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Effect of Water Mist Nozzle Discharge Height on Fire Suppression Performance: A Review of Experimental and Numerical Studies

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Abstract: ***Water mist is a fine water spray in which 90% of the flow-weighted cumulative volumetric distribution of droplets (Dv0.90) is smaller than 1000 micrometres, and it has become an established alternative to conventional sprinklers and gaseous clean-agent systems because it combines a low water demand with an environmentally acceptable extinguishing action. It suppresses fire through combined mechanisms of gas-phase cooling, oxygen displacement, fuel-surface wetting and cooling, and radiant heat attenuation, allowing it to interrupt more than one side of the fire tetrahedron simultaneously. The height at which the discharge nozzle is installed above the fuel is a key design variable governing how effectively these mechanisms are mobilised at the seat of a fire, since it affects droplet trajectory, momentum loss before the droplets reach the flame, spray-cone dispersion, and the balance between direct fire suppression and ambient cooling of the protected space. Design practice, however, still leans heavily on test data generated at nozzle heights below roughly 3 metres and on single-fuel, fixed-height experimental programmes, even though real occupancies such as warehouses and tunnels often require much greater installation heights. This review synthesises five experimental and numerical (Fire Dynamics Simulator) studies covering a railway tunnel rescue station, a shielded diesel compartment fire, a shielded wood-crib fire in a partition room, a simulated warehouse compartment with nozzle height varied from 3 m to 9 m, and oil spray fires in confined spaces, examining how nozzle height interacts with operating pressure, flow rate, fuel type and shielding to govern suppression time, heat release rate and cooling performance. Across the reviewed literature, a consistent pattern emerges: lower or closer nozzle positions favour rapid direct suppression while higher positions favour general area cooling but take substantially longer to extinguish a fire unless compensated by higher pressure, higher flow rate or faster (smoke-based) detection. However, no single study varies both nozzle height and fuel type together under otherwise identical conditions, which is identified as the principal research gap motivating the experimental programme proposed in this work.***

Keywords: Water mist; Nozzle discharge height; Fire suppression; Extinguishment time; Fire dynamics; Droplet momentum; Fire protection

1. Introduction

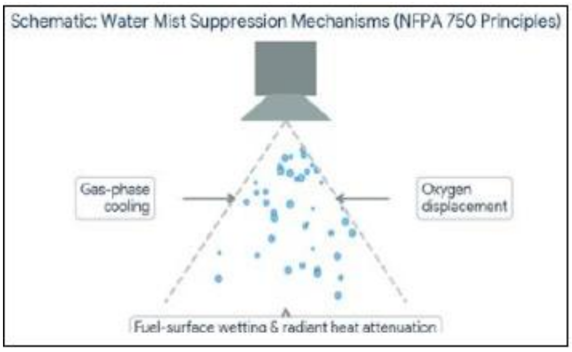
Water mist is a fine water spray in which 90% of the flow-weighted cumulative volumetric distribution of droplets (Dv0.90) is smaller than 1000 micrometres. It is classified into three droplet classes and three operating-pressure ranges as defined by NFPA 750 [6], and it has become an established alternative to conventional sprinklers and gaseous clean-agent systems because it combines a low water demand with an environmentally acceptable extinguishing action.

Fire suppression by water mist relies on several combined physical mechanisms acting together on the fire tetrahedron: gas-phase cooling through evaporation of fine droplets, oxygen displacement and dilution caused by the rapid generation of steam, wetting and cooling of the fuel surface which reduces the pyrolysis rate, and attenuation of radiant heat feedback to the surrounding unburned fuel [7]. Because these mechanisms interrupt more than one side of the fire tetrahedron simultaneously, water mist can be effective even where sprinkler droplets, being larger and slower to vaporise, would be less efficient.

A key design variable that governs how effectively these mechanisms are mobilised at the seat of a fire is the height at which the discharge nozzle is installed above the fuel. Nozzle height affects droplet trajectory, momentum loss before the droplets reach the flame, the degree of dispersion of the spray cone, and the balance between direct fire suppression and ambient cooling of the protected space.

