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# Investigation of sprinkler wetting patterns for fire protection of exposed timber

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## Abstract

In this experimental study, a range of sprinkler head types were tested to evaluate the wetting potential of exposed timber ceilings and walls in addition to providing water to the room's contents. Water distribution tests were conducted using standard single sprinklers at high and low pressures with different mounting orientations. Water capture below the sprinklers allowed the assessment of actual delivered density against requirements. A specifically designed test rig was used to evaluate water delivery rates to walls, and ceiling wetting patterns were captured photographically and through measurement for later analysis. The aim of this study is to provide evidence and data to inform organisations/ standards bodies of potential changes that can optimise sprinkler systems for the protection of mass timber buildings with exposed internal combustible timber surfaces. The results presented demonstrate that, through careful consideration of sprinkler head type and positioning, improved surface wetting of ceilings and walls can be achieved without compromising water delivery to the contents/fuel load. It is estimated that minor changes to system design can greatly improve system performance for mass timber construction at minimal cost. This work is presented with a view to support the adaption of current UK sprinkler standards to this new protection scenario.

## Highlights

- Contemporary sprinklers do not directly discharge water on exposed timber wall and ceilings. Some sprinklers are specifically designed to discharge water simultaneously on exposed timber ceilings and contents from the fire.
- Appropriate sprinkler head spacing is critical to ensure adequate wall and ceiling surface coverage of combustible surfaces.

**Keywords** CLT (Cross Laminated Timber) · Mass timber · BS EN 12845 · LPC rules · Sprinkler · Density

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Extended author information available on the last page of the article

# 1 Introduction

Timber is gaining popularity in construction, not only for its aesthetic appearance, but also to enhance sustainability metrics. Timber is being used in the primary structure and secondary finishes as exposed surfaces in interior compartments [1–7]. The biggest driver for the increase in the use of timber in the UK is the government [8], helping their vision to tackle climate change by reducing $CO_2$ emissions in UK construction. However, the substitution of steel and concrete for timber brings with it new challenges for fire protection.

Timber is a combustible material that will need to be protected against fire. This can be achieved with fire retardants [9], encapsulation using plasterboard, or with the installation of an active fire suppression system. Fire retardants increase costs and may need to be reapplied at specified intervals, which may be difficult in existing buildings. Encapsulation is another consideration; however, this removes the visual aesthetics of the raw material and has been seen to fall away during a fire through inadequate fixings and general failure. Encapsulation also has the potential to allow and hide smouldering combustion [10].

Sprinkler statistics [11–13] confirm that the effectiveness of sprinklers to control fires and halt fire spread is over 96%, and with proper design, inspection, and maintenance this can improve to 99%. Studies show that from 2017 to 2021, deaths were reduced by 90% when sprinklers were present, and firefighter injuries per fire were 35% lower. Where sprinklers were present, fires were contained to the room of origin or object in 94% of fires reported, and sprinklers operated in 92% of fires recorded and were 97% effective in controlling the fire. However, there is concern that this track record will be impacted if the same protocols are used in buildings with combustible walls and ceilings.

As fire safety and sustainability goals converge, fire sprinkler systems are increasingly seen as a carbon-conscious investment in resilient, low-impact timber building designs. That said, adaptation of the design of fire sprinkler systems is required to ensure that both contents and any exposed timber surfaces are appropriately protected. The additional fuel load and propensity for timber to smoulder and later re-ignite, means an optimised response from the fire sprinkler system is required to ensure containment and prevent spread to inaccessible seams and voids. A published study is described later in this introduction in which a sprinkler system in an exposed timber corridor was unable to control a fire starting in an adjoining unsprinklered bedroom. This was due to the sprinklers' inability to deliver water to the ceiling's surface and is presented as evidence of need for this approach. Specific protection of the ceiling is also critical to ensuring the integrity of Mechanical & Electrical (M&E) services that rely on them for structural support.

Fire protection of buildings with internal timber surfaces using sprinkler systems is not a new concept. In Victorian Britain, sprinkler systems, and the type of sprinkler head used, were designed to protect timber mill floors/ceilings. Sprinkler heads were designed to provide water upward to the ceiling and downward to the fuel load below. These sprinklers are known as 'Conventional' type. Manufacturers still produce these sprinklers today, also known as 'old-style conventional sprinklers.' However, due to changes in building methods and materials, modern sprinklers have been developed to provide 100% of the water discharge downward to cover the fuel load at floor level, based on the assumption that modern buildings have essentially limited or non-combustible walls and ceilings (this is accepted in current sprinkler installation rulesets described below).

There are a number of suppression standards that can be applied to different building types and occupancies in the UK today. The most commonly used standards are for sprinkler systems, which separately cover Commercial and Industrial [14, 15] and Residential and Domestic [16, 17] premises.

Standards used for sprinkler head testing vary, from commercial to residential. Table 1 provides general details of test standards and their specific requirements.

Table 1 highlights differences between used standards. Sprinklers installed in the UK are typically approved to European and American standards and are subjected to numerous tests shown in the table.

The same distinction is applied to watermist standards [26–28]: however, watermist is not generally considered appropriate for property protection by UK insurers and is therefore not considered in this study[1]. There are also an extremely limited number of approved watermist nozzles available.

Sprinkler systems have been around for over two centuries, with the first known system being installed at Drury Lane Theatre, London, in 1812 [15]. They work through heat activation of the thermal sensing element located in the sprinkler head itself. In the event of fire, heat accumulating at the ceiling (where the sprinklers are located) activates the sprinklers when the temperature reaches a specified value. Sprinkler head(s) closest to the fire will activate, providing water to the fire below.

The amount of water discharged, based on the risk profile or occupancy hazard classification, is specified according to the standard adopted. Water discharge from sprinkler heads is measured as density of water (depth) in mm $\text{min}^{-1}$ $\text{m}^{-2}$ (~5–30 mm $\text{min}^{-1}$ $\text{m}^{-2}$),[2] over an estimated fire area (confirmed by the hazard classification, usually between 72 and 300 $\text{m}^2$). Sprinklers are located where the hottest gas layer would be expected at ceiling level (75–150 mm below the ceiling), to ensure early activation. Commercial/industrial sprinklers are spaced between 2 m (minimum) and 3.7/4 m (maximum) apart to cover an area of 9 to 12 $\text{m}^2$ per sprinkler depending on hazard classification. Each sprinkler is designed to discharge in a circular spray pattern, covering the fire area at floor level. The droplet size distribution for sprinkler systems is deliberately large (> 1 mm), so droplets penetrate the fire plume to provide cooling and pre-wetting of the fuel load without cooling the ceiling gas layer (which would inhibit subsequent sprinkler heads from opening). Using sprinkler water to wet timber linings (walls, floors, and ceilings) will help to prevent flame spread within a compartment.

Sprinkler heads come in varied sizes having a range of ‘K’ factor constant coefficients that relate the orifice diameter, depth, and shape, to the operational pressure and output flow.

Equation 1 shows the relationship between ‘K’ factor, pressure, and flow rate.

$$\mathrm{K} = \mathrm{Q}/\sqrt{\mathrm{P}} \tag{1}$$

where Q is the flow of water (L/min).

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[1] Watermist is perceived by some to be an alternative to sprinklers but is a relatively new form of suppression. The technology was developed for quite different environments derived from offshore needs, such as protecting engine bays in ships. Watermist is a more three-dimensional system than sprinklers, using heat absorption and oxygen displacement. It has more in common with gaseous fire protection systems in its mode of operation than with sprinkler systems.

[2] Within the sprinkler industry, density measurement is normally expressed as mm/min/$\text{m}^2$, which represents the depth of water in mm over an area of 1 $\text{m}^2$, for 1 min after activation.

**Table 1** Summary of sprinkler head test standards

| Standard | Container Size (WxDxH) (mm) | Ceiling height above container (mm) | Sprinkler Flow Rate (l/min) | Wall Wetting Distance from ceiling (mm) | Head Pressure (bar) | Test Duration (mins) | Permitted containers less than 50% (qty) | Sprinkler coverage (mm) | Discharge Downwards (%) |
|---|---|---|---|---|---|---|---|---|---|
| BS EN 12259-1 * [18] | H – 500 | 2700 | 61.3 | N/A | 0.59 | Satisfactory average time | 5 | N/A | 40–60 |
| BS 9252 ** [19] | H – 300 | 2500 | 56.6 | 700 | 0.5 | 6 | N/A | N/A | 80–100 |
| BS EN 12259-14 ** [20] | 300 × 300,<br>500 × 500 | 2400 | 56.6 | 711 | 0.5 | 20/10 | N/A | N/A | 80–100 |
| UL 199 * [21] | 300 × 300 × 300 | 2300, 3050, 1200 | 57 | N/A | 0.5 | 10 | 5 | 3050 | 40–60 |
| UL 1626 ** [22] | 300 × 300 × 300 | 2440, 2080 | 57 | 710 | 0.5 | 20/10 | N/A | N/A | 80–100 |
| FM 2000 *[23] | 305 × 305 | 2300 | 57 | N/A | 0.5 | 10 | 5 | 3050 | 40–60 |
| FM 2030 ** [24] | 300 × 300 | 2400, 2030 | 57 | 711 | 0.5 | 20/10 | N/A | N/A | 80–100 |
| LPS 1039 * [25] | H – 500 | 2700 | 60 | N/A | 0.59 | N/A | 5 | N/A | 40–60 |

*Indicates commercial standard

**Indicates residential standard

P is pressure (bar), and.

K is the ‘K’ factor coefficient of the sprinkler head, which is directly proportional to Q and inversely proportional to the square root of the pressure.

Thermal sensitive elements in sprinkler heads differ in terms of type, and sensitivity and are chosen to suit the needs of the risk. They can take the form of a metal fusible link (soldered strut) or a thermal glass bulb containing a liquid that expands with heat to break the glass, as shown in Fig. 1. In each case, once activated, the valve opens, allowing water to flow onto the sprinkler deflector to create the required spray pattern and coverage.

Figure 1 shows a typical commercial sprinkler with glass bulb thermal sensing element connected onto a sprinkler range pipe through a welded socket, sized to match the sprinkler head (15 mm, K80 sprinkler).

In commercial sprinkler systems, sprinklers are spaced to ensure adequate floor coverage is achieved. Spray onto the walls and ceiling is not a consideration. However, there is a maximum spacing limitation of 1.5 m from external walls containing combustible material. Residential sprinkler standards allow for a greater area per sprinkler (~25 $m^2$) and at lower design densities (≥2.04 mm $min^{-1}$ $m^{-2}$). Residential sprinklers are designed to provide an element of wall wetting 0.7 m below the ceiling, to cater for fires involving common household furnishings (curtains, cupboards, sofas, beds, etc.) that are located on the perimeter of rooms, but they are not required to wet the ceiling. Residential sprinkler systems are not specifically considered further in this study.

Knowledge of sprinkler head spray patterns has led this study to focus on Conventional sprinklers due to their ability to provide both an upward and a downward spray pattern, irrespective of whether the sprinkler is installed in a downward (pendant) or upward (upright) position.

Active suppression systems are installed in many types of building to support both life-safety and property/business resilience aims. Exposed timber surfaces, including walls, floors, and ceilings (in addition to the fuel load of the contents), present higher fire potential and increased Heat Release Rate (HRR), as observed by Bateman et al. [29]. Timber contributes to the fuel load of a fire, leading to longer and more severe fires, as studied by Hadden et al. [30]. In some instances, due to delamination of Cross Laminated Timber (CLT) slabs, secondary flashover occurs when the first lamella falls from the panel at the outermost glue line, exposing fresh timber to the fire.

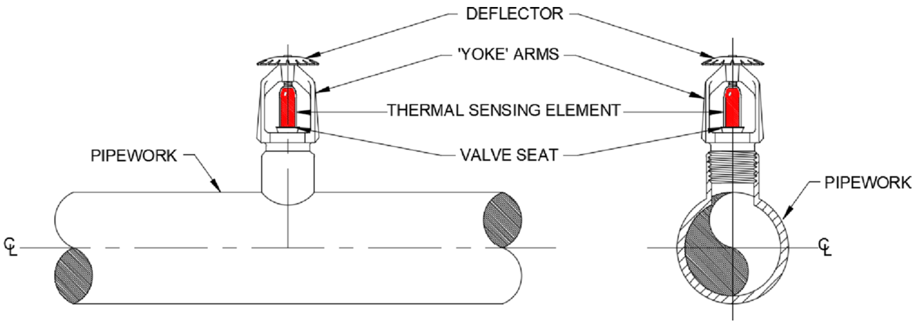

**Fig. 1** The main components of a sprinkler head with feed pipework (shown in the ‘upright’ mounting position)

Bartlett et al. [31] conducted small-scale tests on specimen CLT within a furnace to analyse the additional contribution and energy absorption. The small-scale testing led to six larger full-scale tests on a compartment that contained an exposed CLT slab at the ceiling with varying sizes of external openings leading to different oxygen and ventilation concentrations in each test. Due to the differences in openings, results from the tests varied. However, the tests confirmed that compartments with exposed timber linings contribute to a higher energy release than a standard compartment fuel load without the addition of timber linings. In addition to flaming combustion of exposed timber linings, smouldering combustion [10] in hidden voids [32] may mean that a fire could be unextinguishable by conventional means (fixed or intervention): this was witnessed by Building Research Establishment (BRE) in their TF2000 study [33]. Rein [10] confirms that smouldering combustion is the most persistent type of combustion phenomenon, it can be initiated with weaker ignition sources and is more difficult to suppress, with the potential transition from smouldering to flaming being a significant threat.

Research into the fire safety of timber construction has been conducted over the past decades, and much is already known. Self- or auto-extinguishment[3] [34–41] can only be considered in the decay phase of a fire when the moveable fuel load has been consumed and flaming combustion of the compartment turns to smouldering combustion. Fire tests in timber compartments [42–46] confirm this transitional change of combustion.

Sprinklers have been tested in timber compartments [47–51], and recently watermist has been evaluated [52–54] showing successful suppression. The installation of a fire suppression system that activates in the early stages of a fire, to satisfy property protection requirements, should ensure that severe fire events never become unmanageable, and that a fire will not be allowed to persist long enough to ‘burrow’ or gain access to hidden voids.

