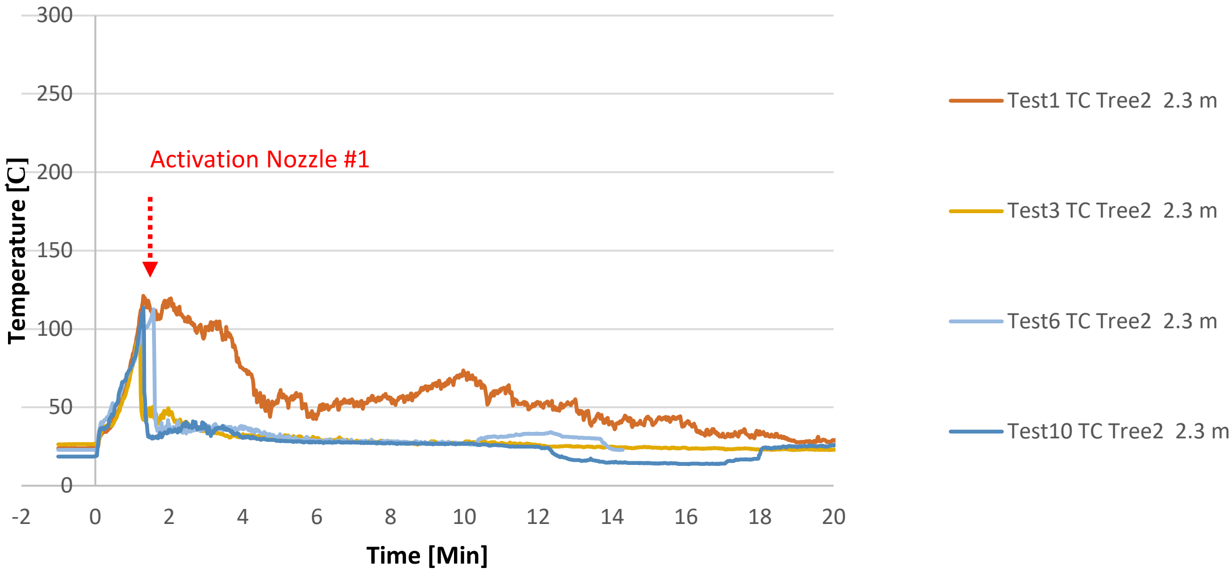


Figure 27 Ceiling gas temperature measured at 2.3 m height near Nozzle #1

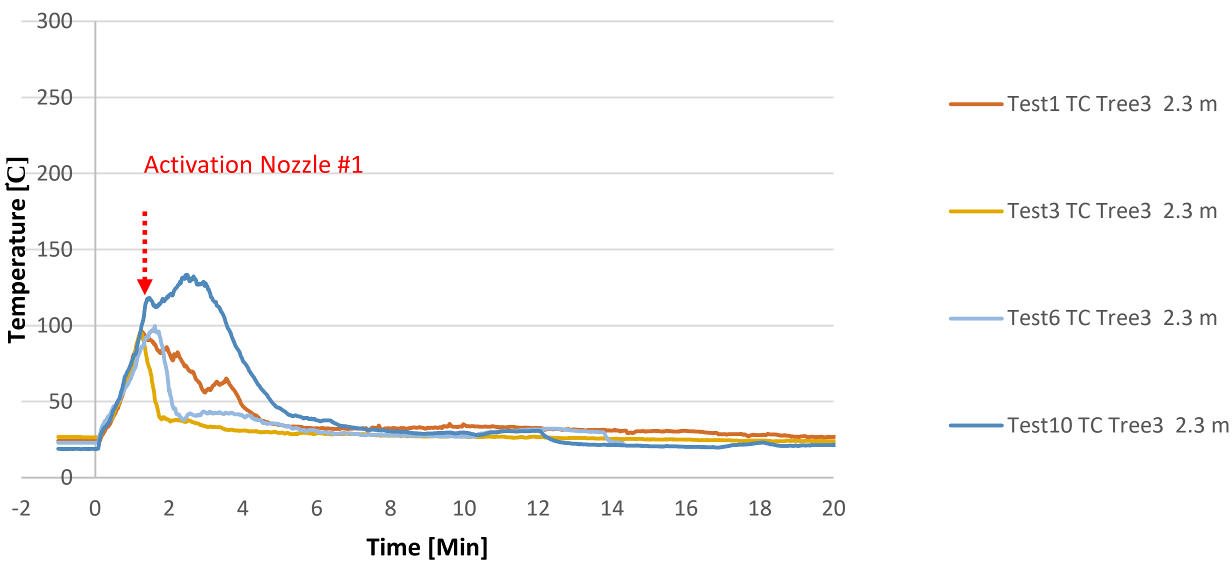


Figure 28 Ceiling gas temperature measured at 2.3 m height at the room centre

The maximum ceiling gas temperature at room center were limited below approximately 130°C by the HPWM, LPWM and sprinkler systems, when automatically activated without any delay for all the tests. In the tests with delayed activations, the maximum ceiling temperatures at the room centre were greater than 280°C, which resulted in significant fire damages on the CLT ceiling panels.

4.4 Tenability and life safety

The main design objective of the suppression system for residential buildings is to ensure life safety of the building occupants. Sprinkler systems are required to limit the severity of the fire so that the system can allow occupants sufficient time to evacuate the building [18]. With its focus primarily on providing life safety, BS 8458 [8] requires water mist systems for domestic and residential occupancies be designed to suppress and control fires. The performance objectives of conventional sprinkler system specified in NFPA 13 [11], NFPA 13D [13] and NFPA 13 R [12] are providing life safety by controlling fire, limiting the effect of fire and decreasing the heat release rate while wetting combustibles and controlling ceiling gas temperature.

The tenability criteria suggested for residential sprinkler systems [18] were as follows:

- Room Temperature: 65.6 ˚C at 1.524 m from the floor
- Oxygen 14% at 1.524 m from the floor
- Carbon monoxide 10,000 ppm (1%)
- Optical density 0.166 1/m, which is equivalent to the smoke obscuration of 31.9%/m (11%/ft)

4.4.1 Room temperatures

With automatic activation of the nozzles, the HPWM, LPWM and sprinkler systems maintained the room temperature at 1.6 m height below the temperature criterion of 65.6˚C. Figure 29 compares the room temperature data measured at 1.6 m height at the centre of the test room for the HPWM, LPWM and sprinkler systems, which also met the requirements by UL2167 and UL1626 of the room temperature not exceeding 93˚C during the test and not exceeding 54˚C for more than any continuous 2-minute period.