Existing performance-based design practice still leans heavily on test data generated at nozzle heights of below roughly 3 metres and on single-fuel, fixed-height experimental programmes, even though the installation height required in large-volume occupancies such as warehouses, tunnels, machinery spaces and high-value storage can vary considerably from these laboratory-scale conditions. Most published studies also isolate a single variable, such as nozzle height, obstruction geometry or fuel type, rather than examining their combined effect. This leaves a gap between the controlled conditions of the experiments and the more complex, multi-variable conditions of a real occupancy. This report therefore reviews the available experimental and numerical literature on nozzle discharge height and synthesises the findings into a coherent picture of how nozzle height, together with related parameters such as operating pressure, fuel type and shielding, governs suppression performance, identifying the research gap that motivates further experimental work.

NFPA 750: Water Mist Classification System



Schematic: Water Mist Suppression Mechanisms (NFPA 750 Principles)

2. Problem Statement and Review Motivation

Water mist systems are increasingly being specified for applications - warehouses, tunnels, machinery spaces, and high-value storage - where the protected volume is large and the installation height of the nozzle above the fire source can vary considerably from the low heights used in most laboratory-scale validation tests. Existing performance-based design practice, however, still leans heavily on test data generated at nozzle heights of below roughly 3 metres and on single-fuel, fixed-height experimental programmes, even though design codes such as NFPA 750 [6] and IS 15519 [8] set installation and performance requirements without specifying how suppression time should be expected to scale with nozzle height.

The problem this creates for the fire protection engineer is twofold. First, the physical process by which a water mist spray reaches and interacts with a flame - droplet momentum decay, spray-cone widening, and entrainment into the fire plume - is height-dependent, so suppression performance validated at one height cannot simply be assumed to hold at another. Second, most published studies isolate a single variable (nozzle height, obstruction geometry, or fuel type) rather than examining their combined effect, which leaves a gap between the controlled conditions of the experiments and the more complex, multi-variable conditions of a real occupancy. There is therefore a need to consolidate the fragmented evidence on nozzle height effects and to identify specifically where further research is required before design guidance can be generalised with confidence.

3. Literature Review Methodology

This review consolidates published experimental and numerical (Fire Dynamics Simulator, FDS) studies that report water mist nozzle discharge height, or a directly related geometric parameter, alongside a measurable suppression outcome such as extinguishment time, heat release rate or ceiling/plume temperature. Studies were selected to span a range of fire scenarios - tunnel, compartment, shielded-fire and confined-space geometries - and fuel types, so that findings on nozzle height could be compared across, rather than within, a single experimental configuration.

For each study, the reported nozzle height, operating pressure, fuel, and the parameter used to characterise performance were extracted and tabulated (Table 1) to support the comparative analysis in Section 5.

3.1 Review Objective

To review the influence of water mist nozzle discharge height on fire suppression performance across different fire scenarios and identify the conditions under which nozzle height becomes a critical design parameter.

3.2 Specific Objectives

- To review experimental and numerical studies on nozzle discharge height.
- To compare the reported effects of nozzle height on extinguishment time, cooling and suppression effectiveness.
- To examine the interaction of nozzle height with pressure, flow rate, fuel type and shielding.
- To identify limitations and inconsistencies in the existing literature.
- To establish a research gap for future experimental investigation.

4. Reviewed Studies

Table 1: Summary of Reviewed Studies

Study	Scenario	Nozzle Height	Operating Pressure	Fuel	Metric	Key Finding
1	Tunnel	1.5 / 4.5 m	10 MPa	Gasoline	HRR	Lower height gives faster suppression
2	Shielded fire	Variable (fixed)	Low pressure (10.5 bar)	Diesel	Suppression time	Shielding/obstruction affects suppression
3	Wood crib	1.5 m	20 bar	Wood	Extinguishment time	Shield/fuel geometry affects performance
4	Warehouse	3–9 m	40 bar	—	Extinction time	Performance deteriorates at greater height
5	Oil spray	Variable (fixed)	2–6 MPa	Oil	Suppression time	Higher pressure gives smaller, faster droplets and shorter suppression time

4.1 Nozzle Height in a Railway Tunnel Rescue Station

Compared water mist nozzles installed at 1.5 m and 4.5 m above a 93# gasoline pool fire in a 30 m x 6 m x 6 m tunnel model, with the system operating at 10 MPa and a total discharge of 220 L/min (a spray density of about 3.05 L/min per square metre). Heat release rate was inferred from a radiant heat-flux meter and ceiling temperature was tracked with nine K-type thermocouples.

