



SAFETY AND TRANSPORT

SAFETY



An evaluation of residential sprinklers and water mist nozzles in a residential area fire scenario

Magnus Arvidson

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Commercial residential sprinklers are usually fitted with 3 mm glass bulbs having a nominal operating temperature of 68°C or a high-sensitivity solder link, usually with a nominal temperature rating of 74°C. Previous work show that there is a significant potential for improving sprinkler response times in a residential room fire scenario by using glass bulbs with a lower Response Time Index (RTI) and lower operating temperature than commonly used. The objective of this study was to investigate any improved performance due to earlier activation of residential sprinklers. A series of fire tests was conducted inside a test compartment sized 3.66 m by 3.66 m. The fire test source consisted of either a simulated or authentic upholstered chair. For the majority of the tests, the flow rate of the residential sprinkler was 30.3 liter/min (corresponding to the minimum design density 2.05 mm/min as per the recommendations in NFPA 13D and 13R). Additional tests were conducted at 60.6 liter/min (the minimum design density 4.1 mm/min as per NFPA 13). Tests were also conducted with commercial low- and high-pressure water mist nozzles and a stand-alone high-pressure water mist system.

The results show that earlier activation of residential sprinklers had a small effect on its performance, especially for the authentic upholstered chair scenario, when flowing 30.3 liter/min. The rather small effect is probably due to that the discharge density was too low to provide fire suppression. When the flow rate was increased to 60.6 liter/min, the performance was considerably improved as compared to the flow of 30.3 liter/min. Any improvement in performance of earlier activation was, however, not investigated for the 60.6 liter/min flow rate.

The flow rates of the commercial low- and high-pressure water mist water mist nozzles ranged from 17.2 liter/min to 36.7 liter/min. Roughly, it could be concluded that the performance of the water mist nozzles were comparable or better than the residential sprinkler at approximately half the water flow rate for the tested fire scenarios.

The stand-alone high-pressure water mist system had a flow rate of 8.2 liter/min. The performance was comparable to that of the other water mist nozzles in the study. The performance was comparable to that of the other water mist nozzles in the study, despite a considerably earlier activation. However, the results indicate that the performance was relatively much influenced whether the simulated upholstered chair was orientated with its front towards the test compartment or with its front towards the back wall (poorer performance). This would suggest that the position of the fire test relative to the position of the unit is a crucial factor and underlines the importance of a thoughtful positioning in practical applications.

Key words: Residential sprinklers, water mist nozzles, residential room fire scenario, large-scale fire tests

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Preface

This report has been prepared within the project “Analys av brandsäkerhetens fysiska bestämningsfaktorer och tekniska åtgärder som stöd till nollvisionen” (“Analysis of fire safety physical determinants and technical measures to decrease the number of casualties in residential fires”), a project which will identify physical and technical parameters which have an impact on the number of fatal residential fires and find means to decrease the number of fatalities and injuries in residential fires.

The project is funded by MSB which is gratefully acknowledged.

Sammanfattning

I Sverige omkommer årligen ca 90 personer vid bostadsbränder. Även om risken att omkomma i en bostadsbrand har minskat i ett längre tidsperspektiv så har antalet omkomna varit ungefär konstant de senaste årtiondena trots introduktionen av brandvarnare och på senare år även självslocknande cigaretter, mobila sprinklersystem och spisvakter.

Myndigheten för samhällskydd och beredskap, MSB, antog 2010 en nollvision om att ingen ska skadas allvarligt eller omkomma till följd av brand i Sverige. Då de flesta som förolyckas i bränder omkommer till följd av en bostadsbrand är det av stor vikt att antalet döda i bostadsbränder minskas. Ett steg i att åstadkomma detta är den utlysning om forskningsmedel som MSB gjorde 2014. Tre projekt beviljades i denna utlysning varav ett var "Analys av brandsäkerhetens fysiska bestämningsfaktorer och tekniska åtgärder som stöd till nollvisionen" där tekniska faktorer som kan ha en påverkan på antalet döda i bostadsbränder identifieras tillsammans med potentiella lösningar.

Tekniken med boendesprinkler utvecklades i USA i början av 1970-talet och erfarenheterna från i första hand USA visar att boendesprinkler reducerar dödligheten, antal skadade och brandskadekostnaderna vid bostadsbränder. Boendesprinkler introducerades i Sverige i början av 2000-talet och är sedan 2012 ett krav i så kallade särskilda boenden och sjukhus. På den svenska marknaden används på senare år mobila sprinklersystem allt mer för att förbättra brandskyddet i befintliga boendemiljöer där det finns ett ökat behov av brandskydd, till exempel för äldre, storrökare, dementa eller handikappade i vårdboenden eller hemmiljö. Det finns ett stort antal dokumenterade fall där mobila sprinklersystem förhindrat dödsbränder. Däremot finns inga studier som visar hur den nationella dödsbrandstatistiken påverkats.

Denna rapport beskriver en serie brandförsök med traditionella boendesprinkler, flera olika munstycken av typen vattendimma och ett mobilt sprinklersystem. Den primära målsättningen var att undersöka om effektiviteten för traditionella boendesprinkler kan förbättras genom att de aktiverar tidigare i ett brandförlopp. Tidigare aktivering åstadkoms vid försöken med en sprinklerglasbulb som har lägre termisk tröghet (lägre RTI) och lägre aktiveringstemperatur än de glasbulber som normalt används. Den sekundära målsättningen var att undersöka effektiviteten med vattendimma. Även dessa munstycken aktiverades av en glasbulb av värmen från branden. Det mobila sprinklersystemet som provades aktiverades av en branddetektor (rök och värme) vilket bidrog till en något tidigare aktivering av systemet.

Försöken genomfördes i ett mindre bostadsrum och som brandkälla användes antingen en simulerad och starkt förenklad stoppad fätölj, eller en autentisk och kommersiell fätölj inköpt från ett möbelföretag. För att utvärdera effektiviteten mättes ytemperaturen på så kallade plattermoelement placerade nära och direkt framför brandkällan, gastemperaturen i taket ovanför branden, gastemperaturen i ögonhöjd i flera mätpunkter och koncentration av kolmonoxid (CO) i en mätpunkt.

Resultaten visar att en tidigare aktivering av boendesprinkler bidrar till en viss förbättrad effektivitet när vattenflödet från sprinklern var 30.3 liter/min (motsvarande 2.05 mm/min). Denna vattentäthet används för boendesprinklersystem i enbostadshus, radhus och liknande lägre byggnader där de boende förväntas kunna utrymma på egen hand och på ett enkelt sätt. När vattenflödet från boendesprinklern fördubblades till 60.6 liter/min förbättrades dock effektiviteten avsevärt. Detta vattenflöde motsvarar den dimensionerande vattentäthet om 4.1 mm/min som används i högre bostadsbyggnader eller i verksamheter där de boende behöver hjälp för att utrymma. Det speglar också delvis att vattenflödet är högre när den första sprinklern i ett system aktiverar.

Boendesprinkler utvecklades för olika boendeformer med den konkreta målsättningen att förhindra övertändning och bidra till längre tid till kritiska förhållanden och för att därmed medge längre tid för utrymning. Försöken visar att boendesprinkler gör att miljön i brandrummet är överlevnadsbar, åtminstone på ett visst avstånd från brandkällan. I direkt anslutning till brandkällan uppmättes höga temperaturen med plattermoelementen (framförallt beroende på hög värmestrålning). Dessutom hade både den simulerade och den autentiska fätöljen omfattande brandskador.

Vattenflödet från de olika munstyckena av typen vattendimma varierade mellan 17.2 liter/min och 36.7 liter/min och vattenflödet för det mobila sprinklersystemet var 8.2 liter/min. En betydligt ökad effektivitet i termer av mer dämpad brand, lägre gastemperatur i taket ovanför branden och i lägre gastemperaturer erhöles med vattendimmunstyckena och det mobila sprinklersystemet jämfört med boendesprinkler. Samma eller bättre prestanda uppnåddes med ungefär halva vattenflödet jämfört med boendesprinklern. Men även för dessa system är brandskadorna i både den simulerade och den autentiska fätöljen så omfattande att det är tveksamt om en person i direkt närhet av branden överlever.

En subjektiv observation från försöken är att ett brandförlopp i en autentisk kommersiell fätölj är förvånansvärt snabbt och intensivt även med en förhållandevis liten antändningskälla.

1 Introduction

The first edition of NFPA 13D [1], the standard for the installation of residential sprinklers in one- and two-family dwellings and manufactured homes, was published in 1975. The intent of the standard was to provide an affordable sprinkler system in homes while maintaining a high level of life safety. Bryan [2] provides a comprehensive summary of the development of residential sprinklers and the associated installation and testing standards. Arvidson [3] has made a compilation of experiences from well-documented residential sprinkler fire tests. The report describes the series of tests that formed the basis of the concept of residential sprinklers.

The 2002 edition of NFPA 13D included changes that established a minimum design discharge density of 2.04 mm/min (0.05 gpm/ft²) and typically two sprinklers in the design area. This change originated due to a concern that began to be expressed about the low water flow rates of some listed residential sprinklers. In addition, the original UL 1626 room fire test was modified relative to the fuel materials and their configuration, in order to provide an improved reproducibility of the fire challenge. The 2016 edition of NFPA 13R [4] recommends the same discharge density, but the number of sprinklers in the design area shall be all of the sprinklers within a compartment, up to a maximum of four sprinklers, that require the greatest hydraulic demand. For light hazard occupancies, NFPA 13 [5] require a minimum design discharge density of 4.1 mm/min (0.1 gpm/ft²) over 139 m² (1500 ft²), using the density/area method. Other design methods are available. Light hazard occupancies are occupancies where the quantity and/or combustibility of contents are low and fires with relatively low rates of heat release are expected. Examples of such occupancies include churches, educational occupancies, hospitals, offices, residential premises and restaurant seating areas, i.e. the field of application is broader than just residential occupancies.

Similar residential sprinkler installation recommendations are given in the Swedish standard SS 883001:2009/INSTA 900-1 [6] that is also adopted as national standards in Norway and Denmark. This standard recommends a minimum design discharge density of 2.04 mm/min for one- and two family dwellings and residential buildings up to an including three levels. The design area is typically two sprinklers. For residential buildings up to a maximum of eight levels, the design area shall include up to four sprinklers. The minimum design discharge density is increased to 4.08 mm/min for care homes or similar occupancies where the occupants need assistance to evacuate and for residential buildings in excess of nine levels. The design area shall include the four sprinklers that require the greatest hydraulic demand.

Although the life safety benefits of residential sprinklers in general terms are well-documented by for example Hall [7] and Hall, *et al* [8], there are fire scenarios where sprinkler activation may occur too late to save the occupants of a room. A review of British fire statistics by BRE Global [9] indicated that most fatalities in care homes arise from occupants accidentally setting fire to bedclothes, nightclothes etc. whilst in bed. There was no available information to determine whether the severity of such a fire at the time the sprinkler operates would be fatal or whether there would be a probability for survival. An experimental program [9] by BRE Global demonstrated

that a residential sprinkler in a bedroom will not operate fast enough to prevent death, or very severe injury, to the occupant of a bed where the nightwear or bed coverings of the bed have ignited. However, other occupants of the room are likely to have survived. For one of the tests, the sprinkler at the ceiling was manually activated upon fire detection of a smoke detector. Both the bed occupant and any other occupants of the room were judged to have survived, with only minor injuries.

There is probably only a short time period available from detection of a fire until burns of any human directly exposed to the fire would occur. Andersson [10] investigated this by arranging fire in clothes with a human doll dressed in either summer or winter clothing. The doll had temperature sensors under the clothing and heated water (37°C) was circulated in thermally insulated hoses, connected the sensors, to simulate bloodstream to evaluate burns. The doll was positioned inside a 3 m by 3 m (9 m²), 2.4 m high “compartment” having two walls. Two smoke alarm detectors was installed at the ceiling, one virtually directly above the doll and one closer to the open corner, thereby simulating a detector position at the centre of a larger room. In the first two tests, the doll was positioned in a chair and the clothing was ignited with matches in the doll’s knee. In the third test, the doll was positioned on a furniture pad that was ignited with a match. In the fourth test, the doll was laid on a polyurethane mattress with cotton sheets under polyester cover. Ignition was made with matches on the duvet.

For the first two tests, the smoke alarm detector positioned above the doll alarmed after approximately one minute. Approximately 10 seconds to 20 seconds later, the sensors at the doll closest to the point of fire ignition indicated temperatures that would correspond to burns. At the time of the alarm of the second detector, that occurred about 2 minutes later than the first detector, the temperature of several of the sensors on the doll exceeds the temperature threshold. These sensors would correspond to 15% to 30% of the skin surface of a human. For the third test, when the fire was lit in the furniture pad of the chair, both fire detectors alarmed prior any indication of burns. However, indications of burns occurred shortly thereafter and less than a minute after the alarm of the second detector, the burn would correspond to 15% to 20% of the skin surface of a human. Additionally, fire had spread to the back of the doll where no temperature sensors were positioned. In the fourth test, where the doll was in a bed, both detectors alarmed prior any indications of burns. However, the temperature sensors were not optimally positioned and from video recordings it was estimated that burns are likely at the time the alarm of the first detector.