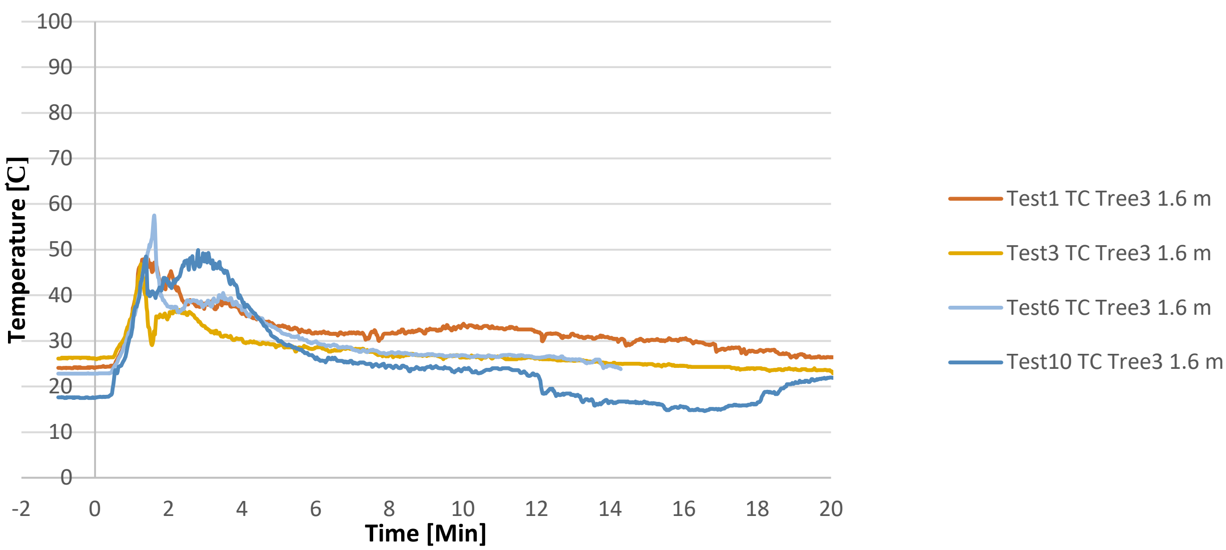


Figure 29 Room Temperature measured at the center 1.6 m height

4.4.2 Smoke obscuration and Visibility

For residential buildings, the smoke obscuration criterion suggested is optical density 0.166 1/m [18], for which the estimated visibility would be 7.81 m for light reflecting signs. Respectively in Figure 30 and Figure 31, plotted are the visibility in the test room calculated for light reflecting signs and the optical density measured in the tests with sprinkler, LPWM and HPWM systems. As shown in Figure 31, the smoke optical density measured in the room increased rapidly and reached the criterion value of 0.166 1/m within 2 minutes from the ignition in all tests.

It should be noted that, while the smoke from the fire contributed most to the low visibility in the room, the water (mist) droplets discharged from the nozzles could also lower the visibility in the room. To quantify the obscuration caused only from the operation of the suppression systems, the optical density was measured during the water spray tests conducted without the fire. As shown in Figure 32, while the operation of the sprinkler system did not affect the obscuration in the room, the water droplets discharged from the LPWM and HPWM significantly affected the obscuration in the room. In particular, the operation of the HPWM with Type B nozzles with no fire resulted in the optical density in the room much higher than the criterion value of 0.166 1/m.

As demonstrated in Test 3, the water mist discharged from the HPWM system did not worsen the visibility in the test room since the same level of optical density was measured in the early stage of the fire. In fact, the HPWM system gradually improved the obscuration in the test room after the rapid fire suppression while the obscuration was not improved with the sprinkler system (Test 10).