The lower nozzle position suppressed the fire far more quickly - HRR fell from roughly 3400 kW to 250 kW within 50 seconds of activation - because the mist reached the flame while still concentrated, whereas the higher nozzle produced better ceiling cooling but let the spray disperse before it could act directly on the flame.

The authors concluded that lower nozzle heights favour rapid direct suppression while higher positions favour general cooling of the tunnel environment, but noted that the study was limited to a single fuel (gasoline) and only two discrete heights, leaving the interaction between height and fuel type unexplored. [1]

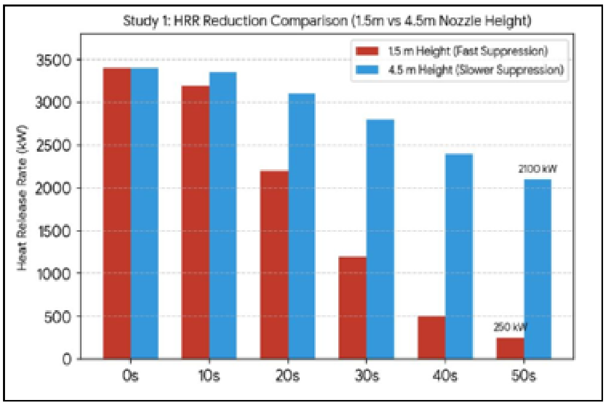


Figure 1: Comparison of Heat Release Rate (HRR) reduction at 1.5m vs 4.5m nozzle heights (Study 1 data)

4.2 Shielded Diesel Fires with a Low-Pressure Multi-Orifice Nozzle

Studied suppression of shielded diesel pool fires in a 2.4 m x 2.4 m x 3.1 m compartment using a single low-pressure (10.5 bar) multi-orifice nozzle mounted above the fire, with obstacle size (15, 25 and 40 cm) and obstacle height (60, 100 and 160 cm) varied systematically. Suppression time, gas concentrations, droplet size and velocity (measured by a Phase Doppler Particle Analyzer) and heat release rate were all recorded. Larger obstacles lengthened suppression time and in some cases prevented full extinguishment, while droplets that bypassed the obstacle still contributed to suppression through flame cooling, oxygen displacement and radiation attenuation. The authors introduced a block ratio and a plume-spray thrust ratio to describe how droplet momentum competes with the fire plume beneath an obstruction, concluding that suppression performance is governed jointly by droplet momentum, obstacle geometry and fire size - again using a fixed nozzle height and a single fuel. [2]

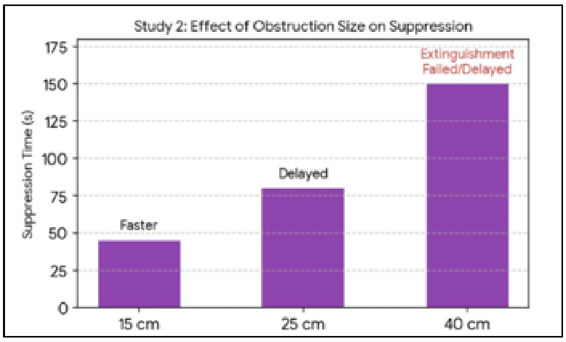


Figure 2: Effect of obstacle size on suppression time (Study 2 findings)

4.3 Shielded Wood-Crib Fires in a Partition Room

Carried out full-scale tests and FDS 6.5.3 simulations of a shielded wood crib fire in a 2 m x 2 m x 2.5 m partition room, using a combination of a fogjet nozzle at the ceiling and fine-spray nozzles at 1.5 m height, operating at 20 bar for a combined flow of about 2.62 L/min. Four combinations of fuel-source and shield location (centre or corner of the room, fuel centred under or offset to one side of the shield) were tested. Extinguishment took between 16 and 30 seconds depending on scenario. Placing the shield at the centre of the room, where mist distribution around the shield was denser, produced faster extinguishment than placing it in a corner, and offsetting the fuel to one side of the shield (reducing the shield's cover area over the fuel) also shortened suppression time.