Commercial residential sprinklers and quick-response spray sprinklers are fitted with 3 mm glass bulbs having a nominal operating temperature of 68°C or a high-sensitivity solder link, usually with a nominal temperature rating of 74°C. Arvidson [11] showed that there is a potential for improving sprinkler response times in a residential room fire scenario by using glass bulbs with a lower thermal sensitivity and lower operating temperature than commonly used. It was observed that the nominal operating temperatures of the glass bulbs have a stronger effect on the results than does the RTI, for all the three fire growth rate scenarios that were used in the tests. As an example, the reduction of the temperature rating from 68°C to 57°C of a 3 mm sprinkler glass bulb would result in a fire size that is in the order of 15% to 30% smaller upon activation, all dependent on the fire growth rate scenario and the compartment

conditions. The residential sprinkler installation practices in NFPA 13D and 13R states that sprinklers installed where the maximum ambient ceiling temperatures do not exceed 38°C (100°F) shall be ordinary-temperature rated (between 57°C and 77°C) or intermediate-temperature rated (between 79°C and 107°C), unless the sprinkler may be exposed to conditions such as direct sunlight or heat from specific heat sources. This suggests that earlier activation of residential sprinklers could be achieved, still fulfilling established installation recommendations.

Similar residential recommendations are given SS 883001:2009/INSTA 900-1. The standard recommends that ordinary-temperature rated sprinklers shall be installed where the maximum ambient ceiling temperature do not exceed 38°C. Sprinklers with an intermediate-temperature rating shall be used where the maximum ambient ceiling temperature is between 39°C and 68°C.

Water mist fire protection nozzles and systems for passenger and public areas on board passenger vessels were introduced to the market at the beginning of the 1990's, as a direct results of the arson fire on board Scandinavian star in 1990, that caused the death of 158 people. The small water droplets associated with water mist nozzles may provide improved performance, especially in small passenger or crew cabins and the small diameter piping was essential to the retrofit program of sprinklers that was commenced. Arvidson [12] has made a comprehensive summary of the development of the installation guidelines and fire test procedures published by the International Maritime Organization (IMO) for "equivalent sprinkler systems" that is contained in IMO Resolution A.800(19). Partly, these requirements have formed base for the requirements of both UL 2167 [13] as well as FM 5560 [14]. Previous versions of IMO Resolution A.800(19) contained a residential area test that was based on the requirement of UL 1626, but having slightly different acceptance criteria. The fire test set-up and requirement of UL 1626 have with some modifications also formed the basis for both the Nordic standard INSTA 900:3 [15] and the British standard BS 8458:2015 [16].

In summary, it can be concluded that residential sprinklers are designed at a minimum design discharge density of 2.04 mm/min in accordance with NFPA 13D and 13R and sprinkler systems for light hazards occupancies are designed at 4.1 mm/min. A residential sprinkler system design with lower discharge densities is not permitted by NFPA standards and UL 1626. The sprinklers that are required to be used should have quick-response thermal response characteristics. SS 883001:2009/INSTA 900-1 recommend a design density of 2.04 mm/min or 4.08 mm/min, all dependent on the number of floor of the building or the occupants' ability to evacuate without assistance. Sprinklers rated 57°C would be permitted to be used for many applications, although higher temperature rated sprinklers are available and are required to be used in areas where temperatures are likely to exceed this threshold. Previous research suggests that a reduction of the temperature rating of sprinklers and the thermal response characteristics would result in significant earlier activation of sprinklers. It is also suggested that performance could improve by the use of smaller water droplets associated with water mist nozzles. These findings were the starting point for the fire tests described in this report.

2 Objective

The primary aim of this study was to evaluate any improved performance of a commercial residential sprinkler by using sprinkler glass bulbs with a lower Response Time Index (RTI) and lower temperature rating than that of the commonly used 3 mm, 68°C glass bulb. In addition, tests were conducted with commercial low- and high-pressure water mist water mist nozzles in order to explore any improved fire suppression performance. A commercial stand-alone high-pressure water mist water system was also tested. The latter is activated by a multi-criteria (smoke and heat) detector and has been tested to the requirements in MSB's advice for extinguishing systems that are easy to mount [17].

3 Experimental set-up

All tests were conducted in the same experimental set-up indoors at the RISE testing facility in Borås.

3.1 The fire test compartment

The tests were conducted inside a compartment having a 3.66 m by 3.66 m (13.4 m²) floor area and a ceiling height of 2.5 m. The compartment was built from non-combustible cement fiber wall boards with a nominal thickness of 12 mm, on a framework of wood studs. The compartment had a doorway opening positioned at the centerline of the front wall. The doorway opening had a width of 920 mm and a height of 2080 mm, which provided for a lintel depth of 420 mm. The compartment is shown in figure 1.



Figure 1 The fire test compartment used in the tests. The compartment was sized 3.66 m by 3.66 m and had a regular doorway opening at centerline of the front wall.

3.2 The fire test sources

Two fire test sources were used in the tests:

- Simulated upholstered chair.
- An authentic upholstered chair.

The fire test sources are described in detail below.

3.2.1 The simulated upholstered chair

The simulated upholstered chair was used as the primary fire test source in the tests due to its low cost. It consisted of a 1000 mm by 1000 mm, nominally 12 mm thick plywood panel nailed to a frame constructed from 40 mm by 40 mm square steel pipe. A polyether foam cushion was glued to the plywood panel. The foam cushion was 150 mm thick and had a nominal density of 33 kg/m³, which corresponded to a nominal weight of 5 kg. No fabric was used to cover the foam cushion. Prior the tests, free-burn fire tests were conducted in order to optimize the thickness of the foam cushion. Three fire tests were conducted using a foam cushion thickness of 100 mm, 150 mm or 200 mm, respectively. The fire growth rates are plotted in figure 2 along with the standard t-squared heat release rate curves commonly used to estimate

transient fire growth for fire protection design purposes. The ignition source is described in section 3.2.3 below.

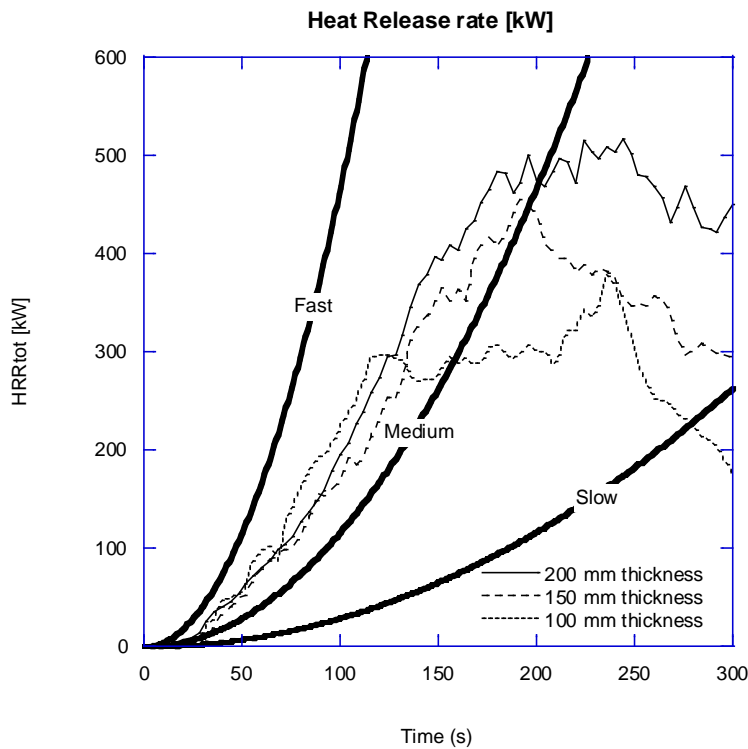


Figure 2 The fire growth rates of the simulated upholstered chair, using different foam cushion thicknesses, compared to the standard α -t-squared heat release rate curves. The 150 mm foam cushion thickness was chosen for the residential sprinkler and water mist nozzle tests.

The graph shows that the fire scenario resembles a 'medium' fire growth rate. As expected, less foam cushion thickness corresponded to a lower peak heat release rate and a shorter fire duration time. At most, the peak heat release approached 500 kW, which is comparable to the peak heat releases obtained in the CBUF project for small upholstered chairs or armchairs but significantly lower than the peak heat releases for sofas [18]. Based on these free-burn fire tests, it was decided to use a foam thickness of 150 mm in the residential sprinkler and water mist nozzle tests. The fire growth rate (foam thickness 150 mm) is depicted in figure 3.

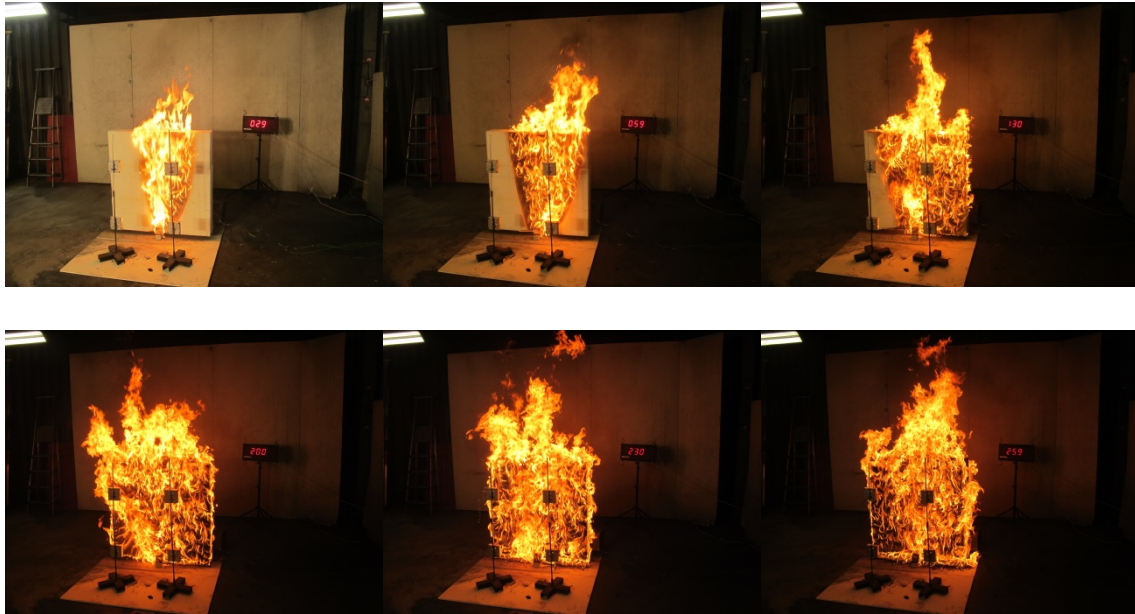


Figure 3 The first three minutes of the fire, with photos at approximately 00:30, 01:00, 01:30, 02:00, 02:30 and 03:00 [min:sec], respectively.

3.2.2 The authentic upholstered chair

An authentic upholstered chair was used to provide directly comparable fire test results with the simulated upholstered chair. The chair had a width of 760 mm, a depth of 800 mm and a height of 1030 mm, see figure 4. The weight was nominally 19 kg. According to the manufacturer, the chair was constructed with a framework of massive poplar, pinewood and plywood. The frame was covered by polyether foam and polyester and had a seat and backrest of polyether foam. The seat was positioned on a steel sinuous spring and coil spring suspension unit. The chair was covered by a polyether foam fabric.

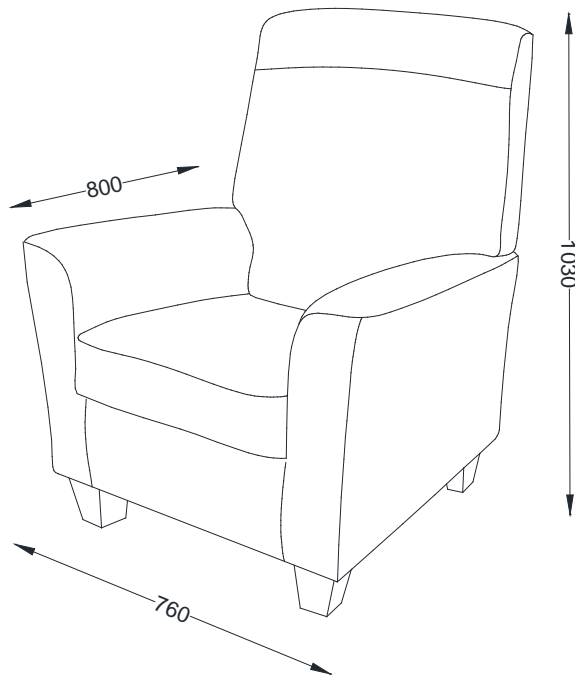


Figure 4 The authentic upholstered chair used in parts of the tests.

The authentic upholstered chair was purchased from a local furniture vendor.

3.2.3 The fire ignition source

The fire ignition source consisted of a cube, 60 mm by 60 mm by 75 mm, made from pieces of low-density (wood) particle fiberboard, soaked with 120 mL of Heptane and wrapped in a thin plastic foil bag.