Saeter Boe et al. [55] conducted fire testing simulating a fire in a student bedsit with an adjacent corridor, both with exposed CLT walls and ceilings, with sprinklers to EN 12845:2015 [11] using 15 mm sprinklers with a ‘K’ factor of 80 at a minimum pressure of 0.35 bar. Two experiments were conducted where the fire was started in the bedsit. In Experiment 1 all sprinklers were active; in Experiment 2 only corridor sprinklers were active. In Experiment 1, sprinklers activated after 2 min and controlled the fire until manual extinguishment. In Experiment 2, flashover of the room occurred at 5 min, with temperatures of 1,000 °C recorded and rapid fire spread on the CLT wall and ceiling. Sprinklers in the corridor activated after 3–4 min, but these did not change the outcome. During the fire, pressure in the sprinkler heads was increased to 2.0 bar, with no effect on the fire. This demonstrates that a fire in an unsprinklered location, or with obstructed or isolated sprinklers, can cause the protection system to be significantly and rapidly overwhelmed within a timber-lined compartment and may point to the need for direct surface wetting. The test also demonstrated that the assurance of complete ‘extinguishment’ in timber structures requires manual follow-on intervention by the fire service.

The failure (overrunning) of the corridor sprinkler system was considered to derive from large flames from the bedsit entering the corridor and an inability of the system to prevent the involvement of the corridor CLT. In the corridor, large parts of the CLT walls remained standing post-fire, due to cooling from the colder air and water from the closest sprinkler

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[3] A confusing term used that, rather than describing ‘extinguishment,’ actually refers to the end of ‘flaming’ combustion, where slower smouldering leads to the frequently observed phenomena of subsequent reignition and further flaming combustion.

(surface wetting). However, with no water application to the upper walls and ceiling provided by the Spray type sprinklers (100% water downward, detailed in Sect. 2 and shown in the figure), damage was significantly greater as the system failed to stop the production of combustible gases that fed the existing flames and contributed to the uncontrolled fire spread along the corridor. The results indicate that appropriately selected sprinkler heads capable of wetting exposed surfaces should prevent CLT involvement and supress fire development and spread. When full sprinkler coverage is provided throughout all compartments, fire spread could be significantly slowed or halted within timber buildings.

With the objective of this investigation being to investigate water delivery from old-style sprinklers within timber enclosures, the discreet phases were as follows:

1. To investigate the suitability of commercially available sprinkler head designs.
2. To assess density of discharge (depth of water) from sprinklers at floor level, as detailed in current standards, appropriate to the risk occupancy classification of the building.
3. To assess wall wetting from adjacent sprinklers up to ceiling level in order to reduce surface spread of flame up compartment boundaries (walls).
4. To assess ceiling wetting from sprinklers, which could potentially contribute to slowing or halting surface spread of flame at ceiling level.

Each investigation, and its corresponding results are discussed in Sects. 2 to 5, respectively below.

## 2 Investigation into sprinkler system design

This study investigated the potential to adapt commercial sprinkler system design requirements for buildings that are considered non-combustible or of limited combustibility, to be suitable for mass timber CLT buildings with exposed timber surfaces. The shift to using increased quantities of timber and other low-carbon combustible materials, has underlined the importance of active fire protection for mass timber buildings, irrespective of height, but what is a suitable system?

For this study, sprinklers were considered as they have more stringent design standards than other suppression systems, alongside third-party certification, product approvals, guidance, history, interchangeable components, and they are not limited to specific contractors or manufacturers.

Sprinklers act on a fire directly by removing heat, and they also pre-wet surrounding fuel, reducing its ignitability and thereby limit the rate of flame spread. However, sprinkler heads differ in design, and their spray characteristics have changed over the decades. The following types of sprinkler heads were investigated, and their typical spray patterns are shown in Fig. 2.

- Conventional (Upright and Pendant) sprinkler (CUP): The CUP sprinkler has a spherical water distribution directed towards the ground and the ceiling over a definite protection area. A conventional sprinkler discharges ~ 40% upward and 60% downward. The upward moving water typically but not consistently, strikes the ceiling and then drips downward, adding to the water below.

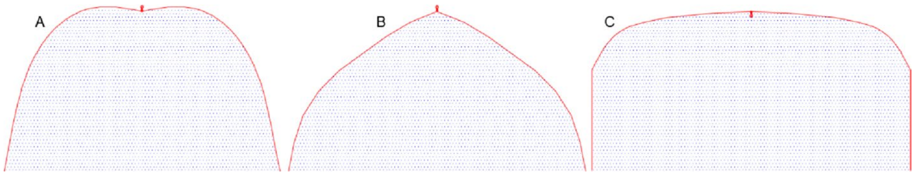


**Fig. 2** 2-dimensional representation of sprinkler distribution patterns. **A** A CUP sprinkler discharging a proportion of water upward to the ceiling and downward to the floor. **B** An SSP sprinkler discharging 100% water downward to the floor. **C** An SSU sprinkler discharging 100% water downward to the floor

- Spray Sprinkler Pendant (SSP) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSP discharges 80–100% of the total water flow downward. SSP sprinklers give the specified distribution by having the jet of water directed downward against the deflector.
- Spray Sprinkler Upright (SSU) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSU also discharges 80–100% of the total water downward. SSU sprinklers give the specified distribution by having the jet of water directed upward against the deflector (as shown in Fig. 1).

Sprinkler system constraints were reviewed to see what changes were needed to head type selection and spacing arrangements to improve water distribution to assist in protection of exposed combustible surfaces.

The study investigated water spray patterns, sprinkler size (‘K’ factor coefficients), distribution above and below the sprinkler deflector, and the potential for wall and ceiling wetting, in addition to providing the specified water density at floor level based on the associated hazard and risk of occupancy for common types of commercial buildings.

In the UK, water to sprinkler systems is generally supplied by centrifugal-type pumps as flow and pressure from town’s mains are limited. Pumps are specified so they deliver water at not less than 0.35 bar to the most hydraulically remote sprinkler head when the maximum number of heads are operating, as specified in BS EN 12845:2015 [14] for Ordinary Hazard classifications. The number of sprinklers operating within a specified fire area (known as the assumed area of operation) differs based on system classification ranging from 6 to 18 sprinklers (72–216 m$^2$). The 0.35 bar delivery pressure limit represents the failure point of the system, but inbuilt safety factors ensure this point is seldom reached and the fire will be managed by fewer sprinklers operating a higher pressure as defined by the pump’s pressure/flow curve. To this end, in addition to testing at 0.35 bar, the sprinklers were also evaluated at 3.0 bar, representing a conservative pressure characteristic of the initial sprinkler head activation.

Entec UK Limited, for the UK Department for Communities and Local Government, reported that sprinklers control or extinguish fires in 99% of activations, with most incidents contained by four or fewer heads [56]. BAFSA data similarly shows that about 60% of commercial fires are controlled by four sprinklers [57]. UK design practice assumes a failure pressure of 0.35 bar for systems operating 18 + sprinklers, though actual pressures vary with system capacity and closed-valve pressure. Single-sprinklers was tested at 3.0 bar, which may be exceeded in practice. This study therefore adopts 3.0 bar as a conservative operating pressure in an Ordinary Hazard system.

# 3 Preliminary sprinkler dispersal patterns, 'K' factor and vertical distribution investigation

## 3.1 Methodology

### 3.1.1 Sprinkler dispersal patterns

An evaluation of different sprinkler head types to determine spray characteristics was conducted. Common sprinkler types were SSU (upright (upward)), SSP (pendant (downward)) and CUP (upright/pendant (ratio 40:60)), shown in Fig. 2. Testing used 15 mm sprinklers with a 'K' factor of 80 at a delivery pressure of 0.35 bar, representing minimum head pressure of the system, and 3.0 bar, representing a single sprinkler head operating in the initial stages of a fire. Sprinklers were visually screen-tested to identify which heads provided a good proportion of upward spray.

Based on visual testing which complemented Fig. 2, Conventional sprinkler head (CUP) types were selected for these specific tests as they provided an upward and downward spray characteristic, confirmed by manufacturers' data sheets. Sprinklers were obtained from five manufacturers with the same characteristics (CUP 15 mm, K80), referenced in this study as manufacturer A (Rapidrop), B (Reliable), C (Tyco), D (Victaulic) & E (Viking). These sprinklers have been shown to perform for the specific spray pattern/test for which they were originally produced. Sprinklers tested have the following approvals:

- A (Rapidrop) LPCB and VdS.
- B(Reliable) LPCB and VdS.
- C (Tyco) LPCB, VdS, UL and C-UL.
- D (Victaulic) LPCB, VdS and C-UL.
- E (Viking) LPCB and C-UL.

### 3.1.2 'K' factor testing

The accuracy of 'K' factors was measured, as it is known that 'K' factors can vary from specified values. This provided an essential baseline so that accurate flow rates could be obtained during distribution testing through water pressure monitoring at the sprinkler head.

Manufacturers' data provided with the sprinkler samples confirm that the 'K' factor for each was 80. Testing to BS EN 12259-1:1999 [58] was used to obtain actual 'K' factors for each sprinkler.

Testing consisted of a water pump, pipework, sprinkler(s), pressure transducer, and water container. Volume of water collected, test duration and accurate pressure readings at the sprinkler allowed 'K' factors to be established using Eq. 1. Results showed variations in 'K' factors from all manufacturers and are reported in Sect. 3.2.

### 3.1.3 Vertical distribution (above and below) water collection

Manufacturers' data states that 40% of water delivered to a CUP sprinkler is distributed upward and 60% downward. To evaluate accurate above and below water distribution, a simplified test set-up based on BS EN 12259-1:1999 [58] Annex D.3 test rig was used,

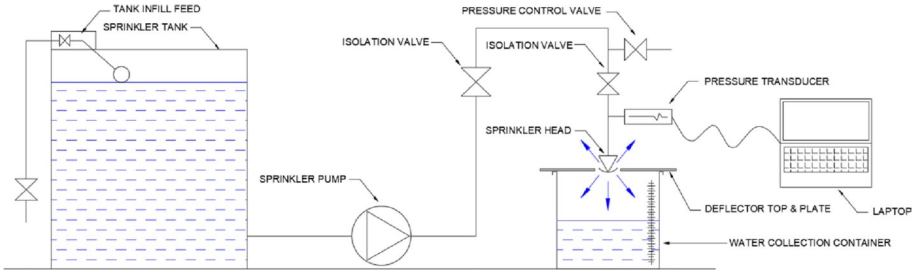


**Fig. 3** Schematic of the test set-up arrangement for sprinkler water collection below the deflector

**Fig. 4** Simplified test set-up for recording below water distribution capture from sprinklers. **A** The test set-up. **B** Water capture below the sprinkler

shown in Figs. 3 and 4. This used the same components as the 'K' factor tests, with the addition of the above/below water deflector plate.

Using sprinkler head pressure and actual 'K' factors, the flow rate through each of the sprinklers was established through calculation (Eq. 1). To evaluate above and below water distribution, measurements were taken from water collected in the container below the sprinkler over a period of time. This allowed water flow calculated below the sprinkler deflector to be deducted from the total flow of water being delivered through the sprinkler head, allowing the above/below ratio to be calculated. Tests were conducted at a range of different pressures over a range of time periods. Results for above and below water distribution are presented in Sect. 3.2.

Figures 3 and 4 show the modified version of BS EN 12259-1:1999 Annex D3 set up. The board on top of the container was fitted with a thin metal plate ~ 2 mm thick which contained a hole that was ~ 1 mm larger than the sprinkler deflector shown in Fig. 4A. The sprinkler deflector was located at the same level as the top of the plate to allow water to be collected in the container below the deflector. The water delivered above the container flowed away and was not collected.

**Table 2** ‘K’ factor test results

| Manufacturer reference | Specified ‘K’ factor (L min$^{-1}$ bar$^{-1/2}$) | Measured ‘K’ factor (L min$^{-1}$ bar$^{-1/2}$) | Tolerance value |
|---|---|---|---|
| Sprinkler A | 80 | 85.45 | +5.45 |
| Sprinkler B | 80 | 82.52 | +2.25 |
| Sprinkler C | 80 | 80.27 | +0.27 |
| Sprinkler D | 80 | 84.22 | +4.22 |
| Sprinkler E | 80 | 84.41 | +4.41 |

In BS EN 12259-1:1990, Table 3’s error range is 80 ± 4

**Table 3** Above and below water distribution results

| Manufacturer reference | Specified distribution (%) | | Measured distribution (%) | |
|---|---|---|---|---|
| | Above | Below | Above | Below |
| Sprinkler A | 40 | 60 | 56.1 | 43.9 |
| Sprinkler B | 40 | 60 | 52.8 | 47.2 |
| Sprinkler C | 40 | 60 | 52.1 | 47.9 |
| Sprinkler D | 40 | 60 | 45.2 | 53.8 |
| Sprinkler E | 40 | 60 | 54.5 | 45.5 |

## 3.2 Preliminary investigation sprinkler results

### 3.2.1 ‘K’ factor testing

Testing was conducted with CUP sprinklers from five manufacturers. Data sheets confirmed a minimum ‘K’ factor coefficient of 80. Testing was undertaken as described in Sect. 3.1.2 and, using Eq. 1, results for accurate ‘K’ factors were obtained, confirmed in Table 2.

Table 2 shows variance between all manufacturers (sprinklers A to E). All sprinklers had slightly higher ‘K’ values, which would result in higher sprinkler flow rates. Two sprinklers fell within tolerance requirements of BS EN 12259-1:1990; three sprinklers fell outside tolerance values. At a consistent pressure provided to sprinklers assessed, those measured with a higher ‘K’ factor would provide higher flow rates. For example, at a pressure of 1 bar, Sprinkler A would provide a flow rate of 85.45 L/min, Sprinkler C would provide a flow rate of 80.27 L/min.

### 3.2.2 Vertical distribution testing (above and below)

Water distribution tests for above and below the sprinkler deflector were undertaken generally in accordance with BS EN 12259-1:1999 Annex D.3 using a modified test rig as detailed in Sect. 3.1.3. with each sprinkler flowing at 4.0 bar pressure. Results shown in Table 3 demonstrate that a good proportion of upward spray was achieved from all sprinklers. Results show different distribution ratios from each sprinkler when considering manufacturers’ data, where more water is distributed above the deflector, which will support ceiling wetting.