The FDS model reproduced the measured mist-distribution pattern and flame-temperature trends with reasonable agreement, supporting the use of FDS for further parametric work of this kind - including, by extension, work on nozzle height. [3]

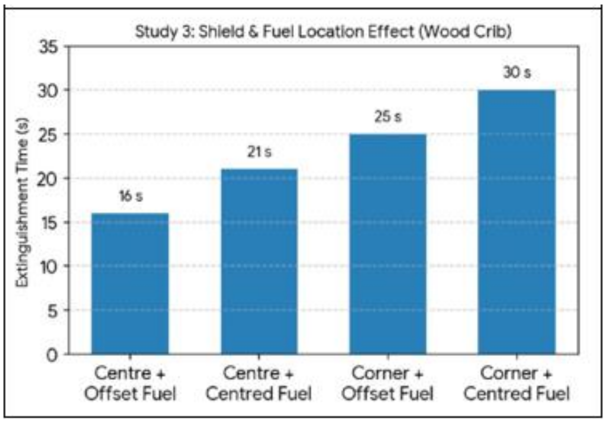


Figure 3: Impact of shield and fuel position on extinguishment time (Study 3).

4.4 Nozzle Height in a Simulated Warehouse

Used a validated FDS model (benchmarked against the enclosure fire-suppression experiments of Kim and Ryou, 2003) to examine water mist performance in an 8 m x 9 m warehouse-type compartment with the nozzle height varied from 3 m to 9 m. Across all tested design cases, suppression performance fell as height increased: for a fixed 40 bar operating pressure and thermal detection, extinguishment time rose from about 95 seconds at 3 m to over 300 seconds at 7 m, and extinguishment could not be achieved at all at 9 m under the same conditions.

The study found that increasing operating pressure and flow rate, or switching activation from thermal to smoke detection, could restore extinguishment capability at greater heights - smoke detection typically activated the system in roughly half the time taken by a 68 degC thermal detector, because it does not require the plume to first heat the ceiling. A supplementary comparison against a conventional sprinkler system at 7.2 m ceiling height showed the sprinkler extinguishing faster once activated (about 20 seconds versus about 60 seconds for water mist), but the water mist system's much faster smoke-based detection meant it achieved a shorter overall time from ignition when detection time was included. [4]

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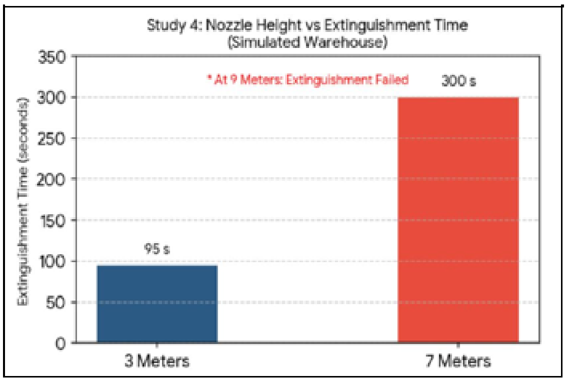

Figure 4: Impact of nozzle discharge height on extinguishment time (Study 4)

4.5 Oil Spray Fires in Confined Spaces

Reviewed experimental data on water mist suppression of gasoline, asphalt and diesel spray (fog) fires in confined spaces such as car engine compartments, factory workshops and marine engine rooms, using Phase Doppler Particle Analyzer measurements to characterise droplet velocity and size. For diesel oil fog fires, operating pressure had a strong influence on suppression time: a 1 MW fire required an operating pressure of at least 2 MPa to extinguish, while a larger 1.6 MW fire took about 85 seconds to extinguish at 2 MPa but only about 40 seconds when pressure was raised to 6 MPa, reflecting the higher droplet velocity and finer atomisation obtained at higher pressure.