When used for the simulated upholstered chair, it was positioned up against the bottom part of the front of the foam cushion, at its vertical centerline. When used for the authentic upholstered chair, it was positioned on the seat, up against the bottom part of the backrest, at its vertical centerline.

3.3 Measurements and instrumentation

The following parameters were measured:

- The response time of the sprinkler or nozzle, from the time the fire was ignited, using a stop watch.
- The temperature of four PT heat flux meters (PTHFM) positioned in front of the fire test source. See the description below.
- The ceiling gas temperature, directly above the center-point of the fire test source (for the simulated upholstered chair) or directly above the center-point of the backrest (for the

authentic upholstered chair). The thermocouple was positioned 10 mm below the ceiling. A welded Type K thermocouple having a diameter of 3 mm diameter was used.

- The gas temperature at eye-level (1.6 m above floor) at the center-point of each of the four quadrants of the test compartment, except for the quadrant with the fire test source, see figure 6. Welded Type K thermocouples having a diameter of 0.5 mm were used.
- The gas temperature close to the residential sprinkler or water mist nozzle. This data is not discussed in the report.
- The concentrations of Oxygen (O_2), Carbon dioxide (CO_2) and Carbon Monoxide (CO) at the eye-level (1.6 m above floor) at the center-point of the quadrant to the right of the quadrant with the fire test source, see figure 6. The concentrations of O_2 and CO_2 are not provided in the report.

The PT heat flux meters (PTHFM) devices consisted of a 100 mm by 100 mm steel plate, nominally 0.5 mm thick. A sheathed 1 mm diameter thermocouple is welded to the backside of the steel plate and the backside is insulated with 50 mm thermal insulation. Figure 5 shows the device figure 6 shows the position of all the measurement points inside the test compartment.

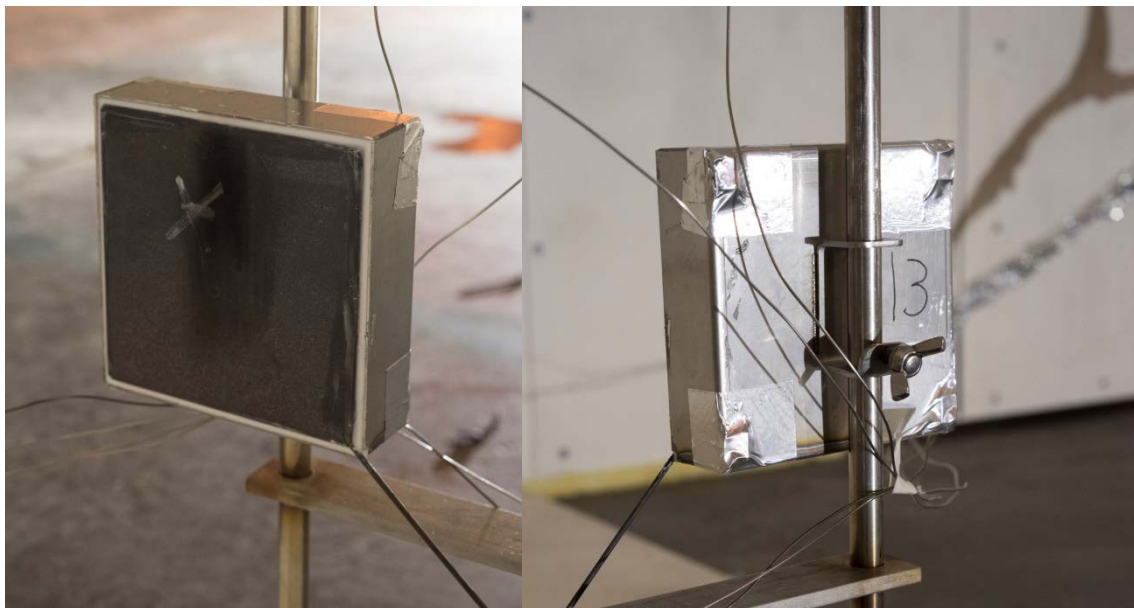


Figure 5 The front (left) and back (right) side of one of the PTHFM devices.

For the tests using the simulated chair, four PTHFM devices were positioned symmetrically in front of the foam cushion, at a horizontal distance of 400 mm from its front surface. For the tests using the authentic upholstered chair, four PTHFM devices were positioned symmetrically in front of the backrest of the chair, at the same horizontal distance.

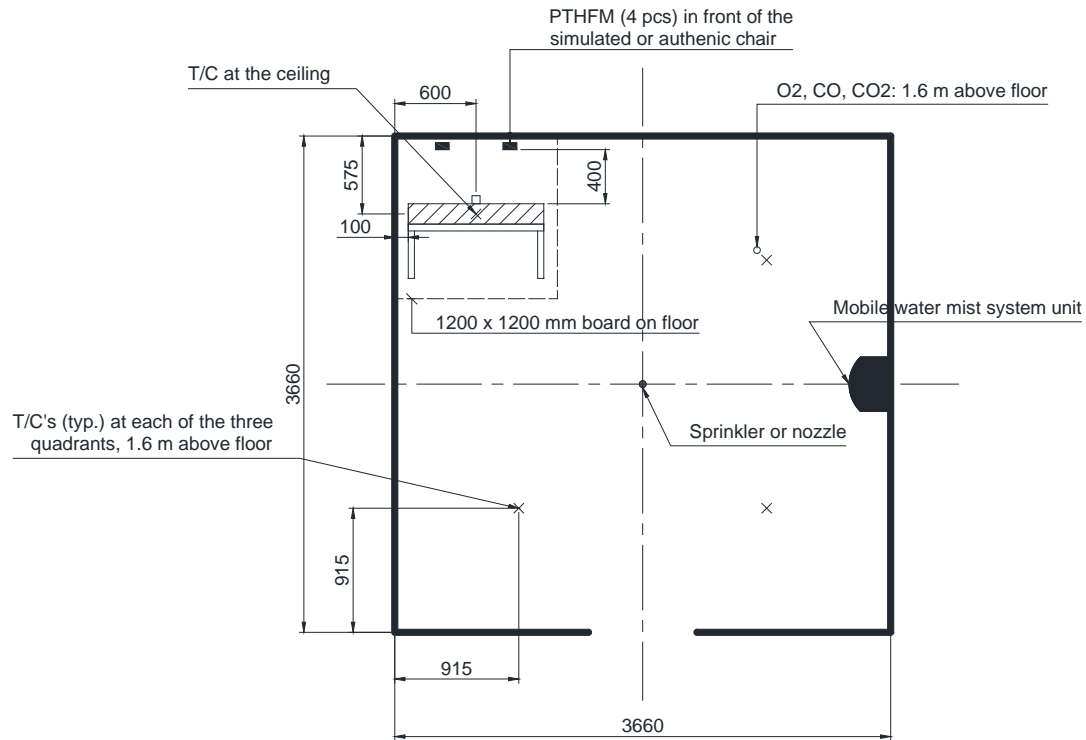


Figure 6 Top view of the fire test compartment and the measurement points, illustrated with the simulated upholstered chair oriented towards the back wall.

Measurements were conducted once every second for all parameters.

3.4 Test procedure using the simulated upholstered chair

The fire simulated chair was either positioned with its front towards the test compartment or with its front towards the back wall, i.e. fire ignition was initiated either at the “front” or at the “back”. For the former scenario, the fire was fully exposed to the water spray and in the latter scenario the fire was partly shielded from direct water application. The horizontal distance measured from the longitudinal centerline of the foam cushion and the back wall was 575 mm, irrespective of the orientation of the simulated chair. The horizontal distance from the short-end of the foam cushion to the left hand side wall was 100 mm. Figure 7 shows the test set-up, with the orientation of the fire test source.



Figure 7 The simulated chair when orientated with its front towards the test compartment (left) or towards the back wall (right).

Prior to the tests, the simulated upholstered chair was conditioned at a temperature of 23°C and a humidity of 50% for at least 48 hours.

The fire ignition source was lit by a small torch and the tested sprinkler or nozzle was allowed to activate automatically. The fire was allowed to burn 20 minutes from fire ignition and any remaining fire was manually extinguished.

3.5 Test procedure using the authentic upholstered chair

The authentic upholstered chair was positioned with the longitudinal centerline of the backrest and its short-side at the same horizontal distances to the walls as described for the simulated upholstered chair. The chair was, however, only positioned such that its front was directed towards the compartment. No tests were conducted where the water application was partly shielded. Figure 8 shows the chair and the position inside the test compartment.



Figure 8 The position of the commercial, authentic upholstered chair inside the test compartment.

The fire ignition source was lit by a small torch and the tested sprinkler or nozzle was allowed to activate automatically. The fire was allowed to burn 20 minutes from fire ignition and any remaining fire was manually extinguished.

Prior to the tests, the authentic chair was conditioned at a temperature of 23°C and a humidity of 50% for at least 48 hours.

4 Tested sprinkler and nozzles

The tests were conducted using a residential sprinkler, low-pressure and high-pressure water mist nozzles and a stand-alone high-pressure water mist system. Their characteristics are summarized in Table 2.

Table 1 The residential sprinkler and water mist nozzles that were tested, with the associated operating pressures and nominal water flow rates.

System	Type of sprinkler or nozzle	Glass bulb diameter [mm]	Temperature rating [°C]	K-factor [(liter/min)√bar]	Operating pressure [bar]	Nominal water flow rate [liter/min]
Residential sprinkler	Single-orifice	3	68	43.2	0.49	30.3
		3	57			
		2.5	47			
		3	68		1.97	60.6
Low-pressure water mist	Single-orifice	3	57	8.5	7.6	23.4
Low-pressure water mist	Multi-orifice	3	57	14.0	5.2	32.0
High-pressure water mist	Multi-orifice	2	57	4.1	80	36.7
High-pressure water mist	Multi-orifice	2	68	2.4	52	17.2
Stand-alone, high-pressure water mist	Multi-orifice	Fire detector		0.75	120	8.2

4.1 The residential sprinkler

A commercial, automatic, pendent residential sprinkler was used. The sprinkler had a K-factor of 43.2 (liter/minute)/bar^{1/2} and was installed non-recessed, using a two-piece escutcheon (cover plate), at the center point of the ceiling. The plane of the frame arms was orientated parallel with the side walls. The sprinkler was fitted with either of the different sprinkler glass bulbs listed in Table 1. The characteristics of the individual glass bulbs were provided by the manufacturer of the bulbs and were not confirmed by any additional testing. By using a specific fluid, the F3-F glass bulbs had response characteristics similar to 2.5 mm glass bulbs, as noted in the table.

Table 2 The different Response Time Index (RTI) and nominal glass bulb operating temperature combinations that were tested.

Type of bulb	RTI* [(ms) ^{1/2}]	Bulb diameter [mm]	Nominal operating temperature [°C]	Color code
F3	32	3	68	Red
F3	32	3	57	Orange
F3-F	24	3** (2.5)	47	Transparent

*) Provided by the manufacturer and calculated using a C-factor of 0.5.

**) By using a specific fluid, the RTI of the glass bulb was similar to a 2.5 mm glass bulb.

The residential sprinkler was designed to optimize flows for small coverage areas. For the 3.66 m by 3.66 m compartment used in the tests, the sprinkler is UL Listed at a flow

rate of 30.3 liter/min at 0.49 bar. This particular flow rate was used during the majority of the tests and the discharge density corresponds to the minimum 2.05 mm/min recommended by NFPA 13D and 13R. Additionally, tests were conducted at a discharge density of 4.1 mm/min, which corresponds to the minimum density recommended by NFPA 13. The operating pressure at these tests were 1.97 bar and the water flow rate 60.6 liter/min.

All residential sprinkler tests at the higher flow rate, corresponding to a discharge density of 4.1 mm/min, was conducted with a residential sprinkler fitted with a 3 mm glass bulb, having a nominal operating temperature of 68°C. The influence on the performance of earlier activation at the higher discharge density was not investigated.

4.2 The low-pressure water mist nozzles

Two commercial, automatic, pendent low-pressure water mist nozzles were tested. The first nozzle was a pendent, single-orifice nozzle that is FM Approved for HC-1 occupancies, at a maximum nozzle spacing of 3.66 m by 3.66 m, i.e. identical with the area of the test compartment. FM Global defines Hazard Category 1 (HC-1) occupancies as “Lightly loaded non storage and non-manufacturing areas with ordinary combustibles” Examples of such occupancies include: Apartments, hospitals and hospital laboratories, hotel rooms, institutions, museums, offices, restaurant seating areas and schools and universities classrooms.

The nozzle had a K-factor of 8.5 (liter/minute)/bar^{1/2}. The flow rate of 23.4 liter/minute at the minimum operating pressure of 7.6 bar is lower than that of the benchmark residential sprinkler. The nozzle was fitted with a 3 mm glass bulb, having a nominal operating temperature of 57°C.