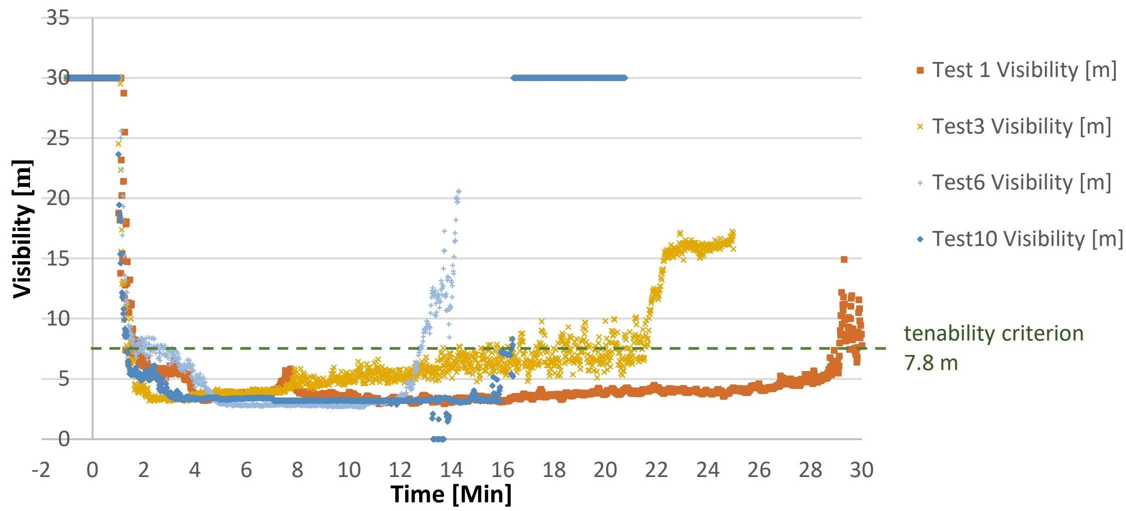


Figure 30 Visibility measured in the test room at 1.6 m height

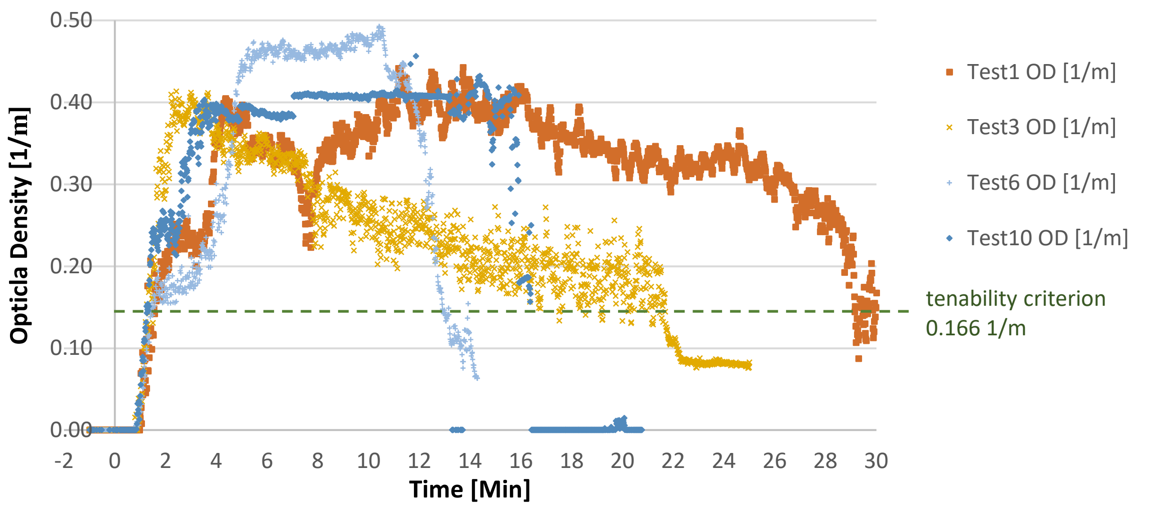


Figure 31 Optical density measured in the test room at 1.6 m height

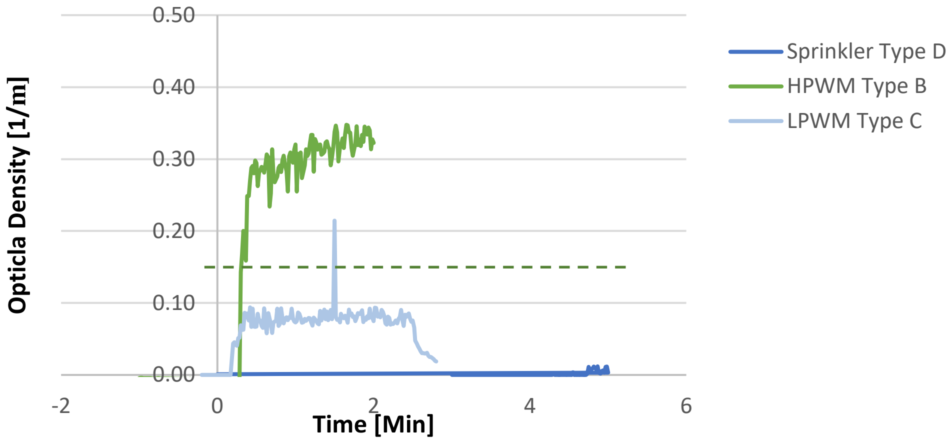


Figure 32 Optical density measured in the test room at 1.6 m height without fire

4.4.3 Gas concentrations

The gas samples collected at the centre of the room at 1.6 m height were analyzed to estimate the oxygen and carbon monoxide concentrations in the room. The oxygen concentrations and carbon monoxide concentrations are plotted in Figure 33 and Figure 34, respectively. Both oxygen and carbon monoxide concentrations were maintained much lower than the criteria values suggested by the standards for the sprinkler, LPWM and HPWM systems with automatic activations. However, the delayed discharge of water (by approximately 1 minute) in Test4 let the oxygen concentration decrease to 12.7% and the carbon monoxide concentration increase to 0.7% (reflecting the condition of the fire prior to the activation of the system). However, the gas concentrations were recovered within 2 minutes from the activation of the suppression.

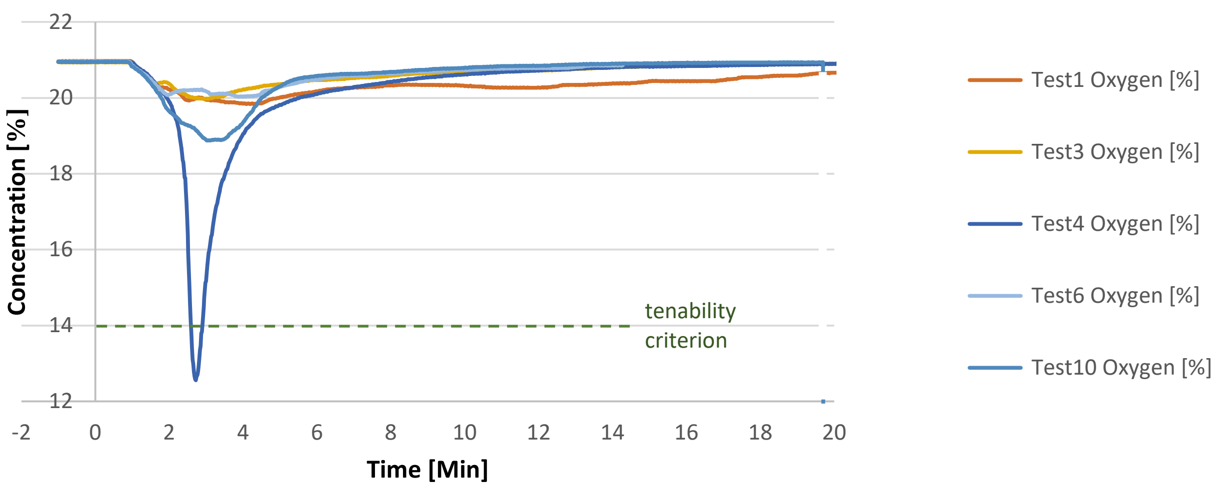


Figure 33 Oxygen concentrations measured in the test room at 1.6 m height

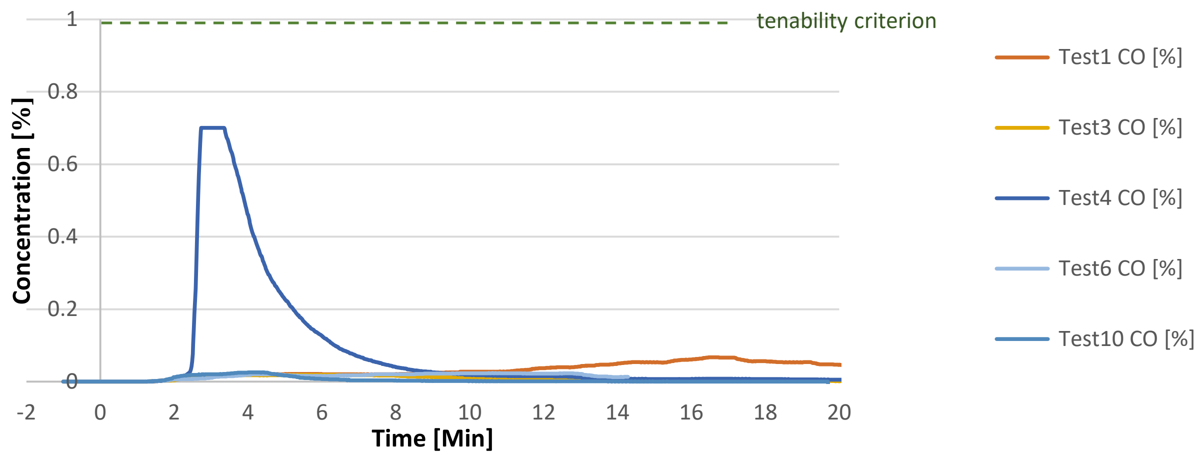


Figure 34 Carbon monoxide concentrations measured in the test room at 1.6 m height