The review also reported that side-mounted nozzles extinguished spray fires faster than nozzles opposing the plume directly, because side spray is entrained into the flame root without first having to penetrate the rising plume, and that reducing the distance between the nozzle and the fuel spray source improved suppression efficiency for asphalt fires specifically. Taken together with the nozzle-height studies above, this reinforces that the geometric relationship between nozzle and fire - of which height is one dimension - is a first-order variable in suppression performance. [5]

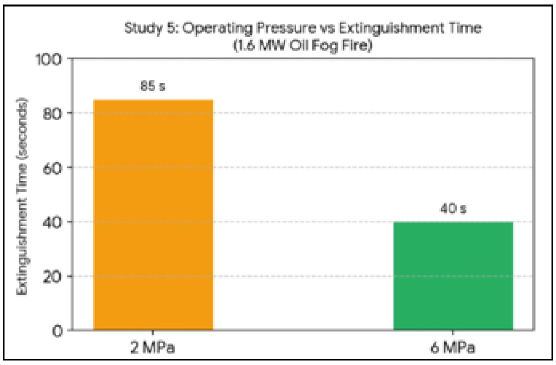

Figure 5: Impact of operating pressure on extinguishment time (Study 5).

4.6 Combined Summary of Extinguishment Times

The following chart synthesises the diverse extinguishment and suppression times recorded across the different scenarios and configurations in the reviewed studies. It highlights the drastic variation in system effectiveness caused by changing key design variables such as nozzle height, operating pressure, and obstruction size.

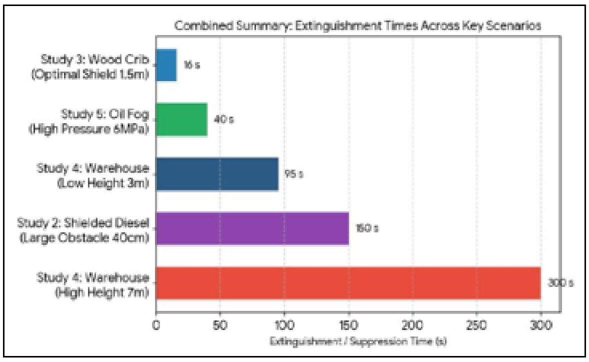

Figure 6: Comparative summary of extinguishment times across multiple tested scenarios from Studies 2, 3, 4, and 5.

5. Comparative Analysis

5.1 Effect of Nozzle Height

Nozzle height governs suppression performance mainly through its effect on droplet momentum and spray-cone dispersion, and the reviewed studies point to a consistent, physically explainable contrast between low and high installation. At low nozzle heights, as in the 1.5 m position of [1] and the fine-spray side nozzles at 1.5 m in [3], droplets travel only a short distance before reaching the fire and therefore retain most of their discharge momentum. This gives better flame penetration, a higher local water mass flux at the fuel surface, and correspondingly faster direct suppression - the tunnel study recorded HRR falling from roughly 3400 kW to 250 kW within 50 seconds at the lower height. At high nozzle heights, as demonstrated numerically across a 3-9 m range by [4], the increased travel distance allows droplets to decelerate under drag, the spray cone widens and disperses over a larger area, and a greater proportion of the finer droplets evaporate before reaching the flame. The combined effect is a reduced local water flux at the seat of the fire and a corresponding increase in extinguishment time, from about 95 seconds at 3 m to over 300 seconds at 7 m, with extinguishment failing altogether at 9 m under the conditions tested.

This trade-off is not purely a loss, however. The same mechanisms that reduce direct suppression efficiency at greater height - a wider, more dispersed spray reaching a larger volume of the compartment - improve general area and ceiling cooling. The tunnel study found that the higher (4.5 m) nozzle cooled the ceiling more effectively even though it suppressed the fire more slowly than the 1.5 m position. This distinction between direct suppression (favoured by low height, high local momentum and flux) and volumetric cooling (favoured by greater height and broader coverage) is a useful way of framing why no single nozzle height is universally optimum: the appropriate height depends on whether the design intent is rapid extinguishment at the fire source or protection of the wider enclosure.

5.2 Effect of Operating Pressure

Operating pressure interacts strongly with nozzle height because it governs droplet size and initial velocity, both of which determine how much momentum survives the travel distance from nozzle to flame. [4] showed that the loss of suppression performance at greater height could be substantially recovered by raising operating pressure and flow rate, effectively compensating for the momentum lost to a longer travel path. [5]'s review of oil spray fires reinforces this: at a fixed geometry, raising pressure from 2 MPa to 6 MPa produced smaller, faster droplets that penetrated the fire plume more effectively, roughly halving extinguishment time for a 1.6 MW oil fog fire. Pressure and height therefore act as partially interchangeable variables - a higher nozzle position can, within limits, be compensated by a higher discharge pressure - which is significant for design practice but has not been quantified systematically across fuel types.