The second nozzle was a pendent, multi-orifice nozzle that is approved by The Loss Prevention Certification Board (LPCB) for residential occupancies at a maximum nozzle spacing of 4.0 m by 4.0 m, i.e. slightly larger than the area of the test compartment. The nozzle had a K-factor of 14 (liter/minute)/bar^{1/2}. The flow rate of 32 liter/minute at the minimum operating pressure of 5.2 bar is marginally higher than that of the benchmark residential sprinkler. The nozzle was fitted with a 3 mm glass bulb, having a nominal operating temperature of 57°C. The spray pattern is characterized by a high wall wetting ability.

Both types of low-pressure water mist nozzles were installed non-recessed, using a two-piece escutcheon, at the center point of the ceiling.

4.3 The high-pressure water mist nozzles

Two commercial, automatic, pendent high-pressure water mist nozzles were tested. The first nozzle was a pendent, multi-orifice nozzle that is FM Approved for HC-1 occupancies, at a maximum nozzle spacing of 5.0 m by 5.0 m, i.e. considerably larger than the area of the test compartment. The nozzle had a K-factor of 4.1 (liter/minute)/bar^{1/2}. The flow rate of 36.7 liter/minute at the minimum operating

pressure of 80 bar is higher than that of the benchmark residential sprinkler. The nozzle was fitted with a 2 mm glass bulb, having a nominal operating temperature of 57°C.

The second nozzle was a pendent, multi-orifice nozzle that is listed by Underwriters Laboratories Inc. (UL) for residential occupancies, at a maximum nozzle spacing of 4.27 m by 4.27 m (14 ft. by 14 ft.), i.e. slightly larger than the area of the test compartment. The nozzle had a K-factor of 2.4 (liter/minute)/bar^{1/2}. The flow rate of 17.2 liter/minute at the minimum operating pressure of 52 bar is significantly lower than that of the benchmark residential sprinkler. The nozzle was fitted with a 2 mm glass bulb, having a nominal operating temperature of 68°C.

Both types of high-pressure water mist nozzles were installed non-recessed, using an escutcheon, at the center point of the ceiling.

4.4 The stand-alone high-pressure water mist system

The stand-alone high-pressure water mist system consisted of a unit with an integrated water tank, a high-pressure water pump and a water mist nozzle. The unit is connected to a multi-sensor fire detector. For these tests the detector was running with a medium sensitivity parameter set. Alarm evaluation combines signals from all sensors and allows that smoke only and heat only can activate the alarm. The heat only alarm will respond at a 25 K temperature increase (at 10 a K/min increase rate).

The unit was positioned on the right hand side of the doorway opening. The nozzle was horizontally orientated and positioned approximately 1900 mm above floor level. The water mist nozzle had a K-factor of 0.75 (liter/minute)/bar^{1/2}. The flow rate of 8.2 liter/minute at the minimum operating pressure of 120 bar is significantly lower than that of the benchmark residential sprinkler.

5 Test results

5.1 Time to activation

Table 3 shows the time to activation in seconds, as measured from fire ignition for the different systems and the different fire scenarios.

Table 3 The time to activation in seconds, as measured from fire ignition.

System	Type of sprinkler or nozzle	Glass bulb diameter [mm]	Temperature rating [°C]	Time to activation		
				Simulated chair		Authentic chair [seconds]
				Front [seconds]	Back [seconds]	
Residential sprinkler	Single-orifice	3	68	77/76*	71/76*	60/68*
		3	57	64	67	55
		2.5	47	41	48	51
Low-pressure water mist	Single-orifice	3	57	65	62	60
Low-pressure water mist	Multi-orifice	3	57	74	66	66
High-pressure water mist	Multi-orifice	2	57	60	61	64
High-pressure water mist	Multi-orifice	2	68	74	68	70
Stand-alone, high-pressure water mist	Multi-orifice	Fire detector		39	38	43

*) The tests using 60.6 liter/min instead of 30.3 liter/min.

It should be recognized that a comparison of the time to activation is only permissible if the fire growth rate of the fire scenario is repeatable. In these tests, the impression was that the fire growth rate, especially for the simulated upholstered chair scenario, was reasonably repeatable, which makes a comparison of activation time valid. The following observations are made:

- The time to sprinkler activation for the residential sprinkler correlates well with the temperature rating and the RTI of the glass bulb. The sprinkler with the 3 mm, 68°C glass bulb activated the latest, the sprinkler with the 3 mm, 57°C glass bulb somewhat earlier and the sprinkler with the 2.5 mm, 47°C glass bulb the earliest.
- The low-pressure, multi-orifice nozzle, that had a 3 mm, 57°C glass bulb generally activated a little later than the residential sprinkler and the low-pressure, single-orifice nozzle having the same type of glass bulb. The reason may be that the design of the bulb holder exposed

the glass bulb less to the flow of gases as compared to the open frame arm design of the residential sprinkler and the low-pressure, single-orifice nozzle.

- The high-pressure nozzle having a 2 mm, 57°C glass bulb generally activated earlier than the nozzle with a 2 mm, 68°C glass. The design of these nozzles is from all other aspects similar, which makes the observation valid.
- The earliest activation was achieved with the stand-alone, high-pressure water mist system that was activated by a fire detector. As mentioned, the detector was running with a medium sensitivity parameter set in these tests.

It can also be observed that activation times when using the simulated chair as compared to the authentic upholstered chair is reasonably similar, for each of the combinations of RTI and nominal temperature rating of the glass bulbs.

Figures 9 through 17 show the fire in the authentic upholstered chair at the moment immediately prior or after the activation of the residential sprinkler and water mist nozzles, respectively. Additionally, the fire size one and two minutes later, respectively, is depicted. These photos illustrate that the differences in activation times correlates well with the visual variance in fire size. The photos do also illustrate the effect on the fire development by the application of water, as also captured by the PTHFM devices and discussed in the section below.



Figure 9 Fire events: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 30.3 liter/min, at 1) moments prior the activation at 60 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 10 Fire events: Residential sprinkler having a 3 mm, 57°C glass bulb flowing 30.3 liter/min, at at 1) moments after the activation at 55 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 11 Fire events: Residential sprinkler having a 2.5 mm, 47°C glass bulb flowing 30.3 liter/min, at 1) moments prior the activation at 51 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 12 Fire events: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 60.6 liter/min, at 1) moments after the activation at 68 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 13 Fire events: The single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar, at 1) moments prior the activation at 60 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 14 Fire events: The multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar, at 1) moments prior the activation at 66 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 15 Fire events: The multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar, at 1) moments prior the activation at 64 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 16 Fire events: The multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar, at 1) moments prior the activation at 70 seconds, 2) one minute after activation and 3) two minutes after activation.



Figure 17 Fire events: The stand-alone water mist system flowing 8.2 liter/min at 120 bar, at 1) moments prior the activation at 43 seconds, 2) one minute after activation and 3) two minutes after activation.

5.2 The surface temperatures measured with the PTHFM devices

As described, the PTHFM devices were installed close to the fire test source. Any reduction of their temperature would be a result from the suppression of the fire, direct cooling of water hitting the front surfaces of the devices, any reduction of the heat radiation by water droplets between the flame and the devices or a combination of the

three. The evaluation was based on the mean surface temperature calculated from the readings of the four PTHFM devices positioned in front of the fire test source.

The graphs for the tests involving the simulated upholstered chair is based on the mean value from the test when it was orientated with its front towards the test compartment and the test when it was orientated towards the back wall. The influence on the performance of the tested systems based on the orientation of the simulated upholstered chair is discussed later in the report.

The measurement data is shown in figures 18 and 19, respectively.

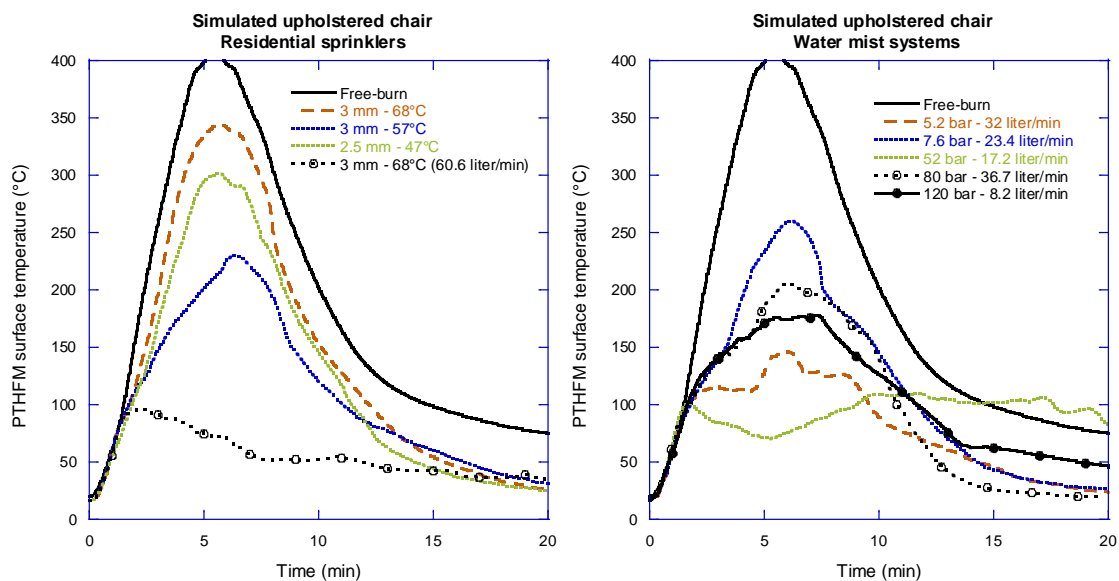


Figure 18 The surface temperatures measured with the PTHFM devices for the tests using the simulated upholstered chair.

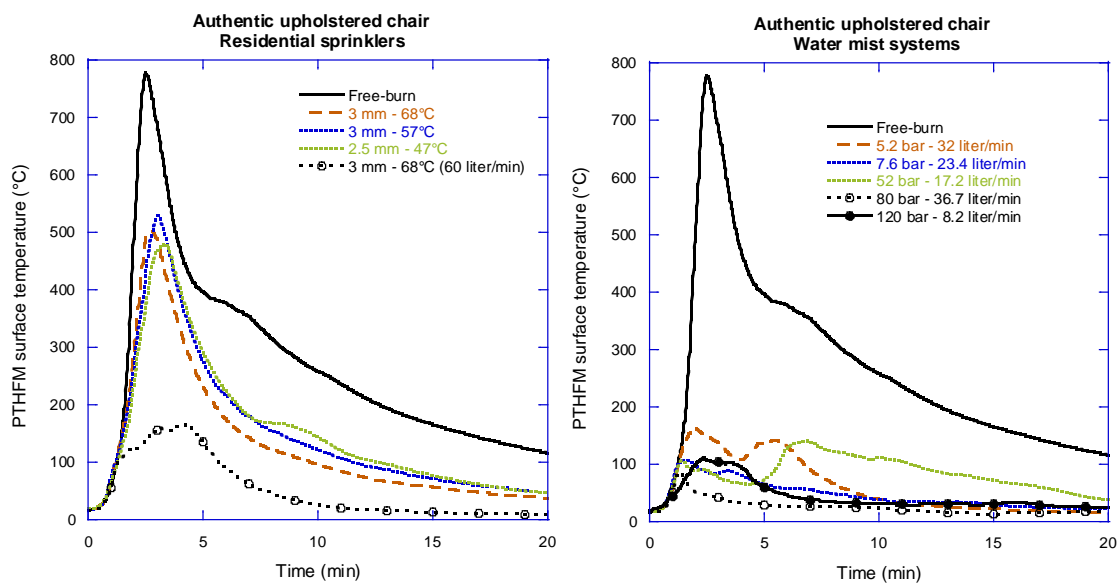


Figure 19 The surface temperatures measured with the PTHFM devices for the tests using the authentic upholstered chair.

The peak surface temperature measured during the free-burn tests of the authentic upholstered chair was almost twice that of the simulated upholstered chair. The

explanation is likely that the peak heat release of the authentic upholstered chair was higher (as discussed in section 6.1) and because the fire was spreading towards the measurement devices when the seat and armrests became involved in the fire, which directly exposed the devices to the flame.

When comparing the performance of the residential sprinklers, it can be observed that the earlier activation associated with a lower RTI and operating temperature corresponded to lower temperatures when using the simulated upholstered chair. The results are, however, not straightforward as the lowest temperature, for the simulated upholstered chair, was observed for the sprinkler having the 3 mm, 57°C glass bulb and not the sprinkler with the 2.5 mm, 47°C glass bulb. For the authentic upholstered chair scenario, any improvement in performance due to the RTI and operating temperature is negligible; the measured temperatures are fairly similar.

For both fire scenarios, the surface temperatures were significantly lower when the flow rate of the residential sprinkler was increased from 30.3 liter/min to 60.6 liter/min.

The water mist systems generally reduced the surface temperatures better than the residential sprinkler flowing 30.3 liter/min. For the scenario involving the simulated upholstered chair, the lowest temperature was recorded for the high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar. The highest surface temperature was recorded in the test with the single-orifice low-pressure water mist nozzle flowing 23.4 liter/min at 7.6 bar. The measured surface temperatures for the latter nozzle were slightly higher than the surface temperatures measured for the residential sprinkler having the same type of glass bulb, i.e. the 3 mm, 57°C glass bulb.