4.5 Property protection

In order to assess the property protection capability of each system, both the damage on the CLT panels and CLT ceiling temperature were considered. One thermocouple was installed on the CLT ceiling panel at the fire corner to measure the surface temperature. As shown in Figure 35, initially for the first 1 minute, the CLT ceiling temperature increased rapidly until the activation of the fire suppression system. Notably, the ceiling surface temperature abruptly decreased with the activation of the HPWM used in Test 3, while the HPWM in Test 1 was able to decrease the temperature after spraying water for about 2.5 minutes. The results from Test 5 showed that the delay in activation would result in fire spread to the ceiling. In Test 6, the measured CLT ceiling temperature also decreased within 1 minute from the activation of the LPWM system, which was also designed for light hazards. With the sprinkler system in Test 10, the measured maximum CLT ceiling temperature was 264˚C, and the temperature decreased to 180˚C after the first activation of Nozzle #1 and decreased further after the activation of Nozzle #2.

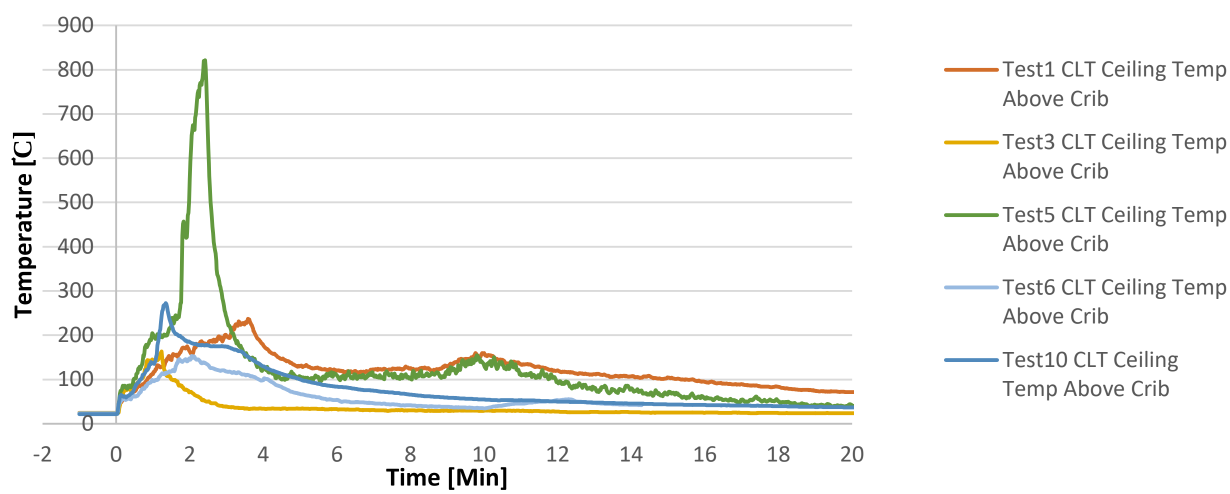


Figure 35 CLT ceiling temperature (the measurement location being above the wood crib)

While the HPWM, LPWM and sprinkler systems kept the room temperature low, the damage made on the CLT wall and ceiling panels varied depending on the system types and nozzle specifications. With the normal operation of the suppression systems, there was no severe fire damage made on the ceiling CLT panel. For the wall panels, however, the HPWM system tested in Test 1 resulted in damage on both sides of the CLT wall panels, with significant charring at the corner mainly due to the wood crib fire. Figure 36 shows the fire damage on the CLT panels. The HPWM system using Type B (in Test 3) nozzles, which are designed for light hazards, protected the CLT wall panels, leaving only slight charring on the wall panels. Similarly in Test 6, the LPWM system using Type C nozzles, which are also designed for light hazards, provided relatively good protection for the wall panels (see Figure 36). The sprinkler system also provided good wall protection as the water spray angle was wide enough to wet the walls up to ¾ of the room height.

Figure 36 Fire damage on the CLT panels

4.6 Delayed activation and fire damage on CLT panels

In Test 4, 5 and 7, the activation of the nozzle was delayed approximately one minute to investigate the performance of the HPWM (Test 4 and 5) and LPWM (Test 7) with delayed activation. Figure 37 shows the fire damage on the CLT walls and ceiling with delayed activation of the suppression system. With the delayed activation of approximately 1.0 and 1.3 minutes in tests 4 and 7, respectively, the fire spread to the CLT walls and ceiling, and the flame was also penetrating through the joints of the CLT walls and ceiling. The HPWM and LPWM system effectively suppress the fire, but the CLT panels were severely damaged (i.e a large area was charred, and the depth of charring in some areas was approximately 5-10 mm). When delayed by approximately 56 seconds in Test 5, the damage on the walls and ceiling was less severe. The camera footage revealed that the fire at the system activation (after the delay time of slightly over 1 minute) in Test 4 was much more violent than the fire at the system activation (after the delay time of 56 seconds) in Test 5,

When delayed activations are expected in system designs (e.g. employing dry pipe systems), the risk of fire spread to the combustible mass timber should be considered. Also, the delayed time requirements for the suppression systems designed for the protection of the mass timber structure should be re-examined to ensure the protection for the exposed mass timber structural elements.

Test 4

Test 5

Test 7

Figure 37 Fire damage on the CLT walls and ceiling with delayed activation of suppression systems

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4.7 Water damage

The water damage from different tests was assessed based on the moisture content of the CLT panels. The ambient temperature was measured in each test, and the average value was 20±5˚C. The relative humidity in the testing site (San Antonio, Texas), during the week of the testing in October peaked at 84% in the night then drops to 17-56% by mid-afternoon. The average humidity during the week of the testing was 56±21%.

Moisture contents were measured on the wall and ceiling panels before and after the fire test at the measruement points on the exposed CLT surface, as shown in Figure 4. The measurements were made with a pin-type moisture meter at approximately 5 mm deep from the exposed surfaces. Post-test moisture contents were mesuerd in selected tests at the same locations. In Figure 38, the moisture contents measured in each test are plotted, and Figure 39 compares the average moisture contents measured for the tests conducted.