Table 3 shows different distribution ratios from each sprinkler when considering manufacturers’ data. Results show more water is distributed above the deflector, which will support ceiling wetting. The increase in upward distribution could be attributed to the modified test arrangement being vertical as opposed to horizontal as detailed in BS EN 12259-1:1999

Annex D3, and potentially the lack of ventilation within the container to remove the air volume from within when discharging water and entrained air is directed into the collection container.

## 3.3 Preliminary investigation sprinkler discussion

Three sprinkler types were initially assessed, to recognize spray characteristic patterns. Testing showed that upward (SSU) and downward (SSP) sprinklers discharged 100% water downward, consistent with the manufacturers' literature. Conventional sprinklers (CUP) demonstrated both upward and downward spray, which would benefit exposed combustible timber ceilings.

To establish a basis for sprinkler selection criteria and to evaluate sprinklers in different orientations, pressures, and locations, three criteria were considered, shown in Fig. 5.

The first criterion was wall wetting. A fire located adjacent to a combustible wall has been shown to be larger than a fire in the middle of a compartment [59] where the initial fuel package is equivalent. Potential surface spread of flame upward to the ceiling was deemed to be a significant threat. Therefore, wall wetting is an important fire protection requirement. The next criterion was involvement and surface spread of flames on the ceiling above sprinklers. The final criterion was water flow to floor level for general contents fuel loads, which current sprinkler rulesets consider by specifying a minimum design density of discharge below sprinklers, based on occupancy classification.

Thirty-nine individual water distribution tests were conducted to evaluate the performance of each sprinkler (A – E) against the criteria set out in Fig. 5 and are summarised in Table 4. The complete set of data and results are summarised in the supplementary material.

As described in Sect. 1, automatic sprinkler systems are engineered to limit fire development through direct suppression and by pre-wetting adjacent combustible fuels to inhibit secondary ignition. Water remains the predominant suppression agent due to its favourable thermophysical properties, including a high latent heat of vaporisation and substantial

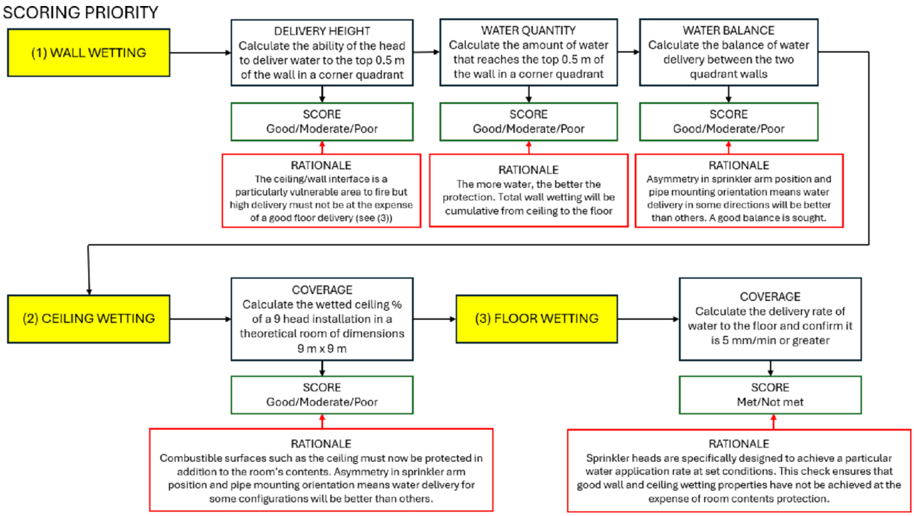


**Fig. 5** Flow chart for sprinkler head characterisation selection

**Table 4** Summary table of water distribution tests

| Test Reference | Sprinkler head manufacturer (A, B, C, D & E) | Target test pressure (bar) | Orientation tested (Downwards/Upwards/Ceiling) | Recorded Pressure (bar) |
|---|---|---|---|---|
| 01 | A | 0.35 | Upwards | 0.35 |
| 02 | E | 0.35 | Upwards | 0.35 |
| 03 | A | 0.35 | Downwards | 0.33 |
| 04 | A | 3.0 | Downwards | 3.02 |
| 05 | C | 0.35 | Downwards | 0.35 |
| 06 | D | 0.35 | Downwards | 0.35 |
| 07 | B | 0.35 | Downwards | 0.35 |
| 08 | E | 0.35 | Downwards | 0.35 |
| 09 | B | 3.0 | Downwards | 3.11 |
| 10 | C | 3.0 | Downwards | 3.10 |
| 11 | C | 0.35 | Upwards | 0.34 |
| 12 | B | 0.35 | Upwards | 0.35 |
| 13 | D | 0.35 | Upwards | 0.34 |
| 14 | B | 3.0 | Upwards | 3.12 |
| 15 | A | 3.0 | Upwards | 3.03 |
| 16 | C | 3.0 | Upwards | 3.11 |
| 17 | C | 3.0 | Ceiling | 2.85 |
| 18 | C | 0.35 | Ceiling | 0.35 |
| W01 | C | 3.0 | Upwards | 3.13 |
| W02 | A | 3.0 | Upwards | 2.99 |
| W03 | E | 3.0 | Upwards | 2.98 |
| W04 | D | 3.0 | Upwards | 3.05 |
| W05 | B | 3.0 | Upwards | 3.09 |
| W06 | B* | 3.0 | Upwards | 3.10 |
| W07 | B | 0.35 | Upwards | 0.34 |
| W08 | A | 0.35 | Upwards | 0.35 |
| W09 | C | 0.35 | Upwards | 0.35 |
| W10 | C | 3.0 | Downwards | 3.12 |

**Table 4** (continued)

| Test Reference | Sprinkler head manufacturer (A, B, C, D & E) | Target test pressure (bar) | Orientation tested (Downwards/Upwards/Ceiling) | Recorded Pressure (bar) |
|---|---|---|---|---|
| W11 | A | 3.0 | Downwards | 3.00 |
| W12 | E | 3.0 | Downwards | 3.02 |
| W13 | B | 3.0 | Downwards | 3.10 |
| W14 | D | 3.0 | Downwards | 3.05 |
| W15 | B | 0.35 | Downwards | 0.34 |
| W16 | A | 0.35 | Downwards | 0.34 |
| W17 | C | 0.35 | Downwards | 0.36 |
| W18 | C | 3.0 | Ceiling | 2.85 |
| W19 | C | 0.35 | Ceiling | 0.37 |
| W20 | B | 0.35 | Ceiling | 0.35 |
| W21 | B | 3.0 | Ceiling | 2.80 |

Test W06 (*) sprinkler was located at 1.5 × 1.1 m spacing specific heat capacity, which enable efficient absorption of thermal energy from the fire environment and attenuate heat transfer to nearby materials. Historically, conventional ‘Victorian-era’ sprinkler configurations have demonstrated enhanced wetting of exposed timber surfaces (ancestral mill floors and ceilings), contributing to reductions in incident heat flux and suppression of surface pyrolysis. This pre-wetting action delays ignition and decreases the rate of flame spread across timber substrates, thereby enhancing overall compartment fire resilience.

# 4 Ceiling and floor wetting

## 4.1 Methodology

A hybrid test was established to evaluate water distribution, capture water volume at floor level and measure ceiling surface wetting. It was decided to use elements of the different standards shown in Table 1 to optimise testing for this study.

The test set-up consisted of a tank, pump, pipework, fixings, pressure transducer, sprinkler(s) (CUP), water collection buckets, load cell and laptop for recording data, shown in Fig. 6.

The design layout for water collection is shown in Fig. 7: 108 identical buckets were located at 500 mm centres on a semi-circle layout with a maximum radius of 4 000 mm to capture water. The CUP sprinkler head(s) were located between 150 and 180 mm below the ceiling. Location of sprinkler deflector below the ceiling is critical in terms of response time activation. Ideal locations for sprinkler thermal element (glass bulb) are 75–150 mm below the ceiling. Sprinklers were installed with the yoke arms running perpendicular to the sprinkler pipe. Using standard industry bracket material, allowed the sprinkler to be installed at 150 mm below the ceiling when tested in the upward position. However, due to physical bracketry size, when tested in the downward position, a range of 150–180 mm was achieved, depending on sprinkler head design. Table 1 summarizes the various sprinkler test standards, which specify ceiling heights ranging from 2030 mm to 3050 mm. For the present study, a ceiling height of 2600 mm above the tops of the buckets was selected,

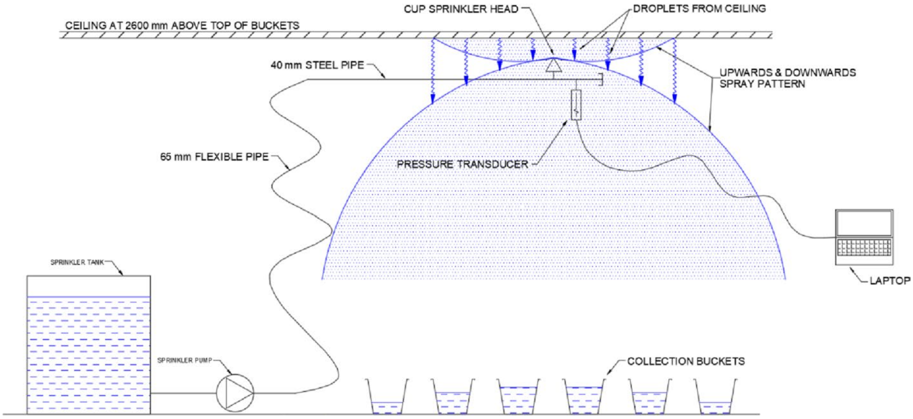


**Fig. 6** Schematic of water collection layout and major components

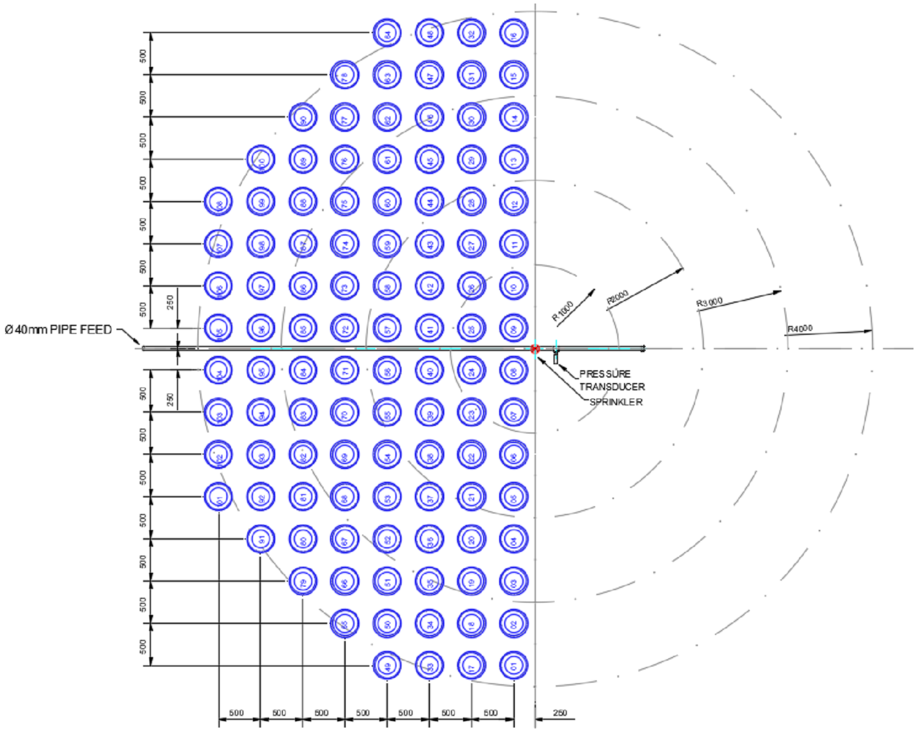


**Fig. 7** Test set-up for water distribution capture and ceiling wetting analysis from sprinklers. The blue concentric circles represent buckets

corresponding to the mean value of the surveyed standards. Based on these standards, it was assumed that this height provides sufficient clearance beneath the sprinkler to allow full development of the intended spray pattern. A ceiling height of 2600 mm is also representative of typical floor-to-ceiling heights in buildings without suspended ceilings, where mechanical and electrical services remain exposed. The experimental configuration further assumed the absence of any service-related obstructions to water discharge, ensuring that the resulting spray characteristics could be observed and recorded without interference.

To enable sprinkler wetting patterns to be quantified, the open area and the lip of a standard bucket was measured. Water droplets hitting the lip were predicted to have a 50% chance of entering the bucket. The area of the bucket, including half of the lip, was used as the area of capture for water discharge from the sprinkler(s).

Water collected in each of the 108 buckets was quantified gravimetrically and entered into Microsoft Excel according to each bucket's spatial position, producing a 180° distribution profile that was mirrored under the assumption of radial symmetry to obtain a full 360° representation. Application density (mm $\text{min}^{-1}$ $\text{m}^{-2}$) was calculated by dividing the measured mass by test duration and bucket opening area, and a corresponding plan-view density map was generated. For enhanced visualisation, density data were imported into Microcal Origin, arranged on an $8 \times 16$ grid, and mirrored to form a $16 \times 16$ matrix. This matrix was then up-scaled to $64 \times 64$ using the software's grid-interpolation function, which estimates intermediate values by fitting a smooth surface between measured points. The resulting high-resolution interpolated matrix enabled the production of detailed contour plots that more accurately depicted spatial density distribution. This procedure was applied uniformly across all sprinkler models evaluated, shown in Sect. 4.2.2.

The ceiling was marked up at 500 mm intervals, north–south and east–west from the centre point of the sprinkler, so that wetting patterns at ceiling post-test could be measured, photographed, and simulated. Figure 8 shows the test set-up with the buckets located below the ceiling, with pipework and sprinkler head above.

Given the optimum distance of sprinkler deflector below ceiling is 75–150 mm, testing at the lower level of 150/180 mm allowed space for the sprinkler to spray upward and develop a wetting pattern on the ceiling. This lower level would increase the activation time of the sprinkler slightly, but this would be offset by more efficient wetting of the timber ceiling.

Results for ceiling wetting were photographed, measured, and visually replicated in AutoCAD showing ‘wetted’ areas.