For the authentic upholstered chair scenario, the lowest surface temperatures were recorded in the test with the multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar. The highest surface temperatures were recorded in the test with the multi-orifice low-pressure nozzle flowing 32 liter/min at 5.2 bar.

For three of the tests, it can be claimed that the fire was suppressed by the activation of the system, as defined by an immediate reduction of the surface temperature upon the activation of the sprinkler or nozzle, without any increase in surface temperature thereafter. The tests were:

- The residential sprinkler flowing 60.6 liter/min in the test involving the simulated upholstered chair.
- The multi-orifice high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar, in the test involving the authentic upholstered chair. It is noticeable that this particular nozzle performed among the least good of the water mist nozzles in the scenario with the simulated upholstered chair.
- The single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar, in the test involving the authentic upholstered chair. It is noticeable that this particular nozzle performed the least good of the water mist nozzles in the scenario with the simulated upholstered chair.

For a fourth test, the test with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar, the fire in the authentic chair was almost suppressed, observed as an immediate reduction of the surface temperature. However, a second peak followed that almost reached to the temperature level of the first peak.

5.3 Ceiling gas temperatures

The ceiling gas temperature was measured more or less directly above the point of fire ignition. The graphs for the tests involving the simulated upholstered chair is based on the mean value from the test when it was orientated with its front towards the test compartment and the test when it was orientated towards the back wall. The influence on the performance of the tested systems based on the orientation of the simulated upholstered chair is discussed later in the report. The measurement data is shown in figures 20 and 21, respectively.

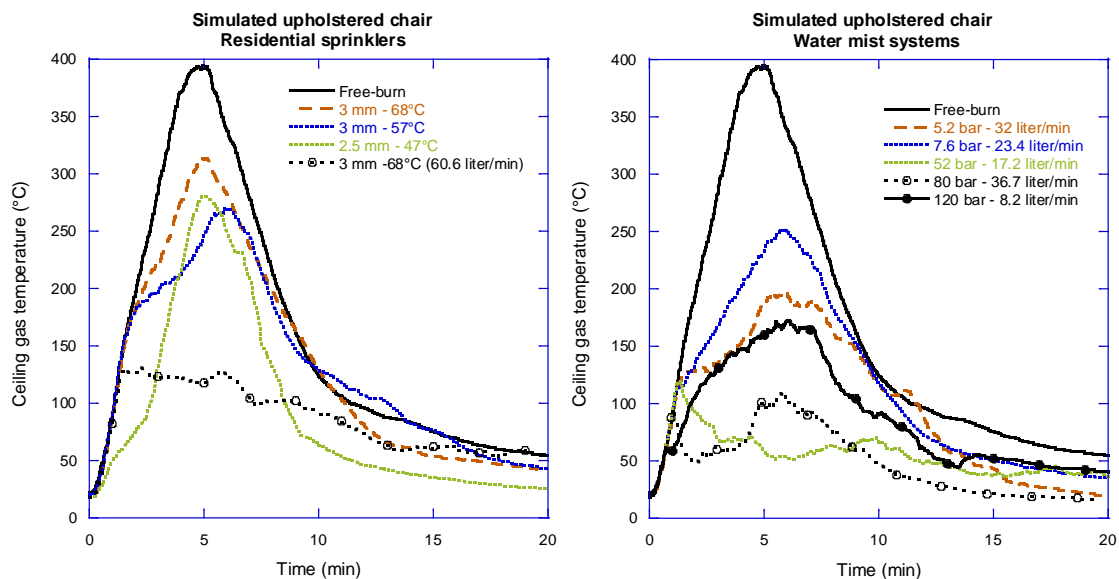


Figure 20 The ceiling gas temperatures for the tests using the simulated upholstered chair.

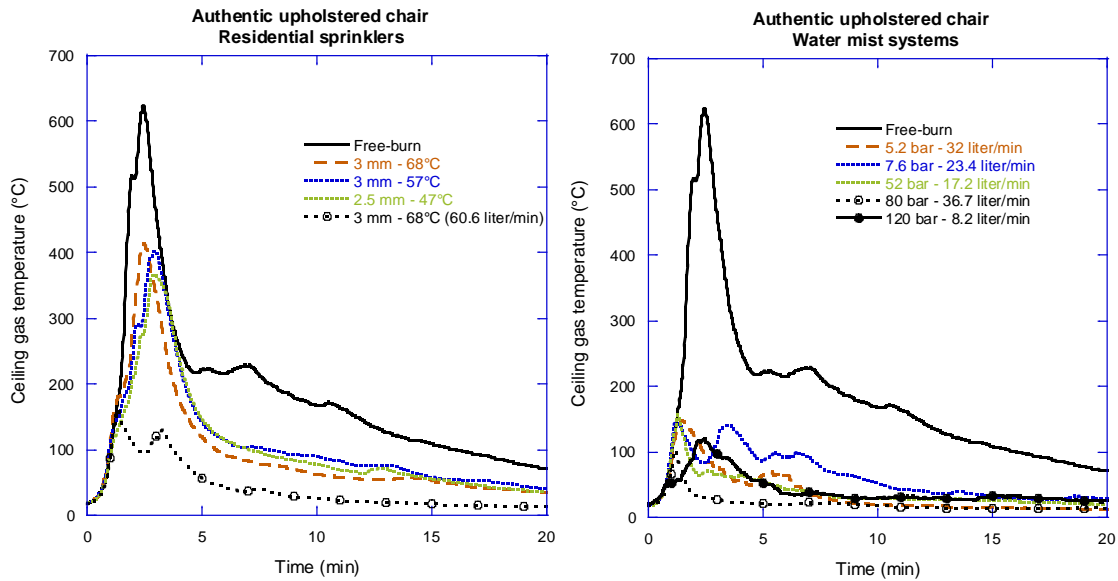


Figure 21 The ceiling gas temperatures for the tests using the authentic upholstered chair.

The peak ceiling gas temperature measured during the free-burn test of the authentic upholstered chair was approximately 200°C higher than that of the simulated upholstered chair. As previously discussed, the explanation may be that the peak heat release rate of the authentic upholstered chair is higher. It can also be observed that the duration time is shorter for the authentic upholstered chair which indicates that it is consumed faster.

When comparing the performance of the residential sprinklers, it can be observed that the earlier activation associated with a lower RTI and operating temperature corresponded to lower ceiling gas temperatures when using the simulated upholstered chair. The results are, however, not straightforward as the lowest peak temperature was observed for the sprinkler having the 3 mm, 57°C glass bulb and not the sprinkler with the 2.5 mm, 47°C glass bulb. For the authentic upholstered chair scenario, the effect of RTI and operating temperature is minor, but consistent with the activation times of the sprinklers.

The water mist nozzles generally performed better than the residential sprinklers flowing 30.3 liter/min. For both fire scenarios the lowest temperature, respectively, was recorded for the high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar. Slightly lower temperatures were recorded for this nozzle as compared to the high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar.

The highest ceiling gas temperatures were experienced with the two low-pressure water mist nozzles, for both scenarios.

5.4 The mean gas temperature at eye-level

The gas temperature was measured at eye-level (1.6 m above floor) at the center-point of each of the four quadrants of the test compartment, except for the quadrant with the

fire test source. The evaluation was based on the mean gas temperature of these three measurement points.

The graphs for the tests involving the simulated upholstered chair is based on the mean value from the test when it was orientated with its front towards the test compartment and the test when it was orientated towards the back wall. The influence on the performance of the tested systems based on the orientation of the simulated upholstered chair is discussed later in the report. The measurement data is shown in figures 22 and 23, respectively.

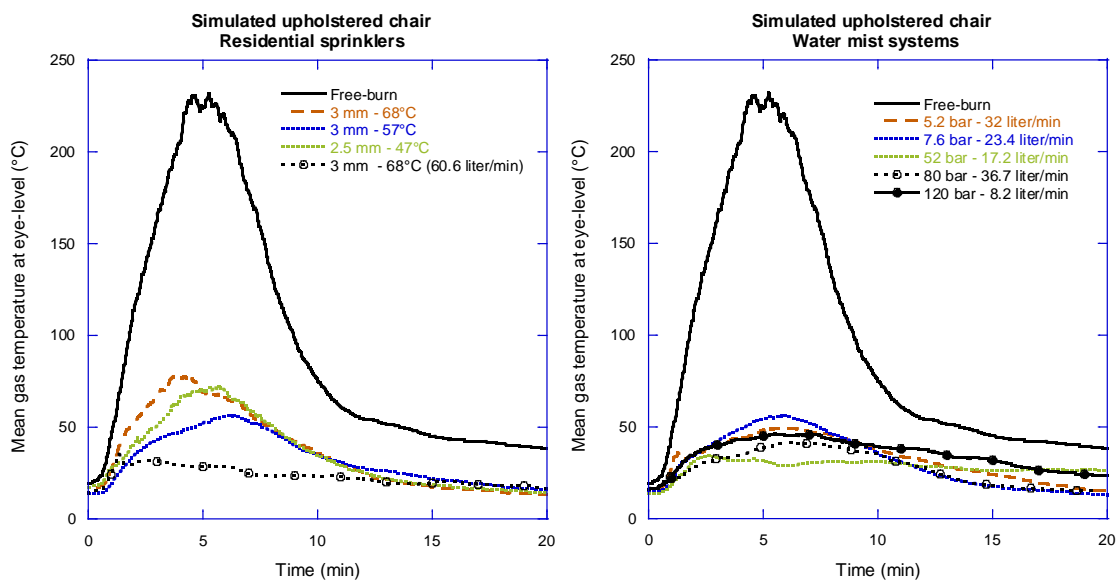


Figure 22 The mean gas temperature at eye-level for the tests using the simulated upholstered chair.

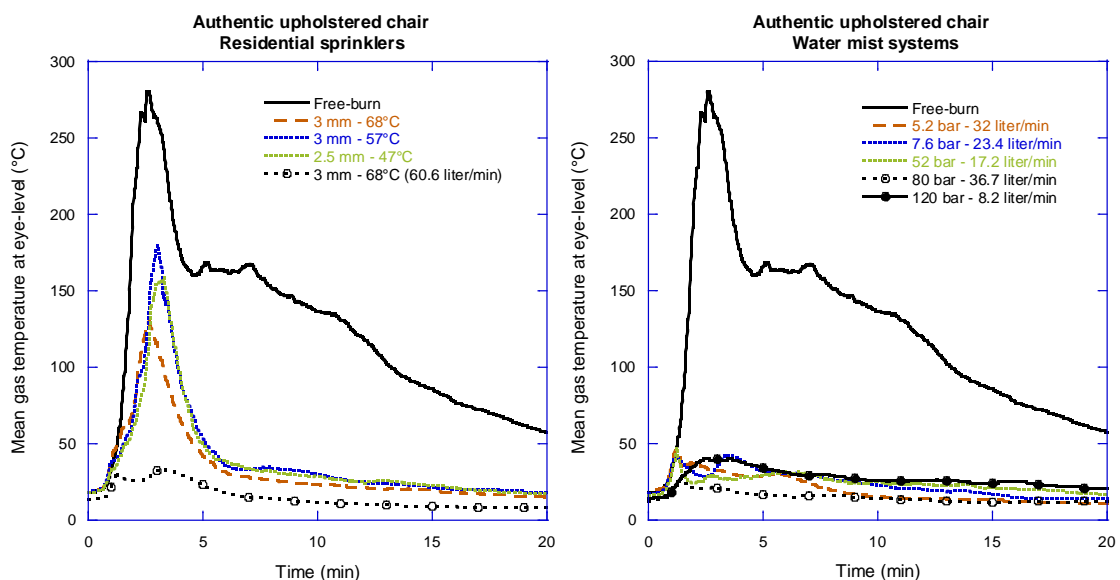


Figure 23 The mean gas temperature at eye-level for the tests using the authentic upholstered chair.

The peak gas temperatures at eye-level measured during the free-burn tests of the authentic upholstered chair was somewhat higher than that of the simulated

upholstered chair. As previously discussed, the explanation may be that the peak heat release rate of the authentic upholstered chair is higher.

When comparing the performance of the residential sprinklers, it can be observed that the earlier activation associated with a lower RTI and operating temperature corresponded affected the peak temperatures when using the simulated upholstered chair. As with the measurement results described above, this is not straightforward as the lowest peak temperature was observed for the sprinkler having the 3 mm, 57°C glass bulb and not the sprinkler with the 2.5 mm, 47°C glass bulb. For the authentic upholstered chair scenario, no significant positive effect of the lower RTI and lower operating temperature could be observed. In fact, the maximum temperature was around 50°C higher for the 47°C and 57°C glass bulbs as compared to the 68°C glass bulb, which is opposite to the expected effect.

In absolute numbers, the temperature levels were not significantly lower for the water mist nozzles as compared to the residential sprinklers for the simulated upholstered chair scenario. The difference was much larger for the scenario involving the authentic upholstered chair.

The high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar provided the best cooling for the simulated upholstered chair scenario, while the single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar provided the least cooling. For the scenario involving the authentic upholstered chair, the high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar provided the best cooling and the single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar provided the least cooling also for this scenario.