The pre-test moisture contents were similar among the tests, and the values averaged over the 10 measruement points were in the range of 12.3 – 15.1% for all tests. The post-test values measured in 18- 24 hours were similar to the pre-test value. When measured in 18-24 hours after Tests 1 (HPWM Type A nozzles), 5 (HPWM Type A nozzles) and 7 (LPWM Type C nozzles), the moisture contents were recovered to the pre-test measruments.

Overall, the moisture contents measured on the CLT panel surfaces after the fire suppression test were not sensitive to the type of system tested since the water spray wetted only the surface and were not absorbed deeper into the CLT panels from the surface. After stopping the water spray, the wet CLT panel surfaces quickly dried. In Test 8, the measurements were made in 20 minutes after the sprinkler test, and the value was 37% highter than the pre-test value. When measured in 2 hours after the LPWM test (Test6), the post-test value was 17.2%, which was close to the pre-test measrument of 15.1%. Therefore, the recovery of moisture contents were not monitored beyond the time period of 24 hrous since the changes were not apparent beyond the time.

Water sprayed on the wall and ceiling surfaces was not deeply absorbed into the CLT panels but dropped and formed a large pool on the floor. The amount of the pooled water appeared proportional to the total water spray rate in each test. Unlike the wall and ceiling surfaces, water penetrated into the joints (wall-ceiling and the wall-floor interfaces), and the whole bottom edge of the CLT wall panels, in particular, absorbed water. The moisture contents measured on the bottom edges after 24 hours from the HPWM test (Test2) were 35% higher than the pre-test value. It should be noted that the edge measurements were obtained from the wall panels after they were dismentled and stored outdoor for 24 hours. In an actual building, it is expected that the water pooled on the floor could cascade down and penetrate deeply to connecting structural elements through the edges unless they are sealed.

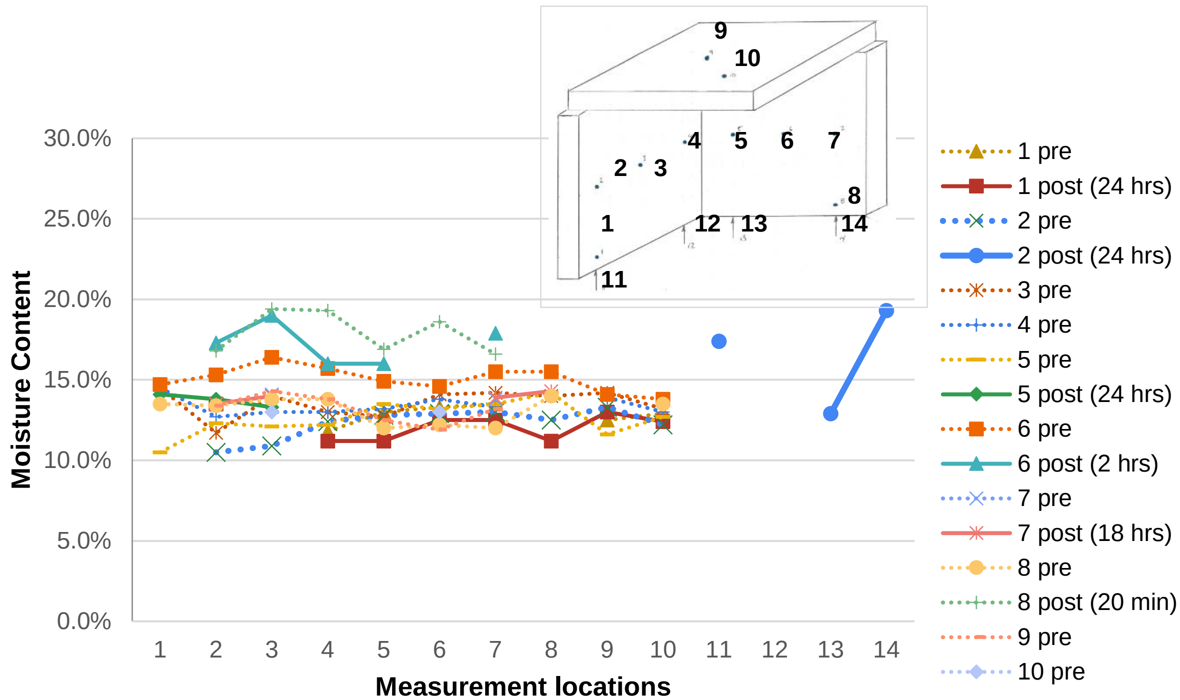

Figure 38 Moisture contents measured in each test

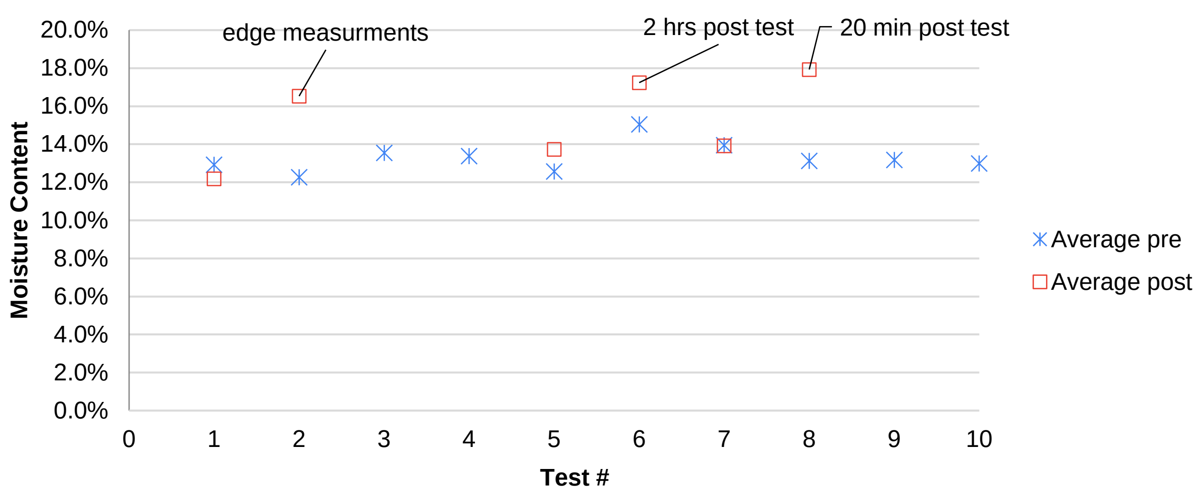

Figure 39 Average moisture contents

5 Conclusions

The effectiveness of HPWM (Type A and B nozzles), LPWM (Type C) and sprinkler systems (Type D) was investigated in a residential fire involving mass timber structures exposed without thermal barriers. For each system, two nozzles were installed as per manufacture's specifications in the test room (with dimensions of 8.53 m (L) × 4.27 m (W) × 2.4 m (H)).