Table 4 shows the summary of the varying tests undertaken with sprinklers located in an open area (tests 01–16), shown in Figs. 6 and 7, and in a corner wall location prefixed with the letter W, (tests W01-W17) shown in Figs. 17 and 18 where sprinklers were located at 1.5 m from each wall. For tests 17, 18, W18, W19, W20 and W21, sprinklers were selected based on best/worst performance and were tested where only the sprinkler head is exposed below the ceiling/soffit. Due to availability of the test laboratory, sprinkler performance was evaluated during testing and results obtained at lower pressures were used to select and rank sprinklers for testing at the higher pressure of 3.0 bar. Sprinklers A–C were chosen as best, average and worst performing. Sprinklers D and E were not tested at 3.0 bar as they fell in-between best/worst ranking at the lower pressure.

Table 4 shows all water distribution testing undertaken for each sprinkler, in different orientations at different pressures. ‘Ceiling’ referenced within Table 4 refers to the sprinkler head being installed downwards (pendant) within a suspended ceiling configuration and with

**Fig. 8** Water collection buckets in a semi-circular layout below the sprinkler

sprinkler pipework being located above the ceiling. This is a common installation method for compartments with suspended ceilings where the sprinkler deflector is located ~ 40–50 mm below the ceiling (depending on manufacturer).

#### 4.1.1 Distribution criteria (ceiling and floor)

Ceiling wetting distribution is not a requirement in current sprinkler standards and was assessed purely on physical wetted area measured to the nearest $m^2$. The largest wetted area was considered best performing sprinkler and smallest measured area considered worst performing sprinkler for each orientation and pressure.

Sprinkler water distribution was evaluated at the floor using actual measured density. The largest area covered within the minimum design density of 5 mm $min^{-1}$ $m^{-2}$ was considered to have the best performance, the smallest area meeting the minimum design density was considered worst performance.

### 4.2 Ceiling and floor results

#### 4.2.1 Ceiling wetting

Tests conducted at a system pressure of 3.0 bar confirmed that a substantial proportion of the ceiling surface received a continuous flow of water across it which manifested as a wetting pattern. The results are presented in diagrammatic form to illustrate the extent and distribution of the wetted ceiling area. For the purposes of this study, the wetted area was defined as the region of sustained water spray observed to contact and remain on the ceiling surface during testing.

Figures 9 and 10 summarise both measured and photographic records of the ceiling wetting patterns. These data were transferred into AutoCAD to provide a visual representation of surface wetting and to estimate the area of coverage produced by the sprinkler discharge. Observations showed that water spray from the sprinkler impinged on the ceiling and spread radially across the surface, forming a characteristic wetting pattern from which larger droplets detached and fell towards floor level.

Owing to the geometry of the sprinkler deflector, the remaining droplets were predominantly projected horizontally and downward in an umbrella-shaped spray distribution. This spray pattern governed water delivery to the floor, where measurements were collected to determine the actual application density achieved at floor level.

**4.2.1.1** Pendant (downward) patterns Results show sprinklers installed in the downward position produce slightly smaller wetted areas than sprinklers in the upward position. In downward orientation, it can clearly be seen how the pipework feeding the sprinkler (above the sprinkler head) impacts water distribution and coverage directly above, with a ‘dry’ area of ceiling. This is known in the sprinkler industry as *pipe shadowing* and would produce a larger ‘dry’ area with a larger-diameter sprinkler pipe.

Figure 9 shows the ceiling pattern has an elongated shape, potentially due to the location of the sprinkler yoke arms causing an obstruction to the spray pattern. This complemented

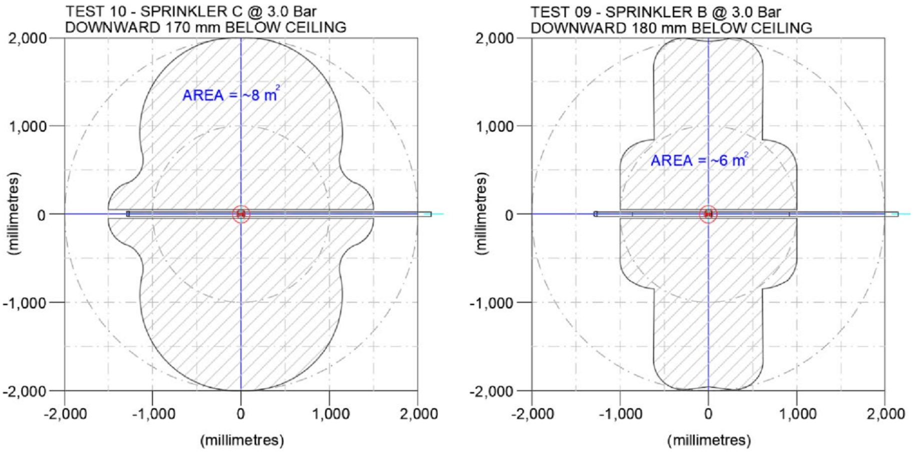


**Fig. 9** Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the downward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler B

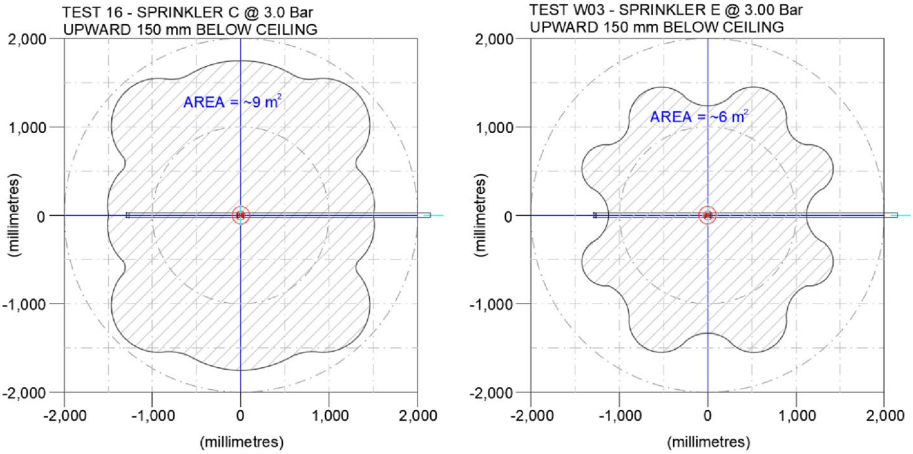


**Fig. 10** Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the upward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler E

results from wall tests where better water distribution was achieved where the sprinkler yoke arms did not impact directional spray.

**4.2.1.2** Upright (upward) patterns Ceiling wetting patterns for sprinklers in the upward orientation are more circular than those in the downward orientation. Figure 10 shows the best and worst ceiling wetting patterns.

Figure 10 shows a more circular wetted ceiling area directly above the sprinkler head from the upward orientation of the sprinkler. When comparing both orientations, it is clear from the results that the surface area of wetted ceiling from sprinklers in the upward position would allow a more uniform spacing of sprinklers to cover ceiling area than those in the downward position which is simulated in Fig. 23. For the full range of wetting patterns, see supplementary material.

### 4.2.2 Floor distribution

A requirement for all sprinklers, irrespective of type and orientation, is to provide water discharge to cover the floor where the contents fuel load will be present. A specified density of discharge from sprinklers is required to cover the contents and is based on occupancy classification. Current requirements for standard type commercial occupancies (Ordinary Hazard) require a design density of discharge of 5 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ over an assumed floor area varying from 6 to 18 sprinklers (72–216 $\mathrm{m}^2$). Results at floor level shown in Sect. 4.2.2.1 and 5.2.2.2 have been capped at an adequately compliant density of 6 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$. These areas are shown in elevated black sections in Fig. 11.

Figure 11 shows the actual density of water delivered from sprinkler A at a pressure of 3.0 bar. The peak recorded density is at ~ 16 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ over a small area. At ~ 5 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ (minimum requirement) the results show that the area adequately covered by the sprinkler is ~ 12 m² (3 × 4 m).

**4.2.2.1** CUP in the Pendant (downward) position Figures 12 and 13 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the downward orientation.

Figure 12 demonstrates > 6 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ density of discharge over an area of ~ 8 $\mathrm{m}^2$ and an average density of 2.5–5.0 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ for the remaining area up to ~ 12 $\mathrm{m}^2$. The red and black areas in the right-hand figure correspond to the area that complies with the standard for Ordinary Hazard.

Figure 13 demonstrates > 6 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ density of discharge over an area of ~ 7 $\mathrm{m}^2$ and an average density of 1.0–3.0 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ for the remaining area up to ~ 12 $\mathrm{m}^2$.

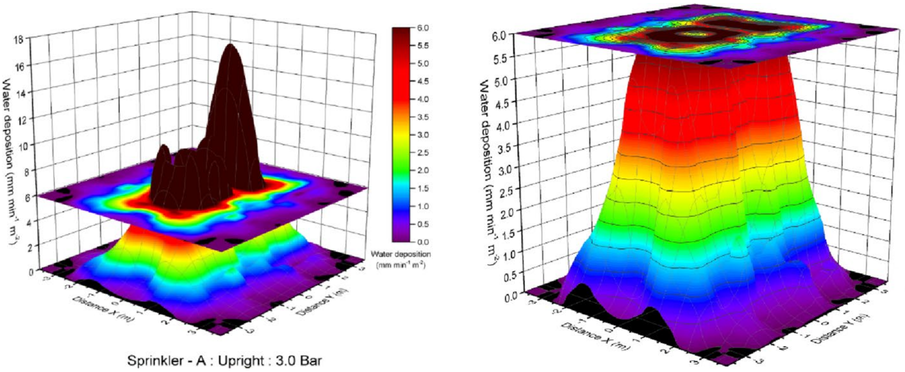


**Fig. 11** Delivery of water density at 3.0 bar in 3-D. Left: showing a density of discharge with higher densities 6–16 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$ shown in black. Right: discharge results capped at 6 mm $\mathrm{min}^{-1}$ $\mathrm{m}^{-2}$

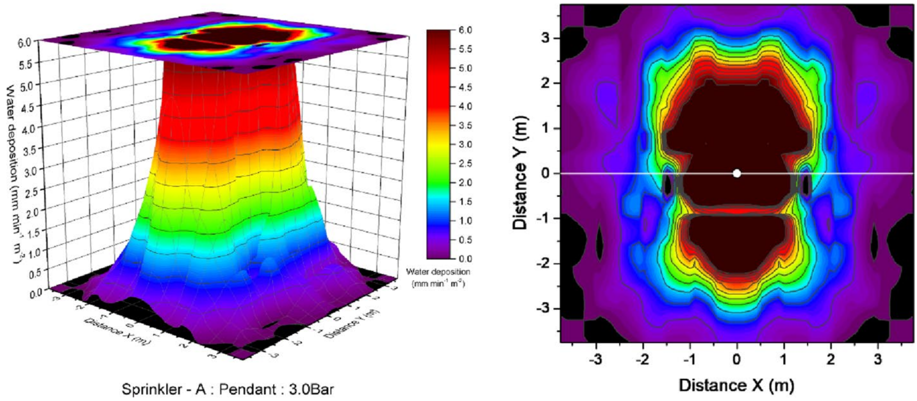


**Fig. 12** Best results of delivery of water density in downward orientation from sprinkler A at 3.0 bar in 3-D and 2-D

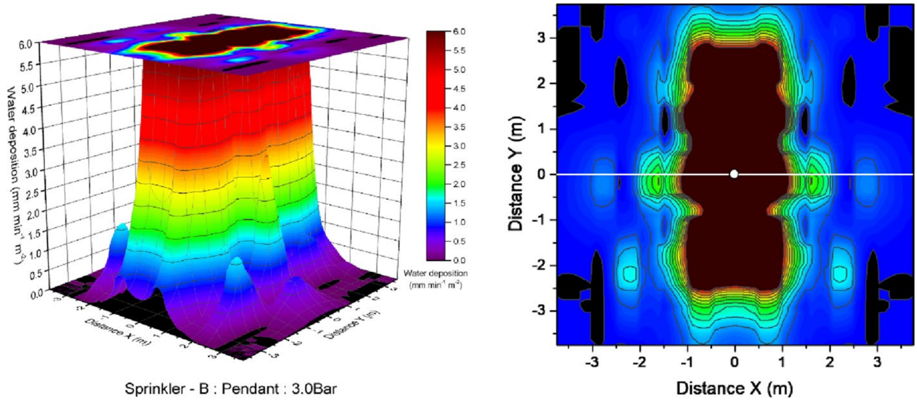


**Fig. 13** Worst results of delivery of water density in downward orientation from sprinkler B at 3.0 bar in 3-D and 2-D

**4.2.2.2** CUP in Upright (upward) position Figures 14 and 15 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the upward orientation.

Figure 14 demonstrates $>6$ mm min$^{-1}$ m$^{-2}$ density of discharge over an area of ~ 8 m$^2$ and an average density of 2.5–5.0 mm min$^{-1}$ m$^{-2}$ for the remaining area up to ~ 12 m$^2$.

Figure 15 demonstrates $>6$ mm min$^{-1}$ m$^{-2}$ density of discharge over an area of ~ 6 m$^2$ and an average density of 1.0–5.0 mm min$^{-1}$ m$^{-2}$ for the remaining area up to ~ 12 m$^2$.

Results in both orientations show the actual delivered density of discharge for single sprinklers operating at 3.0 bar. It is difficult to confirm from a single head test if the appropriate density is achieved: however, results confirm that $>6$ mm min$^{-1}$ m$^{-2}$ is achieved directly below the sprinkler head in areas $\geq 6$ m$^2$ and lower densities are confirmed for areas up to ~ 12 m$^2$. An overall density requirement of 5 mm min$^{-1}$ m$^{-2}$ can be considered achieved from these tests.