5.5 The influence of the orientation of the fire test source

The simulated upholstered chair was either orientated with its front towards the test compartment or with its front towards the back wall. For the former scenario, the fire was fully exposed to the water spray and in the latter scenario the fire was partly shielded from direct water application. This approach provides an opportunity to compare the performance of the tested residential sprinkler and water mist nozzles due to the shielding of the fire.

The comparison was made by comparing the peak temperatures for selected measurements obtained when the simulated chair was orientated with its front towards the test compartment with the value when its front was towards the back wall. It should be noted that a calculated mean temperature (not given) based on the peak temperatures given in the table does not match the temperatures in the graphs, as the peak value in each of the tests may have occurred at slightly different times, respectively.

Table 4 shows the peak mean surface temperatures of the PTHFM devices. It can be observed that the performance of the residential sprinklers was improved (lower peak

temperature) when the fire was partly shielded in all tests except for the tests using the 3 mm, 68°C glass bulb. This was also observed for both low-pressure nozzles as well as for one of the high-pressure water mist nozzles.

Table 4 The peak mean surface temperatures of the PTHFM devices, for the tests using the simulated upholstered chair, whether the simulated chair was orientated with its front towards the test compartment or with its front towards the back wall.

System	Type of sprinkler or nozzle	Glass bulb diameter [mm]	Temperature rating [°C]	Operating pressure [bar]	Water flow rate [liter/min]	Peak surf. temp [°C] Front	Peak surf. temp [°C] Back	Diff. [°C]
Free-burn	-	-	-	-	-	412	402	+10
Residential sprinkler	Single-orifice	3	68	0.49	30.3	335	367	-32
		3	57			288	175	+113
		2.5	47			350	280	+70
		3	68	1.97	60.6	132	83	+49
Low-pressure water mist	Single-orifice	3	57	7.6	23.4	291	234	+57
Low-pressure water mist	Multi-orifice	3	57	5.2	31.9	177	160	+17
High-pressure water mist	Multi-orifice	2	57	80	36.7	168	244	-76
High-pressure water mist	Multi-orifice	2	68	52	17.2	133	117	+16
Stand-alone, high-pressure water mist	Multi-orifice	Fire detector		120	8.2	102	257	-155

For the high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar and the stand-alone water mist system, improved performance was observed when the fire was started on the front side of the simulated upholstered chair.

For some of the tests, the difference in peak surface temperatures is small and for others the difference is considerably larger. The largest difference is observed for one of the residential sprinkler tests and the stand-alone high-pressure water mist system.

Table 5 shows the peak ceiling gas temperatures. Generally, the trends observed based on the peak surface temperature measurements obtained with the PTHFM devices are valid also for the ceiling gas temperatures. However, it could be noticed that the difference in ceiling gas temperatures is relatively small for the residential sprinkler test when flowing 60.6 liter/min and for the high-pressure water mist nozzle test when flowing 36.7 liter/min at 80 bar. For both these tests, the difference in peak surface temperature of the PTHFM devices was large as a result of the fire ignition position.

The observation is an indication that the cooling ability at the ceiling was superior, irrespective of the degree of fire suppression.

Table 5 The peak ceiling gas temperatures for the tests using the simulated upholstered chair, whether the simulated chair was orientated with its front towards the test compartment or with its front towards the back wall.

System	Type of sprinkler or nozzle	Glass bulb diameter [mm]	Temperature rating [°C]	Operating pressure [bar]	Water flow rate [liter/min]	Peak ceil. temp [°C] Front	Peak ceil. temp [°C] Back	Diff. [°C]
Free-burn	-	-	-	-	-	415	375	+40
Residential sprinkler	Single-orifice	3	68	0.49	30.3	334	300	+34
		3	57			306	255	+51
		2.5	47			321	250	+71
		3	68	1.97	60.6	138	132	+6
Low-pressure water mist	Single-orifice	3	57	7.6	23.4	275	233	+42
Low-pressure water mist	Multi-orifice	3	57	5.2	31.9	188	238	-50
High-pressure water mist	Multi-orifice	2	57	80	36.7	97	145	-48
High-pressure water mist	Multi-orifice	2	68	52	17.2	125	129	-4
Stand-alone, high-pressure water mist	Multi-orifice	Fire detector		120	8.2	135	234	-99

The relative difference in peak ceiling gas temperatures was at most between approximately 50°C and 100°C. The largest difference is observed for the stand-alone high-pressure water mist system.

Table 6 lists the peak eye-level gas temperatures showing that the difference in absolute temperatures on the eye level was generally small for all tests.

Table 6 The peak eye-level mean gas temperature for the tests using the simulated upholstered chair, whether the simulated chair was orientated with its front towards the test compartment or with its front towards the back wall.

System	Type of sprinkler or nozzle	Glass bulb diameter [mm]	Temperature rating [°C]	Operating pressure [bar]	Water flow rate [liter/min]	Peak ceil. temp [°C] Front	Peak ceil. temp [°C] Back	Diff. [°C]
Free-burn	-	-	-	-	-	228	237	-9
Residential sprinkler	Single-orifice	3	68	0.49	30.3	78	100	-22
		3	57			54	60	-6
		2.5	47			77	75	+2
		3	68	1.97	60.6	39	34	+5
Low-pressure water mist	Single-orifice	3	57	7.6	23.4	54	59	-5
Low-pressure water mist	Multi-orifice	3	57	5.2	31.9	47	58	-9
High-pressure water mist	Multi-orifice	2	57	80	36.7	40	44	-4
High-pressure water mist	Multi-orifice	2	68	52	17.2	34	42	-8
Stand-alone, high-pressure water mist	Multi-orifice	Fire detector		120	8.2	44	49	-5

5.6 Carbon monoxide (CO) concentrations

The carbon monoxide (CO) concentrations were measured at the eye-level (1.6 m above floor) at the center-point of the quadrant to the right of the quadrant with the fire test source, see figure 6.

As with the other results, the graphs for the tests involving the simulated upholstered chair is based on the mean value from the test when fire ignition was at the front and from the test when fire ignition was at the back of the foam cushion. The measurement data is shown in figures 24 and 25, respectively.

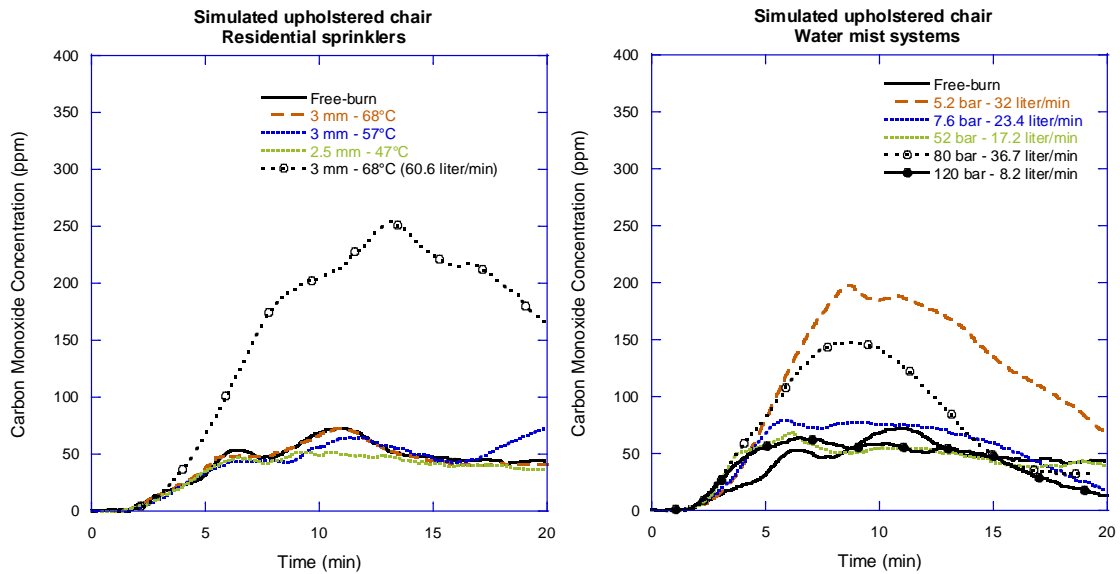


Figure 24 The Carbon Monoxide (CO) concentrations measured during the tests with the simulated upholstered chair scenario.

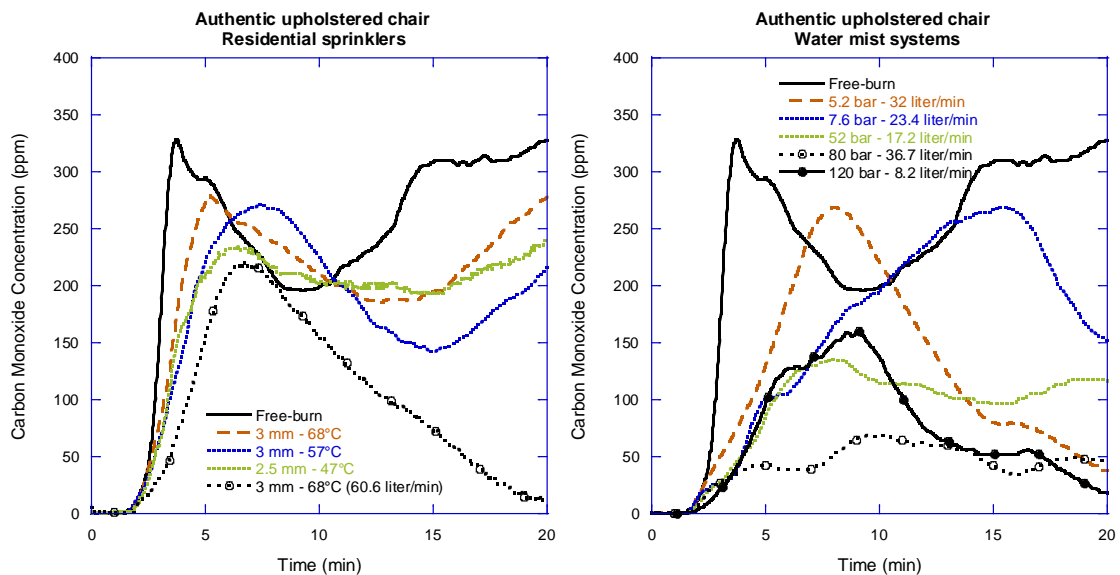


Figure 25 The Carbon Monoxide (CO) concentrations measured during the tests with the authentic upholstered chair scenario.

For the scenario involving the simulated upholstered chair, test data is straightforward from the aspect that similar CO concentrations were measured for all residential sprinkler tests when flowing 30.3 liter/min. The free-burn fire test generated similar CO concentrations. The highest CO concentrations were recorded in the test with the residential sprinkler when flowing 60.6 liter/min. From the other test data, it can be observed that the fire was the most suppressed in this particular test.

For the scenario involving the authentic upholstered chair, the highest CO concentrations were measured during the free-burn test, at the stage when the fire started to decline. The CO concentrations obtained during the residential sprinkler tests are reasonably similar, with the lowest concentrations obtained for the test using 60.6 liter/min. For this particular test, the fire was suppressed the most, which to a

certain degree contradicts the observation discussed above where improved fire suppression correlated to a high level of CO.

For the scenario involving the simulated upholstered chair, the highest CO concentrations were recorded in the test with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar and in the test with the high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar.

For the scenario involving the authentic upholstered chair, the highest CO concentrations were recorded in the test with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar and in the test with the single-orifice low-pressure water mist nozzle flowing 23.4 liter/min at 7.6 bar. For the latter nozzle, the peak occurred at a late stage of the fire duration, when the fire was declining. Even higher CO concentrations were measured during the free-burn test, both when the fire size peaked and at the stage when the fire started to decline. The lowest concentrations were measured for the test with the high-pressure water mist nozzle flowing 36.7 liter/min at 80 bar. For this particular test, the fire was suppressed the most.

5.7 Fire damages

5.7.1 Fire damages in the simulated upholstered chair scenario

For the simulated upholstered chair scenario, the combustible foam cushion was completely or almost completely consumed. Figure 26 shows the fire damages for the tests with the residential sprinkler having a 3 mm, 68°C glass bulb at a flow rate of 30.3 liter/min. Similar fire damages were recorded for the other residential sprinkler tests at 30.3 liter/min and are not shown. Some combustible material remained after the test when the flow rate was 60.6 liter/min as can be seen in figure 27. This is fully in line with the corresponding reduced temperatures of the PTHFM devices and the ceiling gas temperature.



Figure 26 Fire damages: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 30.3 liter/min, when ignition was at the front (left) or back of the simulated upholstered chair (right). *Note: For all other residential sprinkler tests at 30.3 liter/min the fire damages were similar and these photos are therefore not included.*



Figure 27 Fire damages: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 60.6 liter/min, when ignition was at the front (left) or back of the simulated upholstered chair (right).

For the water mist nozzles tests, the extent of the fire damages virtually correlates with the water flow rates of the nozzles as can be seen in figures 28 through 32, except that some material did also remain for the test with the multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar as seen in figure 30.



Figure 28 Fire damages: The single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar, when ignition was at the front (left) or back of the simulated upholstered chair (right).