Five tests were conducted using the HPWM system; 2 tests using Type A nozzle (at 2 different pressures), 1 using Type B nozzle and 2 test for delayed activation of Type A and B nozzles. From these tests, it can be concluded that:

1- The effect of operating pressure (i.e. within the range given by the manufacture) for the same type of HPWM nozzles was marginal on smoke cooling and fire suppression.
2- Type B nozzle (approved for light hazards applications) resulted in more effective fire suppression and smoke cooling than Type A nozzle (approved for residential applications).
3- The delayed activation of the nozzles resulted in more damage to the CLT panels and higher ceiling gas temperatures since the fire spread quickly to the CLT walls and ceiling before the activation of the suppression system.

Two tests were conducted for the LPWM; one with automatic activation and the other manually delayed activation. Finally, one successful test was conducted using sprinklers system. The performance of the 3 systems was compared from different considerations:

1- Spray characteristics: The most distinct characteristic of the HPWM and LPWM systems was fine water droplets generated from the nozzles. Operated at the relatively high pressures (52 – 80 bar), the HPWM is expected to generate finer water droplets with a lower mean droplet size than the LPWM, which was operated at 8.6 bar. Due to the fine water droplets, both HPWM an LPWM system demonstrated effective smoke cooling in the room. However, the visibility in the room was reduced for the fine mists when the HPWM and LPWM systems were tested even without a fire in the room, while the visibility in the room was not affected when the sprinkler system was operating without a fire.

The HPWM system with Type A nozzle, used in Test 1, 2 and 5, sprayed fine water mist with a relatively narrow spray angle (approximately 90°), and the fine water mist, filling up the test room, suppressed the fire and limited the fire spread to the CLT walls and ceiling. On the contrary, the HPWM system with Type B nozzle, the LPWM system with Type C nozzle and sprinkler system with Type D nozzle sprayed water at wide angles, which were enough for water sprays to reach the walls surrounding the fire corner. These systems with wide spray angles resulted in limited fire damage on the CLT walls.

Current standards require to have a wide spray pattern for traditional sprinklers for their primary suppression mechanism of direct surface wetting. However, current water mist system standards do not set any requirements for the spray pattern as such, as it is the system performance in full scale fire tests that counts, and the same performance objective may be reached with very different water mist sprays with direct surface wetting being only one of the contributing mechanisms like gas cooling, local oxygen depletion and blocking of radiant heat.

2- Water spray rate: Only nozzle #1 was activated in the LPWM and HPWM tests, while the 2 nozzles were activated in the sprinkler test. The HPWM system had the lowest spray rate among the 3 systems. The spray rate of the LPWM and sprinkler systems were comparable (48.4 l/min and 42 l/min); however the total spray rate of the sprinkler was higher (twice the aforementioned value) due to the activation of the 2 nozzles.

The total water discharged to decrease the ceiling temperature at the fire corner to 50˚C was approximately 340 l, 50 l, 170 l and 480 l for HPWM Type A nozzle (Test 1 and 2), HPWM Type B nozzle (Test 3) and sprinkler Type D nozzle (Test 10), Among the systems tested, the HPWM Type B nozzle demonstrated the most effective fire suppression relative to the total amount of water used (i.e. the HPWM Type B nozzle used only 10% of the total water used by the sprinkler Type D nozzle to demonstrate the comparable effectiveness). Consequently, the HPWM Type B nozzle could minimize the potential water damage to the building.

Also, the varying total amounts of water discharge indicate that the required spray duration needs to be considered along with the spray rate in designing a fire suppression system. The minimum water supply duration currently required by NFPA 750 [16] , NFPA 13 D [13] and NFPA 13 R [12] is 10 minutes and 30 minutes for residential one-and-two family dwellings and low-rise residential occupancies, respectively.
.

3- **Fire suppression performance:** Due to the distinct spray angles, spray patterns and water spray rates, each system resulted in varying degrees of protection for the test room. HPWM Type A nozzle required the longest time (17 minutes) to control the flame temperature below 300˚C, but HPWM Type B nozzle required only 1.5 minutes to extinguish the fire. It should be noted that direct comparison of Type A and Type B nozzles is not fair, since the HPWM Type B nozzle was designed for property protection in light hazard application and the HPWM Type A is designed for life safety in residential application. In comparison to the HPWM Type A system (equivalent system for residential application), the sprinkler system appeared less effective in suppressing the simulated furniture fire since the flame was partially shielded by the boards from the direct water sprays .When comparing Type B and Type C (i.e. both are designed for light hazard application), the HPWM Type B nozzle demonstrated much faster fire suppression discharging an amount of water much less than the LPWM Type C (30% of the total water discharge of the LPWM Type C).

4- **Cooling effect:** The HPWM, LPWM and sprinkler systems were able to limit the ceiling gas temperature at the room centre below approximately 130°C, when automatically activated without any delay. The sprinkler system resulted in slightly higher ceiling temperature than the water mist systems although the water spray rate of the sprinkler system (83.8 l/min via the two nozzles activated) was four times larger than that of the HPWM using Type A nozzle (17.3 l/min). In the tests with delayed activations, the maximum ceiling temperatures at the room centre were greater than 280°C, which resulted in significant fire damages on the CLT ceiling panels.

5- **Property protection consideration**: It should be noted that the CLT ceiling surface temperature developed very quickly within a short period time in all tests. The CLT ceiling surface temperatures were maintained lower than 272°C with all systems tested with automatic activation without delay, and no fire damage was found particularly on the CLT ceiling panel. On the CLT walls; however, the HPWM with Type A nozzle, LPWM and sprinkler systems did not prevent fire damages. The largest area was found damaged with the HPWM with Type A nozzle, and no damage was found on the CLT panels with the HPWM with Type B nozzle. The performance of the HPWM Type B nozzle was expected to be better than Type A nozzle since Type B is for light hazard application aiming to provide property protection in addition to life safety.

To protect mass timber structures such as CLT panels, a fire suppression system should be designed to limit the surface temperature of structures below the degree that would cause significant fire damage/fire spread. Cellulosic and plastic materials begin to pyrolyze when heated to a temperature of approximately 260˚C [17], and the charring temperature of wood products are 250-300˚C. In addition, the depth of fire damage on the CLT panels depends on the exposure time to high temperatures.