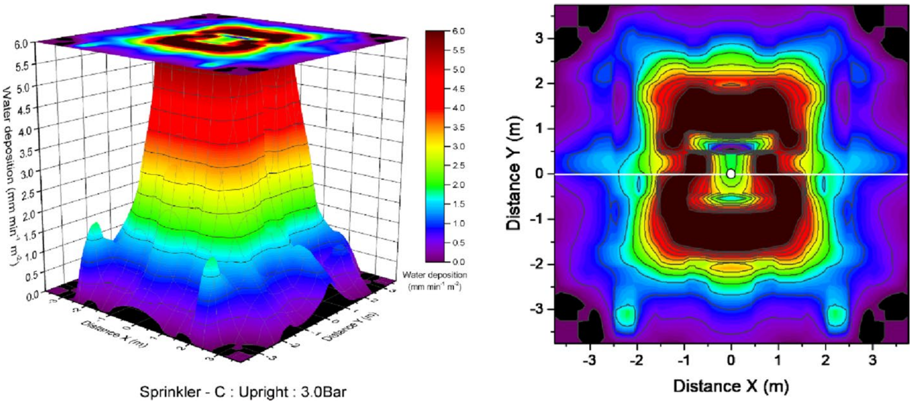


**Fig. 14** Best results of delivery of water density in upward orientation from sprinkler C at 3.0 bar in 3-D and 2-D

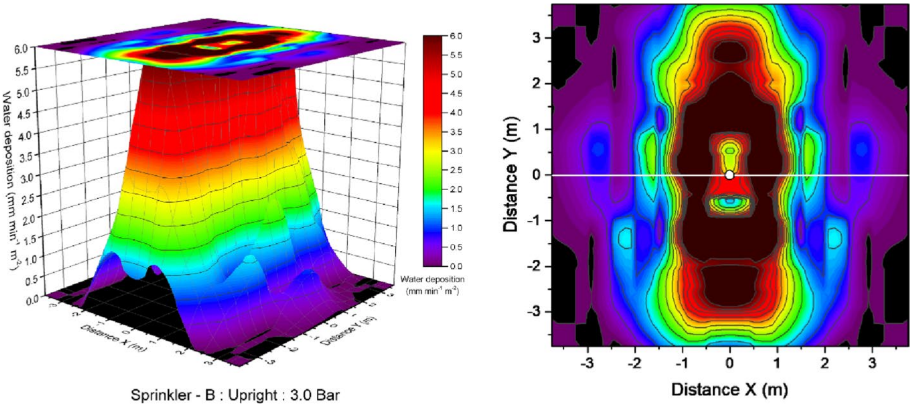


**Fig. 15** Worst results of delivery of water density in upward orientation from sprinkler B at 3.0 bar in 3-D and 2-D

Figure 16 shows a simulation from a group of four sprinklers spaced at 3 m × 3 m, at a minimum pressure (0.35 bar).

Figure 16 shows the density within the area of four sprinklers (9 m2) ranges from ~2.5 to >6 mm $\text{min}^{-1}$ $\text{m}^{-2}$. The capture area shown can be assumed to be ~5 mm $\text{min}^{-1}$ $\text{m}^{-2}$ at 0.35 bar as an average mean collective. Smaller peaks of intensity shown in the figure are not artifacts of the software, they are the product of actual measurements. Results shown are for collected densities at precise locations below the sprinkler, and do not consider full collective mean density at floor level.

## 4.3 Ceiling and floor wetting discussion

Subjective analysis has been conducted confirming ceiling wetting and floor density from sprinklers ranging from best to worst. Results for tests shown in Table 4 can be found in supplementary material.

The experimental programme was conducted under a simplified ceiling configuration, comprising a single ceiling height with no localised mechanical or electrical services or other ceiling-mounted obstructions, and employing single-sprinkler activation only. These conditions were intentionally selected to isolate intrinsic sprinkler discharge and plume interactions in a controlled environment. Consequently, the findings should be interpreted as comparative rather than directly representative of suppression performance in real compartments, where ceiling-mounted services, geometric complexity, and multi-sprinkler interactions are expected to significantly influence fire dynamics and sprinkler effectiveness.

Ceiling wetting results confirm that CUP sprinklers will provide an upward spray pattern to the ceiling. Results at minimum operating pressure of 0.35 bar, with sprinklers located ~ 150 mm below the ceiling show surface area of wetted ceiling is reduced. This is also evident from tests where the sprinkler was located within the ceiling irrespective of test pressure. At the higher pressure of 3.0 bar, with sprinklers located ~ 150 mm below the ceiling, wetting was optimised providing a larger wetted ceiling area.

To maximise the effectiveness of ceiling surface wetting, sprinkler layouts may be optimised through alternative spacing configurations aimed at limiting potential surface flame spread. Acceptable system performance is defined as achieving a wetted ceiling area and distribution that contributes to a measurable reduction in flame spread across combustible surfaces. A staggered sprinkler arrangement, consistent with the guidance provided in BS EN 12845:2015, clause 12.2, Table 20, and Fig. 8, enables each sprinkler to be offset relative to adjacent units, producing a diamond-shaped pattern rather than a conventional square layout.

Staggered sprinkler spacing can enhance overlap of spray distributions at the ceiling, promoting sustained and more uniform wetting rather than isolated wetted areas beneath individual sprinklers. This configuration could reduce wide spacing gaps at combustible

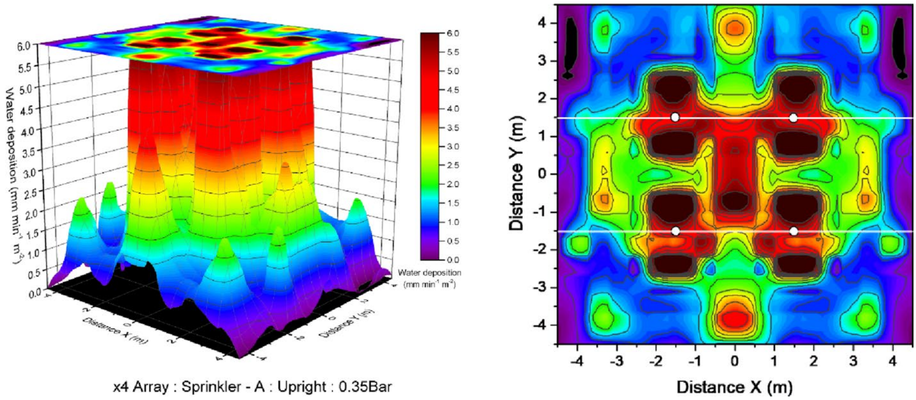


**Fig. 16** A simulated density of discharge from a group of four sprinklers in the upright orientation at a minimum pressure of 0.35 bar

boundaries (< 1.5 m), improving wetting at walls and corners that are otherwise vulnerable to early flame impingement and rapid surface flame spread.

Actual density delivered to the floor at a sprinkler head pressure of 0.35 bar shows that the minimum required density is achieved from all sprinklers in the upward position. However, in downward position, sprinklers B and C do not provide adequate density. At 0.35 bar all sprinklers show reduced floor area coverage at 5 mm $\text{min}^{-1}$ $\text{m}^{-2}$. Sprinklers A, B and C were evaluated at 3.0 bar in both orientations and met minimum density requirements. Sprinklers D and E were not assessed at 3.0 bar. However, it could be assumed that as these fell within best/worst performance at 0.35 bar, they would provide minimum density requirements at 3.0 bar.

Initial considerations regarding sprinkler head selection indicate fundamental differences in spray characteristics between sprinkler types. Modern sprinkler heads are designed to deliver water predominantly in a downward direction, whereas CUP sprinklers distribute water upwards, horizontally, and downwards, enhancing surface wetting in multiple orientations. While the precise coverage patterns of modern sprinklers were not evaluated in this study, both modern and CUP sprinklers are approved to relevant European and American standards, confirming that the minimum floor area coverage requirements prescribed by applicable standards are satisfied. The CUP sprinkler results demonstrate a smaller radius of higher water density concentrated directly beneath the sprinkler head, whereas modern sprinklers are likely to provide a more uniform water density over a larger radial floor area. Consequently, achieving equivalent fire suppression objectives with CUP sprinklers may require adjustment of sprinkler spacing to ensure adequate and consistent floor density coverage across the protected area.

Floor water distribution results at reduced sprinkler head spacing ~ 9 $\text{m}^2$ (based on 3 m x 3 m), at the minimum design pressure of 0.35 bar, show that the minimum design density requirement of 5 mm $\text{min}^{-1}$ $\text{m}^{-2}$ can be achieved.

In the early stages of fire with a single sprinkler operating, a higher pressure will provide a greater density of water directly over the fire area and simultaneously provide a larger ceiling wetting pattern.

## 5 Wall wetting

### 5.1 Methodology

The test set-up for wall wetting incorporated a corner wall scenario, using MDF panels and 100 × 50 mm structural timber batons shown in Figs. 17 and 18. Walls were painted with a water-repellent paint and fitted with a lightweight metal L-shaped 90° angle. The angle was attached to the face of the wall and foil tape was used to seal and create a 5 mm × 5 mm trough.

The troughs were located at 500 mm intervals up the wall, and on the surface. Each 0.25 $\text{m}^2$ area of wall was numbered, with all water touching the surface being collected in the trough below (Fig. 18a and b). The troughs were sloped feeding hoses through to the rear of the wall (Fig. 18c and d). Hoses were glued and sealed into position and fed into corresponding numbered buckets for water capture from the respective section.

Sprinkler pipework and the arms of the sprinkler heads, known as the yokes, are known to contribute to shadowing of the sprinkler discharge spray pattern observed in ceiling wetting results. To prevent double shadowing, yoke arms were aligned with the sprinkler pipework which is the requirement for sprinkler head installation. Results shown in Sect. 5.2 demonstrate the effect of shadowing.

The orientation of yoke arms running with the pipework ensures that spray from the sprinkler is not impeded by either. Running the yoke arms with the pipework allowed for unimpeded spray onto Wall A. Spray to Wall B would be interrupted by both the pipework and the yoke arms. The impact of the interference of water spray onto Wall B from the yoke arms is shown in Sect. 5.2.

An acceptable level of performance from each sprinkler is considered to be the ability to provide sufficient water to the top 0.5 m section of the wall at the intersection of the ceiling, in addition to providing a similar distribution to both walls. This is not defined as a requirement in current standards for commercial sprinkler systems. Fire spread over the walls is likely to reach and involve the ceiling very quickly. The potential for sprinkler spray to reach the top 0.5 m section of the wall will provide wetting to both planes to assist in reducing the impact of surface spread of flame.

Water captured was weighed and converted into volume. The volume was divided by the area of each panel and test duration to provide a density in mm $\text{min}^{-1}$ $\text{m}^{-2}$. Results are represented in graphical form in Sect. 5.2.

### 5.1.1 Distribution criteria (walls)

Sprinklers were evaluated for wall wetting by using density of discharge to each 0.25 $\text{m}^2$ section of wall in mm $\text{min}^{-1}$ $\text{m}^{-2}$, which is not a requirement in current commercial sprinkler standards. The sprinkler providing the most even proportional density and coverage to both

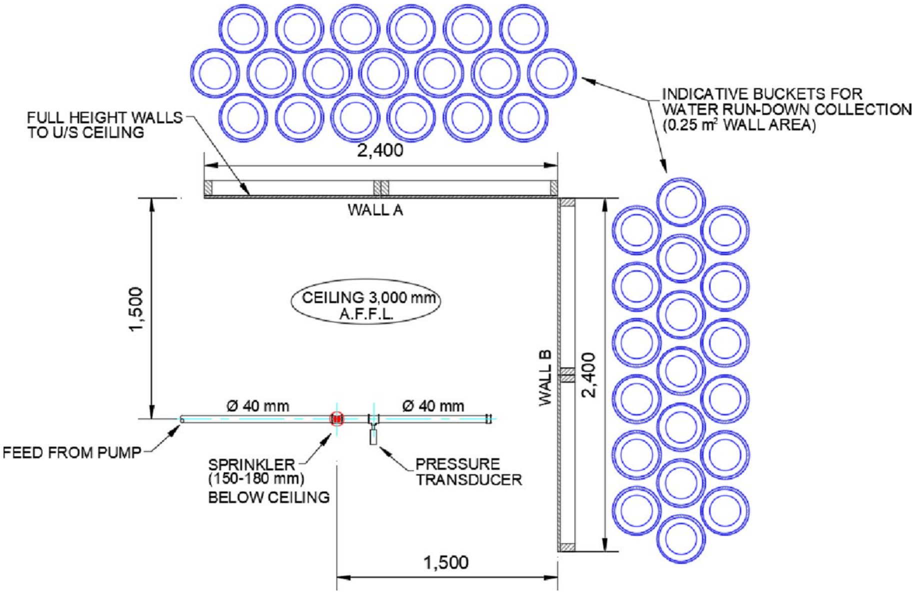


**Fig. 17** Design of water collection for water run-down. Hoses have not been shown for clarity

**Fig. 18** **a** Corner wall set-up. **b** 0.5 × 0.5 m (0.25 $m^2$) measured area. **c** Water collection trough. **d** Water collection buckets with clear tube feed pipes at the rear

walls was considered best performing sprinkler, and least even density with disproportionate coverage on both walls considered worst performing sprinkler.

## 5.2 Results

### 5.2.1 Area density collection

Twenty-one wall wetting tests were conducted using CUP sprinklers in downward and upward configurations at both 0.35 and 3.0 bar pressure. Measurement and capture of water to each 0.5 × 0.5 m (0.25 $m^2$) area was recorded and converted into actual density discharge per unit area of wall on each panel, to establish whether water reached the top wall area intersecting with the ceiling. Figures 19 and 20 show the results for both walls from the sprinkler located at 1.5 m from each wall, indicated as a yellow oval at the top of the wall.

Figures 19 and 20 show two sprinkler positions (upward and downward), delivering water at a pressure of 3.0 bar. Irrespective of orientation, wall wetting is achieved from all sprinklers, with significant differences between individual heads. However, adequate performance was observed for all sprinkler heads.

Actual densities are recorded per 0.25 $m^2$ panel (Figs. 19 and 20). These figures show average density horizontally and vertically on Walls A and B. However, water run-down through cumulative density is a more important consideration. Colour shading is included to indicate actual density of water delivered to each individual panel. Light green/blue indicates a low delivery of water. The blue range indicates good water delivery, with darker shading delivering more water.

Figure 19a shows sprinkler density in near symmetry to both walls. Whilst there are slight differences in the density per 0.25 $m^2$ panel on walls A and B, the mean density per wall is very close. The effect of the yoke arm position can be clearly seen in the density recorded in the upper sections of the wall located closest to the sprinkler.

Figure 19b shows a disproportionate delivery of sprinkler density to each wall. Wall A is provided with greater density at the top two levels. Wall B follows a similar pattern in that more water is delivered to the top two section of wall, but at much lower densities.