Figure 29 Fire damages: The multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar, when ignition was at the front (left) or back of the simulated upholstered chair (right).



Figure 30 Fire damages: The multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar, when ignition was at the front (left) or back of the simulated upholstered chair (right).



Figure 31 Fire damages: The multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar, when ignition was at the front (left) or back of the simulated upholstered chair (right).



Figure 32 Fire damages: The stand-alone water mist system flowing 8.2 liter/min at 120 bar, when ignition was at the front (left) or back of the simulated upholstered chair (right).

5.7.2 Fire damages in the authentic upholstered chair scenario

For the authentic upholstered chair scenario, significantly more combustibile material remained after a test as compared to simulated upholstered chair scenario. Therefore, the fire damages are presented and discussed in more detail. It should be understood that the fire damage evaluation is to a certain degree subjective as it was made by visual

observations only. For the free-burn fire test, the authentic upholstered chair burnt out completely as seen in figure 33.



Figure 33 Fire damages: Free-burn fire tests.

The fire damages of the authentic upholstered chair were visually very similar for all residential sprinklers tests at the 30.3 liter/min flow rate as presented in figures 34 through 36. In other words, earlier activation of the residential sprinklers did not result in smaller fire damages. This corresponds well with the observation that both the surface temperatures of the PTHFM devices and the ceiling gas temperature remained similar at this water flow rate.



Figure 34 Fire damages: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 30.3 liter/min.



Figure 35 Fire damages: Residential sprinkler having a 3 mm, 57°C glass bulb flowing 30.3 liter/min.



Figure 36 Fire damages: Residential sprinkler having a 2.5 mm, 47°C glass bulb flowing 30.3 liter/min.

The fire damages were significantly reduced when the flow rate was increased to 60.6 liter/min as seen in figure 37. This is fully in line with the corresponding reduced temperatures of the PTHFM devices and the ceiling gas temperature.



Figure 37 Fire damages: Residential sprinkler having a 3 mm, 68°C glass bulb flowing 60.6 liter/min.

For the water mist nozzles tests, the extent of the fire damages virtually correlates with the water flow rates of the nozzles as can be observed from figures 38 through 41. The smallest fire damages appeared in the test with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar and in the test with the multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar.

Larger fire damages was observed in the tests with the single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar, the multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar and the test with the stand-alone water mist system flowing 8.2 liter/min at 120 bar. Figure 42 shows the fire damages in the test with the stand-alone water mist system. Its extent demonstrates that the early application of water did not prevent further fire spread in the authentic chair.

There is a reasonable correlation between the extent of fire damage and the surface temperatures of the PTHFM devices. The correlation is lesser for the extent of fire damage and the ceiling gas temperatures.



Figure 38 Fire damages: The single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar.



Figure 39 Fire damages: The multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar.



Figure 40 Fire damages: The multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar.



Figure 41 Fire damages: The multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar.



Figure 42 Fire damages: The stand-alone water mist system flowing 8.2 liter/min at 120 bar.

Comparing the extent of fire damage of the residential sprinklers and the water mist nozzle tests indicates that fire damages for the residential sprinklers flowing 30.3 liter/min is larger than the fire damages experienced with the water mist nozzles having the lowest water flow rates. The fire damages experienced with the residential sprinkler flowing 60.6 liter/min is slightly larger than the damages experienced with the water mist nozzles having the highest water flow rates.

6 Discussion and conclusion

The primary aim of this study was to evaluate if the performance of commercial residential sprinklers could be improved by using sprinkler glass bulbs with a lower Response Time Index (RTI) and lower temperature rating than that of the commonly used 3 mm, 68°C glass bulb. The tests included residential sprinklers with the common 3 mm, 68°C glass bulb, a 3 mm, 57°C glass bulb as well as a 2.5 mm, 47°C glass bulb. However, from a practical perspective, it is essential to recognize that a sprinkler temperature rating as low as 47°C would not be permitted to be used in accordance with the residential sprinkler installation practices in NFPA 13D and 13R as well as in SS 883001:2009/INSTA 900-1. In addition to unwanted discharge, there is also a balance between sprinkler glass bulb sensitivity and the potential for operating excessive numbers of sprinklers. However, the use of the 2.5 mm, 47°C glass bulb provide performance data associated with early thermal activation that is valuable for the comparison of the other glass bulbs used in the tests.

The tests were conducted inside a 3.66 m by 3.66 m test compartment, i.e. the floor area matched the minimum residential sprinkler listing coverage area. The majority of the tests were conducted at the minimum 2.04 mm/min (0.05 gpm/ft²) discharge density recommended in NFPA 13D, 13R and SS 883001:2009/INSTA 900-1. This corresponded to a water flow rate of 30.3 liter/min. For some of the tests, the water flow rate was increased (without changing the sprinkler used) to 60.6 liter/min, which corresponds to the minimum design discharge density of 4.1 mm/min (0.1 gpm/ft²) recommended for light hazard occupancies in NFPA 13 and in SS 883001:2009/INSTA 900-1 for certain residential premises. However, it should be noted that a sprinkler with a larger K-factor probably would be chosen for the higher design density in practice.

In addition to the residential sprinkler tests, tests were conducted with commercial low- and high-pressure water mist nozzles and a commercial stand-alone high-pressure water mist system. Water mist technology may be used in residential area applications as an alternative to residential sprinklers, but there are limited publically available test data for modern water mist technology. Arvidson and Larsson [19] have conducted fire tests comparing residential sprinklers and high-pressure water mist nozzles. However, water mist technology has advanced since these tests were conducted. One of the technology advances includes stand-alone high-pressure water mist systems activated by a fire detector. Such systems are commonly used in Sweden where the resident is elderly, disabled, a smoker or belong to any other group identified as being at most risk of residential fire deaths. One of the advantages of the stand-alone system is its earlier activation.

The performance of the tested residential sprinklers, water mist nozzles and stand-alone high-pressure water mist system was determined by the measurement of the temperature of four PT heat flux meters (PTHFM) positioned in front of the fire test source, the ceiling gas temperature directly above the center-point of the fire test source, the gas temperature at eye-level (1.6 m above floor) at the center-point of each of the four quadrants of the test compartment as well as the concentrations of Carbon Monoxide (CO) at the eye-level. The PTHFM devices consisted of a 100 mm by 100 mm steel plate, nominally 0.5 mm thick. A sheathed 1 mm diameter thermocouple is welded to the backside of the steel plate and the backside is insulated with 50 mm thermal insulation.

6.1 The fire test sources

Two different fire test sources were used, a simulated upholstered chair and an authentic upholstered chair. Free-burn calorimeter measurement pre-tests using the simulated upholstered chair indicate that the initial fire growth rate resembles a 'medium' fire growth rate, in accordance with the exponential t-squared (t^2) fire growth rate curves commonly used for fire protection design purposes. No free-burn calorimeter measurement tests were conducted with the authentic upholstered chair.

Based on the activation times of sprinklers and nozzles, it can be observed that both scenarios provide similar initial fire growth rates. This is verified by the surface temperatures measured with the PTHFM devices and the ceiling gas temperatures as shown in figure 43. However, after the initial stage (after a recorded ceiling gas temperature of approximately 100°C – which would correspond quite well with the activation of a sprinkler or nozzle) the temperature data illustrates that the fire growth rate of the authentic upholstered chair is significantly more rapid. There may be several reasons for this, for example that the geometry of the authentic upholstered chair allows more combustible surfaces to be involved faster in the fire or that the density of the polyether foam was lower. The higher peak gas temperature for the authentic upholstered chair is an indication that the peak heat release rate was higher. This is likely as the amount of combustible materials was larger.

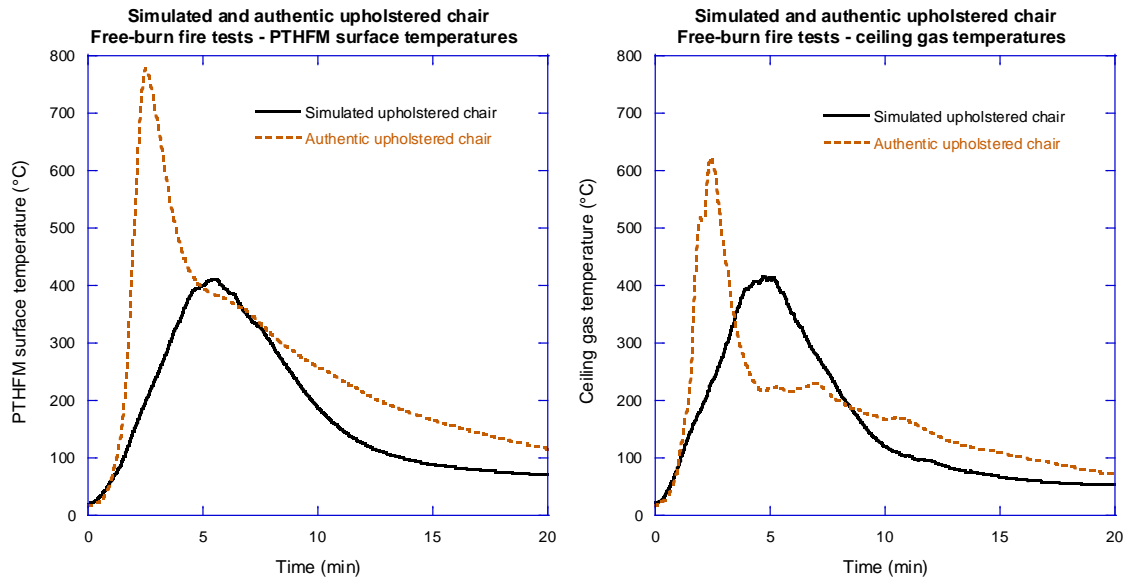


Figure 43 Comparisons of the surface temperatures measured with the PTHFM devices (left) and the ceiling gas temperatures (right) in the free-burn fire tests for the two fire test scenarios.

6.2 Residential sprinkler test results

When comparing the performance of the residential sprinklers, it can be observed that the earlier activation associated with a lower RTI and operating temperature to a certain degree corresponded to improved performance when using the simulated upholstered chair. The results are, however, not straightforward as the lowest peak temperatures were observed for the sprinkler having the 3 mm, 57°C glass bulb and not the sprinkler with the 2.5 mm, 47°C glass bulb. For the authentic upholstered chair scenario, any improvement in performance due to the earlier activation is negligible.

The data from the fire suppression tests indicate that the authentic upholstered chair represented a more challenging fire scenario than the simulated upholstered chair for the residential sprinklers. The faster fire growth rate and the possible higher peak heat release rate of the authentic upholstered chair scenario may explain this. Another explanation may be that the combustible foam material to a certain extent was shielded from direct water application by the fabric cover, especially before the fabric becomes wetted.

A significant improvement in performance for the residential sprinkler occurred when the water flow rate was increased from 30.3 liter/min to 60.6 liter/min. This is an illustrative example of the inherent safety factor of sprinkler systems, as the flow rate of the first activated sprinklers in an actual system would provide a significantly higher discharge density than the design density. It does also reflect the desired performance improvement of an NFPA 13 system design for light hazard occupancies as compared to the design of an NFPA 13D or 13R residential area system as well as the desired performance improvement in SS 883001:2009/INSTA 900-1 for certain residential premises.

The improved fire suppression performance using 60.6 liter/min as compared to 30.3 liter/min resulted in significantly reduced surface temperatures measured with the PTHFM devices, reduced ceiling gas temperatures, reduced gas temperatures at eye-level as well as reduced fire damages. However, the improved fire suppression performance caused higher carbon monoxide (CO) concentrations in the test compartment. This is a result of reduced burning efficiency of the fire and is sometimes observed in fire suppression tests. The NFPA Fire Protection Handbook has summarized the effects symptoms from exposure of CO for an average, healthy adult [20]. Some symptoms include shortness of breath, nausea, dizziness, light headedness or headaches. High levels of CO can be fatal, causing death within minutes. According to the information, 200 ppm would result in "Mild headache after 2-3 hours of exposure" and 400 ppm would result in "Headache and nausea after 1-2 hours of exposure". These levels represent the maximum concentrations that were measured during the residential sprinkler tests. A concentration of 6 400 ppm would cause "Headache and dizziness after 1-2 minutes; unconsciousness and danger of death after 10-15 minutes of exposure". The measured CO concentrations can therefore be regarded as significantly lower than acute lethal levels. However, it should be considered that the doorway to the test compartment was open during the tests and that other hazardous gases may form during a fire.

The fire damages of the authentic upholstered chair were visually very similar for all residential sprinklers tests at the 30.3 liter/min and earlier activation of the residential sprinkler did not result in smaller fire damages. The fire damages were significantly reduced when the flow rate was increased to 60.6 liter/min.

It is likely that earlier activation (by using for example the 57°C instead of the 68°C glass bulb) of the residential sprinkler at a flow rate of 60.6 liter/min would have resulted in more evident performance improvements. However, this was not investigated.