6- **Life safety consideration:** Among various applications and hazard scenarios, fire suppression systems for the protection of residential spaces should provide an additional degree of protection for life. With an automatic activation of the nozzle without any delay, the HPWM, LPWM and sprinkler system maintained the room temperature tenable. The analyses of the gas samples from the centre of the room showed the level of oxygen and carbon monoxide concentrations maintained tenable when the sprinkler and LPWM and HPWM systems were operating without any delay in the activation.

   Unlike the temperature and gas concentrations in the test room, the visibility in the room deteriorated rapidly and reached the untenable condition within 2 minutes from the ignition in all tests with sprinkler, LPWM and HPWM systems.

7- **Delayed activation:** The activation of the nozzle was delayed approximately one minute in selected tests to investigate the performance of the HPWM and LPWM system. It is found that minimizing the delay time is critical in limiting fire spread to the CLT walls and ceiling. With the delay time of approximately 1 minute, the CLT walls and ceiling were found severely damaged by the fire. Therefore, it is recommended to review the delay-time design requirements for the suppression systems in protection of mass timber structure for a residential fire scenario.

   Dry-pipe/pre-action systems are widely used in water-sensitive environment, and these systems could be considered for mass timber buildings to prevent potential water damages in the case of false activations or inadvertent discharges. The systems use air or other inert gases to fill the nozzle-pipe network so that water is supplied only when the nozzles are open. For dry-pipe sprinkler systems, the 2007 edition of NFPA 13, NFPA 13D [13] and NFPA 13R [12] requires water delivery to a dwelling unit in 60 seconds or less from the fire detection. The requirement becomes stringent in the 2010 and 2019 edition of NFPA 13 in which the maximum time of water deliver for dry-pipe sprinkler systems is 15 seconds. For dry-pipe water mist systems, however, there are no specific time requirement for residential occupancy in NFPA 750 [16].

8- **Water damage:** After the fire suppression tests, the wet CLT panel surfaces quickly dried, and the level of moisture contents measured on the wall surfaces in 24 hours after the fire suppression test was similar to that measured before the test for all systems tested regardless of the water spray rate. However, the suppression systems formed a large water pool on the floor in particular for the sprinkler system. For this reason, unlike the wall and ceiling surfaces, water penetrated into the joints along the bottom edge of the CLT wall panels.

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Appendix A: Nozzles

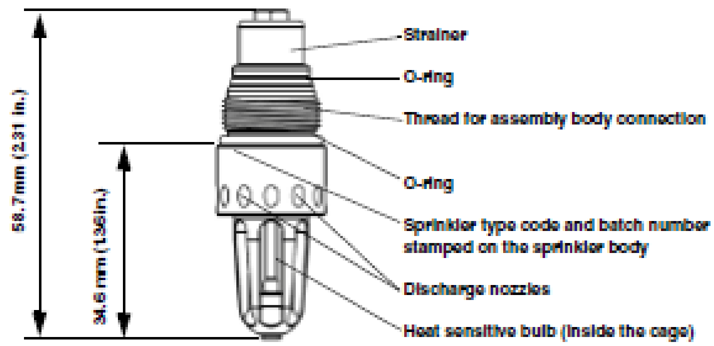
Type A nozzle

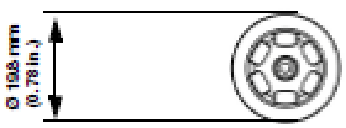
HI-FOG® water mist fire protection

Sprinkler HI-FOG® 2000 Type C40

Stock code C-0002615

TECHNICAL DATA SHEET K0008271 **REVISION** A **DATE** 20 Jul 2018





Stock code	Type	Heat sensitive bulb
C-0002615	C40	68°C-79°C)

General	Body material	Brass	
	Finish	Nickel	
	Mass	0.058 kg	2.05 oz
	K-factor	2.4 lpm/bar$^{0.5}$	0.17 gpm/psi$^{0.5}$
Installation	Location	Ceiling	
	Projection	Pendent	
	Max. ceiling height	6.4 m	21 ft.
	Max. / Min. spacing	4.27 m / 0.61 m	14 ft. / 2 ft.
	Max. distance from walls	2.14 m	7 ft.
	Operating pressure range	52-72 bar	755-1045 psi
Approvals	UL listed for residential applications		

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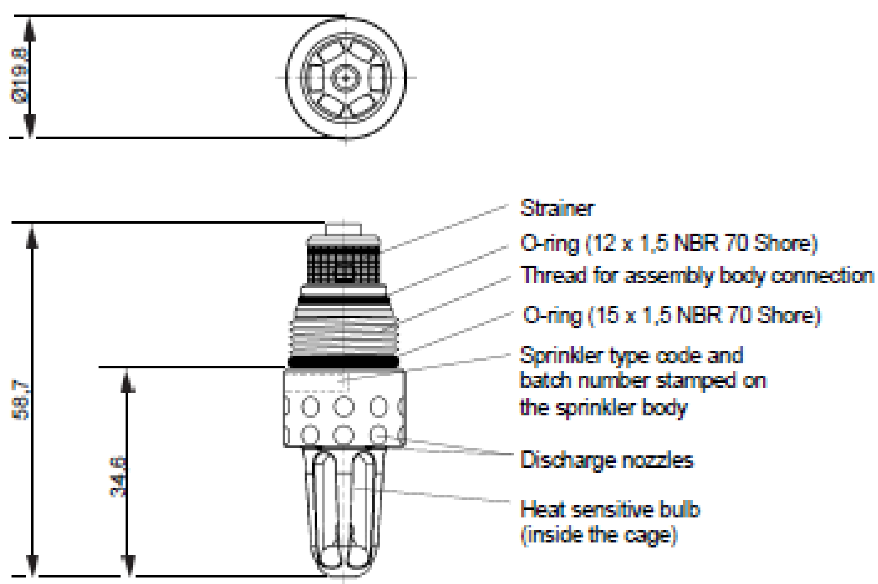
Type B nozzle

HI-FOG® water mist fire protection

Sprinkler HI-FOG® 2000 Type C10

Stock code C61500

TECHNICAL DATA SHEET TC2010 **REVISION** B **DATE OF ISSUE** 25 Apr 2014



General	Body material	Brass
	Finish	Nickel
	Mass	0,058 kg
	Heat sensitive bulb	57 °C (orange color) -79°C
	K-factor	4,1 lpm/bar ^{0,5}
Installation	Location	Ceiling
	Projection	Pendent
	Max. ceiling height	2,5 m
	Max. spacing	5 m
Typical application	Land	Light and ordinary hazards

Marioff

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Type C nozzle

Datasheet
Pendent Automatic Low Pressure Water Mist Nozzle
Model: OH-OS

Description

The VID Fire-Kill Low Pressure Watermist Nozzle Model OH-OS is an automatic, concealed low pressure water mist nozzle ideal for residential areas, offices, data processing areas, meeting rooms, hotels, museums, restaurant seating areas, institutions, schools and such applications. The different finishes and optional painted finishes makes the OH-OS blend in with almost every type of surface.