Figure 20a shows the closest sprinkler density on both walls for sprinklers in the downward orientation. The figure shows that the lowest density recorded is the intersection between wall A and B which is confirmed in the average density of both columns 1.

Figure 20b shows a significant disproportionate delivery of sprinkler density to each wall. Wall A has a significant quantity of the water flow from the sprinkler with good density in columns 2, 3 and 4. Wall B has extremely low densities and the intersection of both walls has the lowest density recorded.

### 5.2.2 Cumulative density collection

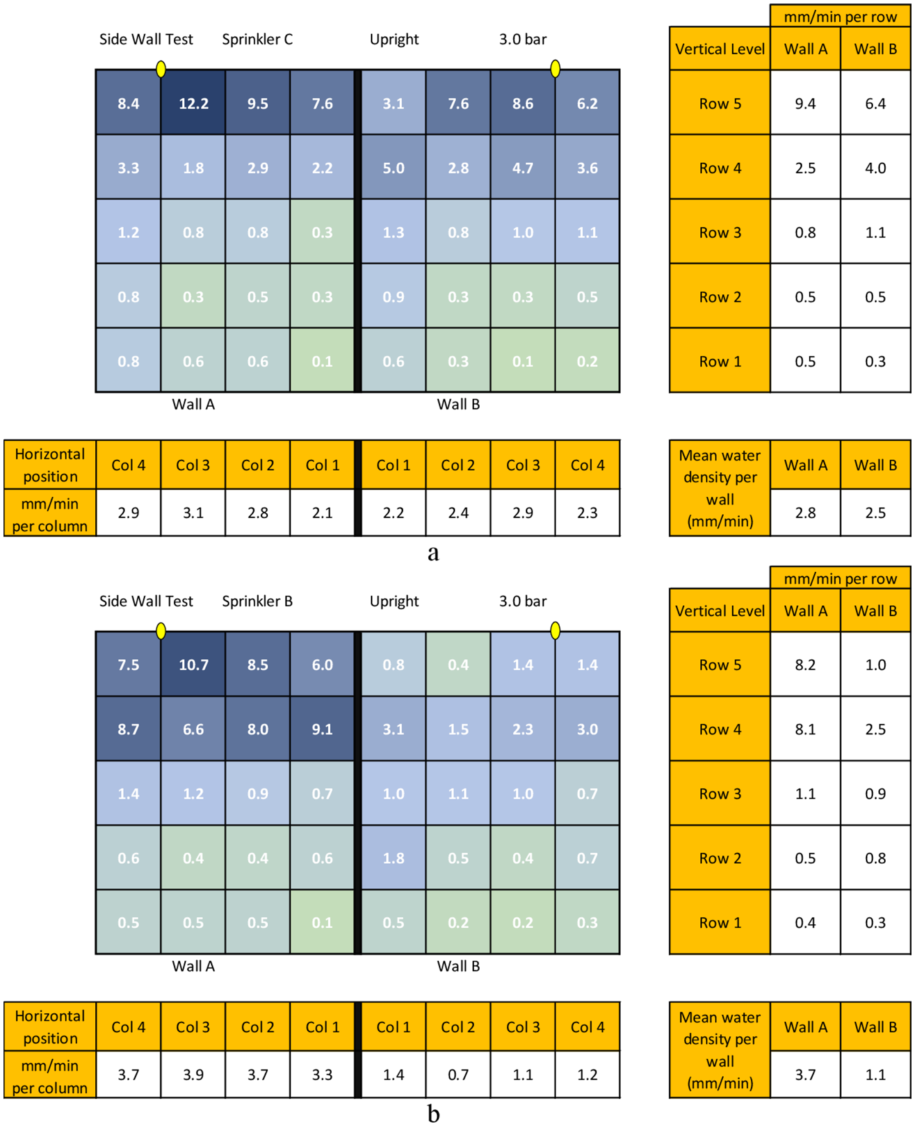
Cumulative density reveals the beneficial effect of water run-down from the top of the wall, providing more than adequate wall wetting towards the floor. Figures 21 and 22 show cumulative recorded densities and water distribution proportions for each wall. Colour shading shows water delivery differences, with darker shading indicating greater water delivery.

Figure 21a shows the close ratio of water delivery to both walls confirming that sprinkler C in the upward position has good symmetry and water run down to floor level.

Figure 21b shows the inferior performance of sprinkler B in the upward position providing less water delivery to wall B and poor water run down capability.

Figure 22a shows the close ratio of water delivery from sprinkler D in the downward orientation. Results from the figure show that less water is delivered to the intersection of walls A and B.

Figure 22b confirms the worst results obtained showing disproportionate water delivery from the sprinkler head. The intersection of wall A and B suffer from poor water delivery in the downwards orientation.



Side Wall Test Sprinkler C Upright 3.0 bar

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8.4 | 12.2 | 9.5 | 7.6 | 3.1 | 7.6 | 8.6 | 6.2 |
| 3.3 | 1.8 | 2.9 | 2.2 | 5.0 | 2.8 | 4.7 | 3.6 |
| 1.2 | 0.8 | 0.8 | 0.3 | 1.3 | 0.8 | 1.0 | 1.1 |
| 0.8 | 0.3 | 0.5 | 0.3 | 0.9 | 0.3 | 0.3 | 0.5 |
| 0.8 | 0.6 | 0.6 | 0.1 | 0.6 | 0.3 | 0.1 | 0.2 |

Wall A Wall B

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 9.4 | 6.4 |
| Row 4 | 2.5 | 4.0 |
| Row 3 | 0.8 | 1.1 |
| Row 2 | 0.5 | 0.5 |
| Row 1 | 0.5 | 0.3 |

| Horizontal position | Col 4 | Col 3 | Col 2 | Col 1 | Col 1 | Col 2 | Col 3 | Col 4 |
|---|---|---|---|---|---|---|---|---|
| mm/min per column | 2.9 | 3.1 | 2.8 | 2.1 | 2.2 | 2.4 | 2.9 | 2.3 |

| Mean water density per wall (mm/min) | Wall A | Wall B |
|---|---|---|
| | 2.8 | 2.5 |

a

Side Wall Test Sprinkler B Upright 3.0 bar

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7.5 | 10.7 | 8.5 | 6.0 | 0.8 | 0.4 | 1.4 | 1.4 |
| 8.7 | 6.6 | 8.0 | 9.1 | 3.1 | 1.5 | 2.3 | 3.0 |
| 1.4 | 1.2 | 0.9 | 0.7 | 1.0 | 1.1 | 1.0 | 0.7 |
| 0.6 | 0.4 | 0.4 | 0.6 | 1.8 | 0.5 | 0.4 | 0.7 |
| 0.5 | 0.5 | 0.5 | 0.1 | 0.5 | 0.2 | 0.2 | 0.3 |

Wall A Wall B

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 8.2 | 1.0 |
| Row 4 | 8.1 | 2.5 |
| Row 3 | 1.1 | 0.9 |
| Row 2 | 0.5 | 0.8 |
| Row 1 | 0.4 | 0.3 |

| Horizontal position | Col 4 | Col 3 | Col 2 | Col 1 | Col 1 | Col 2 | Col 3 | Col 4 |
|---|---|---|---|---|---|---|---|---|
| mm/min per column | 3.7 | 3.9 | 3.7 | 3.3 | 1.4 | 0.7 | 1.1 | 1.2 |

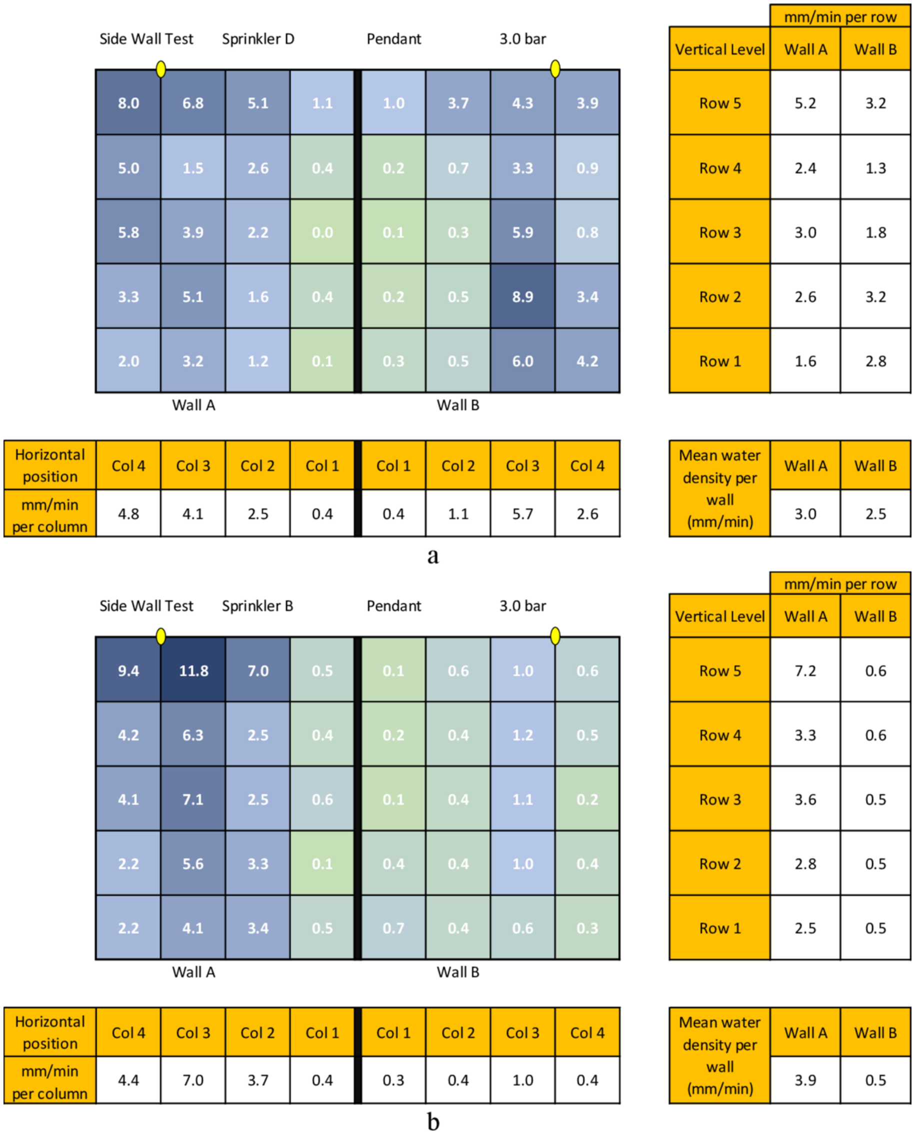
| Mean water density per wall (mm/min) | Wall A | Wall B |
|---|---|---|
| | 3.7 | 1.1 |

b

**Fig. 19** **a** Measured densities from test W01, sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling. **b** Measured densities from test W05, sprinkler B, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling

## 5.3 Wall wetting discussion

The results indicate a difference in performance of sprinklers based on location of the yoke arms relative to the facing wall. Proportionate distribution irrespective of yoke arms is achievable in some sprinklers, but not others. Pipework shadowing is also a contributing



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8.0 | 6.8 | 5.1 | 1.1 | 1.0 | 3.7 | 4.3 | 3.9 |
| 5.0 | 1.5 | 2.6 | 0.4 | 0.2 | 0.7 | 3.3 | 0.9 |
| 5.8 | 3.9 | 2.2 | 0.0 | 0.1 | 0.3 | 5.9 | 0.8 |
| 3.3 | 5.1 | 1.6 | 0.4 | 0.2 | 0.5 | 8.9 | 3.4 |
| 2.0 | 3.2 | 1.2 | 0.1 | 0.3 | 0.5 | 6.0 | 4.2 |

| Horizontal position | Col 4 | Col 3 | Col 2 | Col 1 | Col 1 | Col 2 | Col 3 | Col 4 |
|---|---|---|---|---|---|---|---|---|
| mm/min per column | 4.8 | 4.1 | 2.5 | 0.4 | 0.4 | 1.1 | 5.7 | 2.6 |

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 5.2 | 3.2 |
| Row 4 | 2.4 | 1.3 |
| Row 3 | 3.0 | 1.8 |
| Row 2 | 2.6 | 3.2 |
| Row 1 | 1.6 | 2.8 |

| Mean water density per wall (mm/min) | Wall A | Wall B |
|---|---|---|
| | 3.0 | 2.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9.4 | 11.8 | 7.0 | 0.5 | 0.1 | 0.6 | 1.0 | 0.6 |
| 4.2 | 6.3 | 2.5 | 0.4 | 0.2 | 0.4 | 1.2 | 0.5 |
| 4.1 | 7.1 | 2.5 | 0.6 | 0.1 | 0.4 | 1.1 | 0.2 |
| 2.2 | 5.6 | 3.3 | 0.1 | 0.4 | 0.4 | 1.0 | 0.4 |
| 2.2 | 4.1 | 3.4 | 0.5 | 0.7 | 0.4 | 0.6 | 0.3 |

| Horizontal position | Col 4 | Col 3 | Col 2 | Col 1 | Col 1 | Col 2 | Col 3 | Col 4 |
|---|---|---|---|---|---|---|---|---|
| mm/min per column | 4.4 | 7.0 | 3.7 | 0.4 | 0.3 | 0.4 | 1.0 | 0.4 |