6.3 Water mist nozzle test results

In addition to the residential sprinkler tests, tests were conducted with commercial low- and high-pressure water mist nozzles and a commercial stand-alone high-pressure water mist system. The latter is activated by a multi-criteria (smoke and heat) detector. The water flow rates for the water mist nozzles ranged from 17.2 liter/min to 36.7 liter/min and the stand-alone high-pressure water mist water system did only flow 8.2 liter/min.

For these tests, higher temperature levels (except for the mean gas temperature at eye-level) were generally recorded in the tests with the simulated upholstered chair. For the residential sprinkler, the general trend was the opposite.

The question which of the water mist nozzles that performed the best is not entirely straightforward; the answer depends both on the fire scenario and on the measurement parameter. As an example; for the scenario involving the simulated upholstered chair, the lowest surface temperature of the PTHFM devices was recorded in the test with the

high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar. The results for the scenario involving the authentic upholstered chair indicate that this particular nozzle reduced the surface temperature among the least. For this fire scenario, the lowest surface temperature of the PTHFM devices was recorded in the test with the multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar. Figure 44 shows the surface temperature of the PTHFM devices for the water mist nozzle tests, for both the fire scenarios. In contrast to the graphs shown previously in the report, the free-burn fire test data is not shown, making the reading of the data easier.

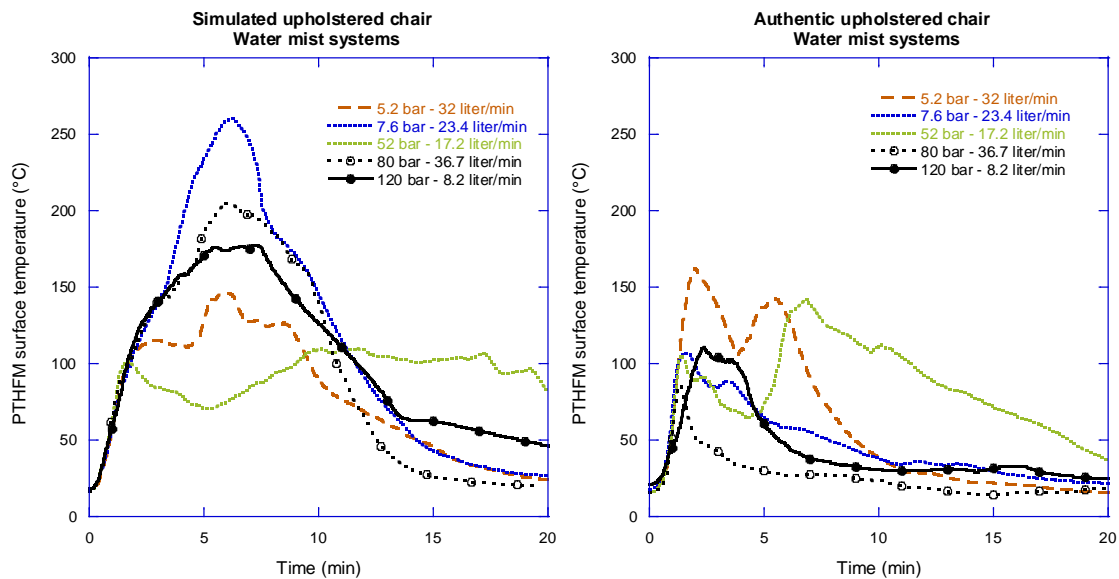


Figure 44 The surface temperatures measured with the PTHFM devices for the water mist nozzle tests, without the free-burn fire test data.

For both fire scenarios, the lowest ceiling gas temperatures were recorded in the tests with the high-pressure water mist nozzles, illustrating the enhanced cooling of smaller water droplets combined with a strong downward momentum of the water sprays that entrain the hot gases from the ceiling level and push them down. Figure 45 shows the ceiling gas temperatures for the water mist nozzle tests, for both the fire scenarios. The free-burn fire test data is not shown, making the reading of the data easier.

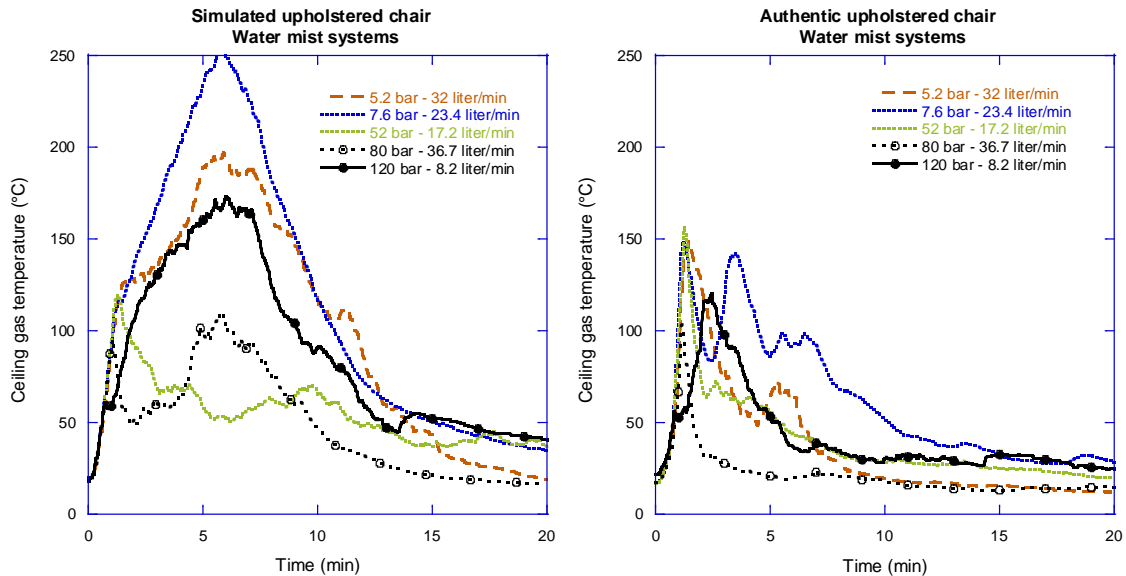


Figure 45 The ceiling gas temperatures for the water mist nozzle tests, without the free-burn fire test data.

Higher ceiling gas temperatures were recorded in the tests with the low-pressure water mist nozzles, especially in the fire scenario with the simulated upholstered chair. The high-pressure water mist nozzles did also reduce the mean gas temperature at eye-level better than the low-pressure water mist nozzles for both fire scenarios; however, the difference is small. Figure 46 shows the mean gas temperature at eye-level for the water mist nozzle tests, for both the fire scenarios. The free-burn fire test data is not shown.

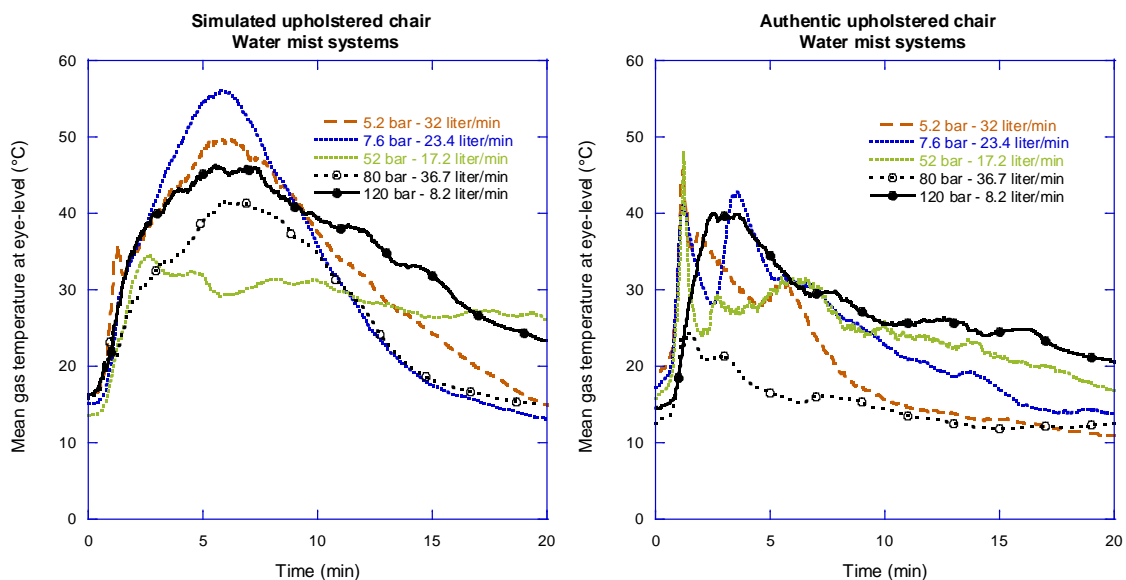


Figure 46 The mean gas temperature at eye-level for the water mist nozzle tests, without the free-burn fire test data.

The fire damages to the authentic upholstered chair seem to reasonably well correlate with the water flow rates of the water mist nozzles. The smallest fire damages appeared in the test with the highest flow rates; the test with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar and in the test with the multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar.

6.4 Test results with the stand-alone high-pressure water mist system

The stand-alone high-pressure water mist system unit was positioned on the wall opposite to the fire test sources and the influence on the performance of other positions was not investigated. The performance was comparable to that of the other water mist nozzles in the study, despite a considerably earlier activation. However, the results indicate that the performance was relatively much influenced whether the simulated upholstered chair was orientated with its front towards the test compartment or with its front towards the back wall (poorer performance). This would suggest that a position of the fire test source at for example the side of the unit could be challenging for the system and underlines the importance of a thoughtful position of the unit in practical applications. It should be acknowledged that the system does not provide the uniform water coverage inside a protected compartment as the tested residential sprinkler and water mist nozzles. The simulated upholstered chair scenario was more challenging for the system than the authentic upholstered chair scenario, as observed with the other water mist nozzles.

The earlier activation of the stand-alone high-pressure water mist system did not contribute to any noticeable reduction in temperatures (as compared to the water mist nozzles) measured with the PTHFM devices positioned close to the fire and the fire damages were large in both fire scenarios.

The duration time of approximately 10 minutes, associated with the limited amount of water in the tank, is similar to the minimum water supply requirements of residential sprinkler systems designed in accordance with NFPA 13D and the Type 1 system requirements in accordance with SS 883001:2009/INSTA 900-1. It was observed that the fire did not re-develop in any of the fire tests at the end of the discharge of the system, although the fires were not completely extinguished.

6.5 Concluding remarks

Residential sprinklers are expected to prevent flashover within the compartment of origin where sprinklers are installed in the compartment. This was accomplished in the tests, although it can be noted that flashover did not occur in any of the free-burn fire tests either. It is judged that survivable conditions were achieved, with the exception that relatively high gas temperatures at eye-level was recorded in the scenario involving the authentic upholstered chair at the 30.3 liter/min flow rate. High temperatures (corresponding to high heat radiation levels) were measured with the PTHFM devices positioned close to the fire and the fire damages were large in both fire scenarios. This is an indication that any person located near the fire would have limited probability for survival unless he/she evacuates, despite the earlier activation achieved with some of the sprinkler glass bulbs that were used.

Improved performance was experienced with the water mist nozzles compared to the residential sprinklers for both fire scenarios. The fact that the authentic chair simply

burnt more intensively than the simulated upholstered chair seems to have resulted in relatively poorer performance of the residential sprinklers as compared to the water mist nozzles.

High temperatures were measured with the PTHFM devices positioned close to the fire and the fire damages were large for all water mist nozzle tests as well as for the test with the stand-alone high-pressure water mist system. The fact that this particular system activated considerably earlier than the thermally activated nozzles did not contribute to reduced temperatures. The mean gas temperature at eye-level was considerably lower in the water mist nozzle tests, especially for the scenario with the authentic upholstered chair.

Roughly, it could be concluded that the performance of the water mist nozzles were comparable or better than the residential sprinkler at approximately half the water flow rate. When flowing 60.6 liter/min, the residential sprinkler provided fire suppression, or a performance close to fire suppression, with low ceiling gas temperatures and reduced fire damages. Similar results were obtained with the multi-orifice low-pressure water mist nozzle flowing 32 liter/min at 5.2 bar and with the multi-orifice high-pressure nozzle flowing 36.7 liter/min at 80 bar. When flowing 30.3 liter/min, the residential sprinkler resulted in fire control, higher ceiling gas temperatures and larger fire damages. The single-orifice low-pressure water mist nozzle flowing 23.4 liter/minute at 7.6 bar and the multi-orifice high-pressure water mist nozzle flowing 17.2 liter/min at 52 bar performed comparable or better.

It should be acknowledged that the data in the report is not an unambiguous proof that water mist nozzles outperform residential sprinklers. There could be residential area fire scenarios where the performance of residential sprinklers is superior, for example scenarios involving combustible wall linings, where the discharge pattern of residential sprinklers could be beneficial. However, the results are a strong indicator that water mist technology is well suitable for residential area applications.

An interesting observation is that the authentic chair provided a more challenging fire scenario for the residential sprinklers than did the simulated upholstered chair. For the water mist nozzles and the stand-alone water mist system, the simulated upholstered chair appeared to be more challenging. This implies that the design of the fire scenario is an essential factor for any approval testing of residential sprinklers or water mist nozzles intended for residential area applications.

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