Installations and approvals

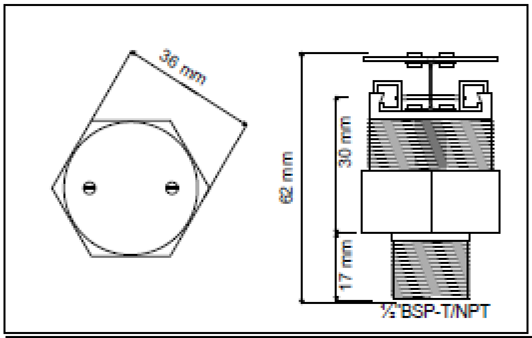
The OH-OS nozzle has been tested and approved to the FM5560 standard for light hazard occupancies. This means that the OH-OS can protect Light Hazards defined in NFPA13 and 750, and Ordinary Hazard 1 and 2 defined in EN 12845.

The OH-OS nozzles are to be installed using the OH-S36 nozzle spanner, as not to damage either nozzle or the surrounding ceiling. It should be installed into a clean pipe made of non-corrosive material. After being installed, the OH-R-T rosette is screwed on to the nozzle to conceal the installation hole in the ceiling occurred around the nozzle.

Compromised or otherwise suspected compromised nozzles are not to be installed, but returned to VID Fire-Kill for testing and refurbishing

Spray Pattern

See page 2 for a diagram illustrating the spray pattern of OH-OS.



General Stats	
Minimum water pressure	10.5 bar
Maximum working pressure	16 bar
K-factor (metric)	16.5 (l/t/√bar)
FM approved nominal release temperature	57°C
Other nominal release temperatures	68°C, 79°C, 93°C
Time Response Index (metric)	RTI < 50 Fast Response Class
Drop size	DV_{90} < 300 μm
Application	
Spacing (max)	16 m^2 (4.0m x 4.0m)
Distance to wall (max)	2 m
Height (max)	5 m
Specific Stats	
Dimension	See fig. above
Weight	0.211 kg
Housing	Brass
Coating	NiSn
Strainer	Stainless Steel
Thread	½" BSP-T/NPT
Standard Finish	Chrome White RAL 9010
Other Finish	Other RAL colors
Hydraulic System	
Water density	3.3 mm/m^2
Minimum system operation time	60 min
Minimum design area	140 m^2 (for areas <140m^2, area size should be used).
Related Products	
Name	Model
Alarm Valve	WAC
OH Rosette	OH-R-T
OH Pipe Spanner	OH-S36

VID Fire-Kill ApS,
Svalbardvej 13
DK-5700 Svendborg
Denmark
Tel: +4562621024, www.vid.eu

FM APPROVED

Doc Name: Datasheet OH-OS
Doc No.: 110426-07-10
v.10
Issue/ Date: 10th March 2013
Page: 1 of 2

Type D nozzle

tyco

Worldwide Contacts | www.tyco-fire.com

RAPID RESPONSE Series LFII Residential Sprinklers 3.0 K-factor Pendent Wet Pipe Systems

General Description

The TYCO RAPID RESPONSE Series LFII Residential Pendent Sprinklers (TY1234) are decorative, fast response, frangible bulb sprinklers designed for use in residential occupancies such as homes, apartments, dormitories, and hotels. When aesthetics and optimized flow characteristics are key considerations, the Series LFII (TY1234) should be the first choice.

The 3.0 K-factor of the Series LFII Residential Pendent Sprinkler has been designed to optimize flows (that is, to avoid over discharging) specifically for small coverage areas up to 14 ft x 14 ft (4,3 m x 4,3 m). The required residential flow rates can then be delivered with the use of smaller pipe sizes and reduced water supply requirements.

The Series LFII Residential Sprinklers are intended for use in the following scenarios:

- wet pipe residential sprinkler systems for one-and two-family dwellings and mobile homes per NFPA 13D
- wet pipe residential sprinkler systems for residential occupancies up to and including four stories in height per NFPA 13R
- wet pipe sprinkler systems for the residential portions of any occupancy per NFPA 13

IMPORTANT

Refer to Technical Data Sheet TFP2300 for warnings pertaining to regulatory and health information.

Always refer to Technical Data Sheet TFP700 for the "INSTALLER WARNING" that provides cautions with respect to handling and installation of sprinkler systems and components. Improper handling and installation can permanently damage a sprinkler system or its components and cause the sprinkler to fail to operate in a fire situation or cause it to operate prematurely.

The recessed version of the Series LFII Residential Pendent Sprinkler is intended for use in areas with finished ceilings. It employs a two-piece Style 20 Recessed Escutcheon.

The Recessed Escutcheon provides 1/4 in. (6,4 mm) of recessed adjustment or up to 1/2 in. (12,7 mm) of total adjustment from the flush ceiling position. The adjustment provided by the Recessed Escutcheon reduces the accuracy to which the pipe drops to the sprinklers must be cut.

The Series LFII Residential Pendent Sprinkler has been designed with heat sensitivity and water distribution characteristics proven to help in the control of residential fires and to improve the chance for occupants to escape or be evacuated.

Corrosion-resistant coatings, where applicable, are utilized to extend the life of copper alloy sprinklers beyond that which would otherwise be obtained when exposed to corrosive atmospheres. Although corrosion-resistant coated sprinklers have passed the standard corrosion tests of the applicable Approval agencies, the testing is not representative of all possible corrosive atmospheres. Consequently, it is recommended that the end user be consulted with respect to the suitability of these coatings for any given corrosive environment. The effects of ambient temperature, concentration of chemicals, and gas/chemical velocity should be considered, as a minimum, along with the corrosive nature of the chemical to which the sprinklers will be exposed.

NOTICE

The Series LFII Residential Pendent Sprinklers (TY1234) described herein must be installed and maintained in compliance with this document and with the applicable standards of the NATIONAL FIRE PROTECTION ASSOCIATION (NFPA), in addition to the standards of any authorities having jurisdiction. Failure to do so may impair the performance of these devices.

NSF

The owner is responsible for maintaining their fire protection system and devices in proper operating condition. The installing contractor or sprinkler manufacturer should be contacted with any questions.

Sprinkler Identification Number (SIN)

TY1234