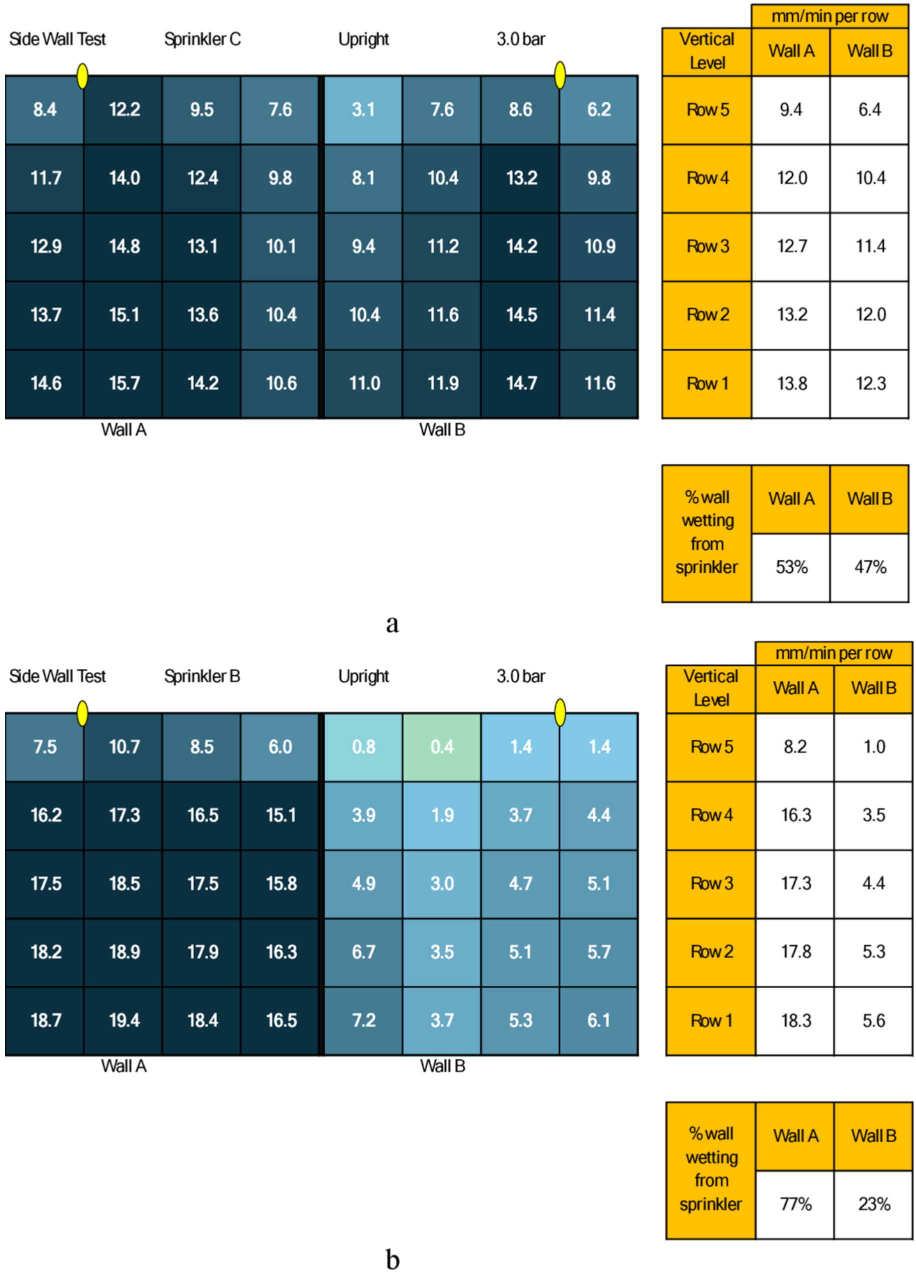
| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 7.2 | 0.6 |
| Row 4 | 3.3 | 0.6 |
| Row 3 | 3.6 | 0.5 |
| Row 2 | 2.8 | 0.5 |
| Row 1 | 2.5 | 0.5 |

| Mean water density per wall (mm/min) | Wall A | Wall B |
|---|---|---|
| | 3.9 | 0.5 |

**Fig. 20** **a** Measured densities from test W14, sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling. **b** Measured densities from test W13, sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling

factor in reduced distribution when sprinklers are installed in the pendant (downwards) position.

Water run-down has been shown in density (mm $\text{min}^{-1}$ $\text{m}^{-2}$) for visual ease: however, this method of measurement is for depth of water at floor level over a specified area, which is captured in Sect. 4.2.2. Irrespective of water measurement, it can be observed from Figs. 19,



Side Wall Test Sprinkler C Upright 3.0 bar

| Wall A | | | | Wall B | | | |
|---|---|---|---|---|---|---|---|
| 8.4 | 12.2 | 9.5 | 7.6 | 3.1 | 7.6 | 8.6 | 6.2 |
| 11.7 | 14.0 | 12.4 | 9.8 | 8.1 | 10.4 | 13.2 | 9.8 |
| 12.9 | 14.8 | 13.1 | 10.1 | 9.4 | 11.2 | 14.2 | 10.9 |
| 13.7 | 15.1 | 13.6 | 10.4 | 10.4 | 11.6 | 14.5 | 11.4 |
| 14.6 | 15.7 | 14.2 | 10.6 | 11.0 | 11.9 | 14.7 | 11.6 |

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 9.4 | 6.4 |
| Row 4 | 12.0 | 10.4 |
| Row 3 | 12.7 | 11.4 |
| Row 2 | 13.2 | 12.0 |
| Row 1 | 13.8 | 12.3 |

| % wall wetting from sprinkler | Wall A | Wall B |
|---|---|---|
| | 53% | 47% |

a

Side Wall Test Sprinkler B Upright 3.0 bar

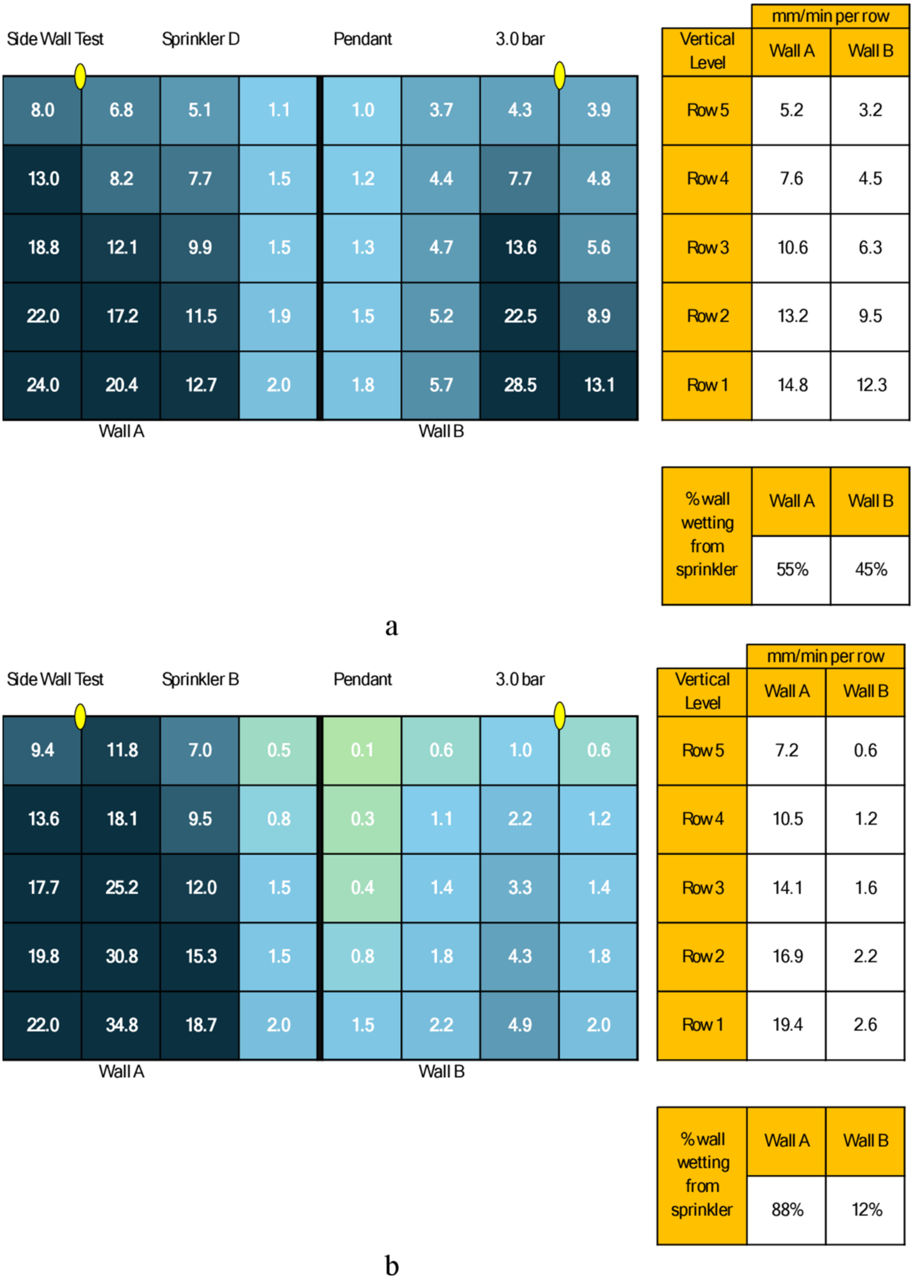
| Wall A | | | | Wall B | | | |
|---|---|---|---|---|---|---|---|
| 7.5 | 10.7 | 8.5 | 6.0 | 0.8 | 0.4 | 1.4 | 1.4 |
| 16.2 | 17.3 | 16.5 | 15.1 | 3.9 | 1.9 | 3.7 | 4.4 |
| 17.5 | 18.5 | 17.5 | 15.8 | 4.9 | 3.0 | 4.7 | 5.1 |
| 18.2 | 18.9 | 17.9 | 16.3 | 6.7 | 3.5 | 5.1 | 5.7 |
| 18.7 | 19.4 | 18.4 | 16.5 | 7.2 | 3.7 | 5.3 | 6.1 |

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 8.2 | 1.0 |
| Row 4 | 16.3 | 3.5 |
| Row 3 | 17.3 | 4.4 |
| Row 2 | 17.8 | 5.3 |
| Row 1 | 18.3 | 5.6 |

| % wall wetting from sprinkler | Wall A | Wall B |
|---|---|---|
| | 77% | 23% |

b

**Fig. 21** **a** Cumulative densities from test W01, Sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling. **b** Cumulative densities from test W05, Sprinkler B for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling



Side Wall Test Sprinkler D Pendant 3.0 bar

| Wall A | | | | Wall B | | | |
|---|---|---|---|---|---|---|---|
| 8.0 | 6.8 | 5.1 | 1.1 | 1.0 | 3.7 | 4.3 | 3.9 |
| 13.0 | 8.2 | 7.7 | 1.5 | 1.2 | 4.4 | 7.7 | 4.8 |
| 18.8 | 12.1 | 9.9 | 1.5 | 1.3 | 4.7 | 13.6 | 5.6 |
| 22.0 | 17.2 | 11.5 | 1.9 | 1.5 | 5.2 | 22.5 | 8.9 |
| 24.0 | 20.4 | 12.7 | 2.0 | 1.8 | 5.7 | 28.5 | 13.1 |

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 5.2 | 3.2 |
| Row 4 | 7.6 | 4.5 |
| Row 3 | 10.6 | 6.3 |
| Row 2 | 13.2 | 9.5 |
| Row 1 | 14.8 | 12.3 |

| % wall wetting from sprinkler | Wall A | Wall B |
|---|---|---|
| | 55% | 45% |

a

Side Wall Test Sprinkler B Pendant 3.0 bar

| Wall A | | | | Wall B | | | |
|---|---|---|---|---|---|---|---|
| 9.4 | 11.8 | 7.0 | 0.5 | 0.1 | 0.6 | 1.0 | 0.6 |
| 13.6 | 18.1 | 9.5 | 0.8 | 0.3 | 1.1 | 2.2 | 1.2 |
| 17.7 | 25.2 | 12.0 | 1.5 | 0.4 | 1.4 | 3.3 | 1.4 |
| 19.8 | 30.8 | 15.3 | 1.5 | 0.8 | 1.8 | 4.3 | 1.8 |
| 22.0 | 34.8 | 18.7 | 2.0 | 1.5 | 2.2 | 4.9 | 2.0 |

| | mm/min per row | |
|---|---|---|
| Vertical Level | Wall A | Wall B |
| Row 5 | 7.2 | 0.6 |
| Row 4 | 10.5 | 1.2 |
| Row 3 | 14.1 | 1.6 |
| Row 2 | 16.9 | 2.2 |
| Row 1 | 19.4 | 2.6 |

| % wall wetting from sprinkler | Wall A | Wall B |
|---|---|---|
| | 88% | 12% |

b

**Fig. 22** **a** Cumulative densities from test W14, Sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling. **b** Cumulative densities from test W13, Sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling

20, 21 and 22 that the top 0.5 m of the wall is wetted. However, results also show significant differences between sprinkler heads.

Experimental testing undertaken in this study demonstrates that, when sprinkler heads are arranged at 1.5 × 1.5 m spacing from corner sections and positioned 150–180 mm below the ceiling, the resulting discharge reliably reaches the ceiling–wall interface. The findings further show that water run-down from the upper wall surface produces sustained wetting, ensuring adequate distribution to lower interface regions. This wetting behaviour is expected to limit fire penetration into unsealed gaps or openings within the wall construction and thereby reduce the likelihood of smouldering.

## 6 Conclusions

This study demonstrates that sprinkler head spray characteristics play a critical role in achieving continuous protective water flow over the ceiling and walls. This is essential for protecting combustible surfaces, such as exposed timber buildings. While both modern and CUP sprinklers meet applicable European and American design standards, they exhibit different water distribution patterns. CUP sprinklers deliver water upward, horizontal, and downwards, whereas modern sprinklers provide a more uniform distribution across the floor area. As a result, sprinkler head spacing becomes a key design consideration when CUP sprinklers are used to ensure sufficient coverage. These findings reinforce the importance of sprinkler selection and layout in meeting fire performance objectives in fully sprinkler-protected timber compartments. Tests were conducted on sprinklers of the same type (CUP), size, temperature, and ‘K’ factor produced by five manufacturers.

‘K’ factor testing confirmed that minimum specifications were achieved. Results showed slightly higher ‘K’ factors, which would result in slightly greater water discharge from the sprinklers. However, this deviation is not likely to compromise the effectiveness of the system based on perceived fires.

Water distribution results above and below the sprinkler head show a closer ratio of water delivery than the manufacturers’ specifications. Water distribution above the sprinkler deflector confirms slightly higher flows, which support ceiling wetting at distances of 150–180 mm below the ceiling.

There is no recognised standard for assessment of wall wetting from commercial sprinklers. Bespoke testing undertaken in this study confirms that wall wetting was achieved at lower and higher sprinkler head pressures. Performance and distribution ratios varied in the twenty-one tests performed. However, results from all tests confirmed that water was delivered to the top 0.5 m section of the wall at the intersection with the ceiling. The worst performing sprinkler provided minimal wetting in the corner wall (Fig. 20b) where a fire could grow more quickly up the walls. In this case closer spacing to the corner wall would allow more water flow from the sprinkler to be distributed onto the wall, improving cumulative water flow to the corner.

Ceiling wetting was achieved by all CUP sprinklers. Results varied between tests, from exceptionally good to extremely poor coverage, which represents worst-case scenarios. If the tests were conducted with a fire plume, it could be anticipated that the upward thrust of gas would help the water to spread further horizontally. Figure 23 shows a simulation of the extremity of the best and worst ceiling wetting in a compartment of 9 m × 9 m for standard sprinkler spacing at 3 m maximum.

Figure 23 shows the extreme limits of ceiling wetting results from testing. At a pressure of 3.0 bar, sprinkler C in an upward orientation demonstrates satisfactory ceiling coverage within a compartment. The same sprinkler head in a downward orientation at 0.35 bar exhibits wholly inadequate ceiling coverage. All other recorded sprinkler coverage tests fell between these two extremes and can be found in supplementary material.

To improve wetting coverage of the ceiling, sprinklers could be spaced in an irregular manner, known as staggered spacing in accordance with BS EN 12845:2015, to provide more of a continuous wetted ceiling line to prevent the surface spread of flame, but selection of the correct sprinkler in the optimum orientation would be required. Staggered spacing would allow sprinklers to be positioned so that each sprinkler is centrally offset from the adjacent sprinkler in more of a diamond shape than square. It is hoped that from this study manufacturers of sprinkler heads consider further development of CUP sprinklers to perform in a more optimal and desirable way in relation to upwards spray to improve surface wetting of the ceiling.

The final criterion was floor wetting/minimum density of discharge at floor level. Results at both tested pressures met the minimum specified densities for occupancy classifications considered within this study (offices, schools, hospitals, and general retail type outlets – classified as Ordinary Hazard occupancies).

Selection of the optimal performing sprinkler shall be evaluated against the three criteria set out in Sect. 3.3.

Wall wetting (criteria 1): Good proportionate coverage to both walls with wetting to the top 0.5 m (wall/ceiling interface) irrespective of yoke arm and pipe shadowing is required to ensure this vulnerable area is wetted from the sprinkler head. Sprinkler head selection shall be taken based on tested results at 0.35 bar and 3.0 bar.

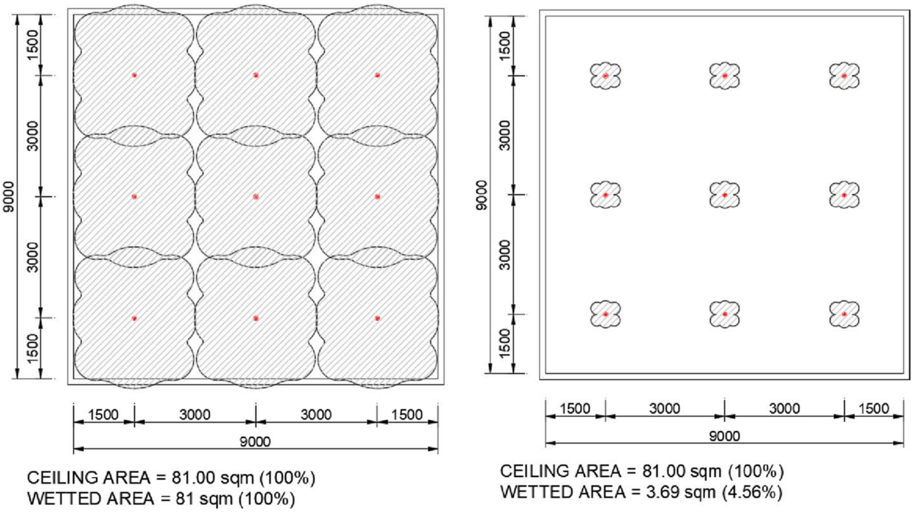


**Fig. 23** Extremities of ceiling wetting areas. Left: Sprinkler C in upright orientation at 3.0 bar. Right: Sprinkler C in pendant orientation at 0.35 bar

Ceiling wetting (criteria 2): Irrespective of sprinkler head orientation (upwards/downwards), the maximum potential water distribution pattern on the ceiling shall be used to select the most appropriate sprinkler. Using the wetting pattern, sprinklers shall be spaced to provide a barrier of wetting to the ceiling to slow or halt fire spread. Knowledge of or tested results showing wetting patterns at pressures of 0.35 bar and higher will confirm sprinkler head selection.

Floor wetting (criteria 3): Sprinklers shall be capable of providing minimum discharge density of 5 $\text{mm}^{-1}$ $\text{min}^{-2}$ over the required area as required for Ordinary Hazard classifications within BS EN 12845:2015.

The goal of this study was to establish whether commercially available sprinkler heads could adequately provide wetting to the surfaces of exposed timber. Modern sprinklers (SSP and SSU) demonstrated they have the ability to cover the floor and a percentage of the walls, but no upward spray can be achieved for the wetting of the ceiling, shown in Fig. 2 when compared to CUP sprinklers. Testing aimed to assess whether a good distribution on ceilings, walls and contents could be achieved from sprinklers mounted in different orientations at two different pressures.

Experimental testing has demonstrated that appropriate selection of sprinkler head type, together with defined constraints on sprinkler spacing, can meet the requirements for achieving a continuous flow of water over combustible timber surfaces with the objective of delaying or preventing surface flame spread, while simultaneously maintaining the minimum required water application density to the contents fuel load at floor level, as illustrated in Figs. 24 and 25.

It is recognised that surface wetting alone does not fully characterise key parameters such as water flux, film thickness, or wetting persistence, all of which influence ignition delay and suppression of timber pyrolysis. However, the continuous water discharge from adjacent operating sprinkler heads onto exposed surfaces may be considered functionally comparable to the pre-wetting of the movable fuel load at floor level. Pre-wetting, in terms of the fire tetrahedron, relates to the effective removal of fuel by rendering the ignitable and combustible components unignitable and non-combustible.

On this basis, the study demonstrates equivalent overall system performance in terms of fuel wetting and fire growth limitation. This pre-wetting of both fixed and movable fuel loads is expected to support occupant evacuation and contribute to improved conditions for firefighting operations undertaken by Fire and Rescue Services.

It is acknowledged that experimental, theoretical, and CFD studies demonstrate that fire plumes and ceiling jets exert substantial influence on sprinkler water sprays by opposing droplet motion, reducing spray penetration, and altering droplet trajectories. Upward plume flows impede downward-moving droplets, while ceiling jets can deflect, entrain, cool, or redirect the spray, collectively modifying droplet momentum, dispersion, and evaporation. Gas jets and buoyant plumes can further distort the spray cone shape and path. Although sprinkler discharge cools and mixes with the ceiling jet, thereby affecting its velocity and temperature, the ceiling jet simultaneously modifies droplet behaviour in ways that can diminish suppression effectiveness if not considered in system design. These interactions confirm that plume and ceiling-jet gases can modify sprinkler discharge patterns and potentially lead to wetting distributions at the ceiling that differ from those observed in this experimental study.

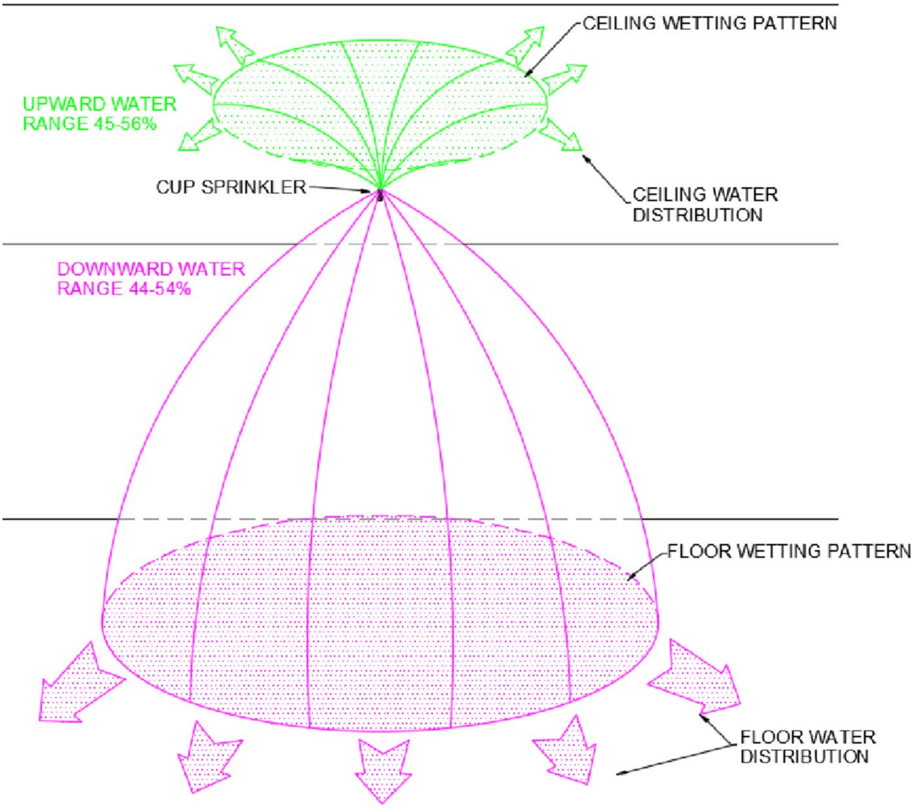


**Fig. 24** Simulated visual discharge characteristic of a CUP sprinkler, demonstrating ceiling and floor wetting achieved from a single sprinkler

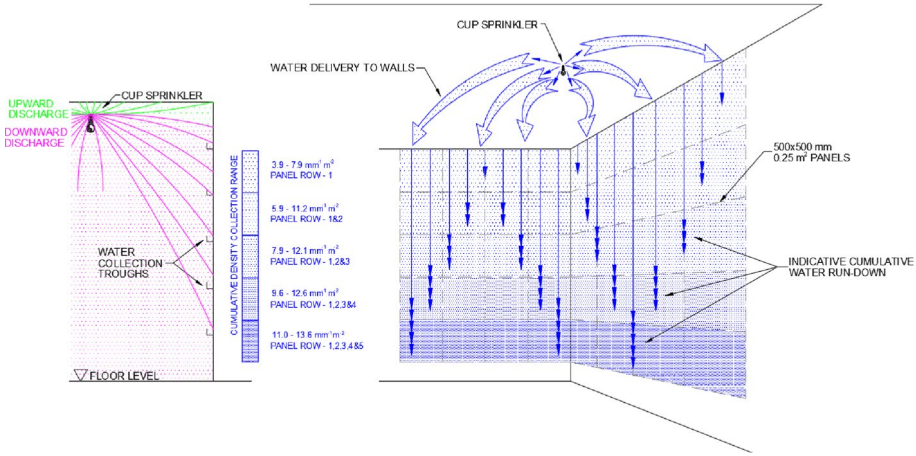


**Fig. 25** Simulated visual discharge characteristic of a CUP sprinkler, demonstrating wall wetting achieved from a single sprinkler

Timber construction is different from traditional non-combustible or limited combustible construction. Fuel load, Heat Release Rate (HRR), surface spread of flame, and duration of fire in timber buildings is increased, requiring a different approach to active fire protection. Existing standards need to consider the location and spacing of sprinklers, and manufacturers could consider optimising sprinkler head spray patterns to ensure surface wetting and optimise their performance specific to timber buildings.

## 7 Potential changes to sprinkler design rules

Results of this study suggest that old style sprinklers are a viable technology to optimise sprinkler systems for the specific protection of buildings with exposed timber surfaces, as might be found in mass timber construction.

Rules for combustible walls, floors and ceilings must be modified. This study has shown that location to walls, location below ceiling, spacing of sprinklers, and selection of sprinkler type are crucial factors to allow wetting of combustible surfaces. Based on the data, the following modifications are deemed necessary.

Head selection should be Conventional type sprinklers, meeting requirements of BS EN 12259-1:1999. Spacing of sprinklers shall be a maximum of 3 m between sprinklers with a maximum spacing per sprinkler limited to 9 m². Spacing from any wall to be 1.5 m or at half the design spacing in accordance with BS EN 12845:2015+A1:2019. Location of sprinkler deflector below ceiling between 75 and 200 mm with sprinkler heads rated as quick response with an RTI of 50 or less as per LPC Rules Technical Bulletin TB207.

General requirements for sprinkler systems protecting mass timber buildings shall cover all areas of the building. Ceiling voids/concealed spaces not less than 300 mm shall be sprinkler protected[4]. Concealed voids less than 300 mm shall be compartmentalised by vertical cavity barriers enclosing areas of no more than 250 m². Fixing into the underside of timber ceilings/substrate as detailed by Kinnersley et al. [60]. Sprinkler pipework shall be steel with screwed or groove jointed connections and all pipework to be drained to a safe place detailed in the Mass Timber Insurance Playbook [61] and Insurer Requirements for Enhanced Escape of Water Protection and Safety in Building Plumbing and Water-Based Fire Suppression Systems [62].

The impact of this study may require a slight increase in sprinkler head numbers, due to spacing limitations and the requirement to protect all areas of a building, but it is seen to be a balanced approach to fire protection of combustible buildings using active sprinkler protection and taking on board best engineering requirements for sprinkler protection.

With minor adaptions of existing sprinkler systems incurring minimal costs, the ability of a system to function for mass timber construction can be greatly increased.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10694-026-01931-1.

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[4] Flat spray type sprinklers might be considered for voids less than 800 mm but greater than 300 mm.

involved in the writing of the report, or in the decision to submit the article for publication. Materials and equipment were kindly provided by ASLR Fabrications, Midfix, Reliable, Rapidrop, Tyco, Viking, and Victaulic. This work would not have been possible without the help of Stevan Grkinic, Nigel Rogers, Chris Shenton, Ian Abley, Richard Glover, and George Edwardes.

**Data Availability** The data supporting this study are openly available in the Central Lancashire Online Knowledge (CLOK) at https://clok.uclan.ac.uk/id/eprint/56883/1/Sprinkler%20Paper%20Supplementary%20Material.docx.

## Declarations

**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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