5.3 Effect of Shielding and Obstruction

Shielding and obstruction, examined in [2] and [3], add a further geometric complication to the height effect. Even where nozzle height itself is fixed, an obstruction between the nozzle and the fuel behaves similarly to an increase in effective travel distance: it lengthens suppression time, and in [2] larger obstacles in some cases prevented full extinguishment altogether. [2] introduced a block ratio and a plume-spray thrust ratio to describe how droplet momentum competes with the fire plume beneath an obstruction, while [3] found that shield location relative to the fuel (centre versus corner of the room, and fuel centred versus offset beneath the shield) changed extinguishment time by nearly a factor of two. The parallel with nozzle height is direct: both height and shielding act on the same underlying mechanism - the momentum and coverage of droplets that actually reach the seat of the fire - which suggests they should be considered jointly rather than as separate design parameters.

5.4 Effect of Fuel Type

Fuel type varies across the reviewed studies - gasoline in [1], diesel in [2], wood crib in [3], an unspecified fuel in the FDS parametric study [4], and gasoline, asphalt and diesel spray fires in [5] - but no single study varies fuel type and nozzle height together under otherwise identical conditions. This makes it difficult to separate fuel-dependent effects (such as differences in pyrolysis rate, flame temperature, or droplet-flame interaction between a liquid pool fire and a solid Class A fuel) from the geometric effects of height itself. The available evidence suggests that the general direction of the height effect - lower height favouring direct suppression, greater height favouring cooling - holds qualitatively across the fuel types tested individually, but the magnitude of the effect, and therefore the height at which the trade-off is optimal, cannot currently be assumed to be fuel-independent.

6. Research Gap

Across the five studies reviewed, a consistent pattern emerges: lower or closer nozzle positions improve direct fire suppression, while higher positions favour general area cooling and, without compensating increases in pressure or improved detection, take substantially longer to extinguish a fire or may fail to extinguish it at all. However, most of the individual studies vary only one parameter at a time. [1] tested only gasoline at two heights; [2] tested only diesel at a fixed height; [3] tested only wood crib at a fixed nozzle arrangement; and [4] varied height numerically but did not vary fuel type. Within the literature reviewed in this study, no study was identified that systematically combines multiple nozzle heights with multiple fuel types under otherwise identical conditions. Consequently, there remains a need for a systematic experimental programme that varies nozzle height and fuel type together, so that an optimum suppression time can be identified for each fuel/height combination rather than inferred by comparing results across studies with different geometries, pressures and fuels.

7. Implications for Future Experimental Research

Building on the gap identified in Section 6, the next phase of this work will move from literature synthesis to a controlled experimental programme, in line with the review objective set out in Section 3.1. A test rig will be set up to allow the nozzle discharge height to be varied systematically across a series of fixed positions, with operating pressure and flow rate held constant between runs so that height remains the isolated variable. Three fire scenarios will be tested at each height: a Class A fuel (wood crib), a Class B fuel (liquid pool fire), and a mixed Class A-B fire, so that suppression performance can be compared directly across fuel types rather than inferred across separate studies as in the reviewed literature.

For each height/fuel combination, suppression (extinguishment) time will be recorded as the primary performance metric, supported by heat release rate estimated from a radiant heat-flux meter and temperature histories from a thermocouple array positioned at the ceiling and within the fire plume, following the instrumentation approach used in [1] and [2]. Repeat trials will be carried out at each condition to account for variability in ignition and droplet dispersion. The resulting data set will be used to identify the optimum nozzle discharge height for each fuel class, to establish whether a single optimum height exists across fuel types or whether it is fuel-dependent, and to check the reviewed literature's finding that performance lost to increased height can be recovered by raising operating pressure, by testing this compensation directly for Class A and Class B fires rather than for a single fuel as in [4].

8. Limitations of Existing Literature

- Most studies test only two or three discrete nozzle heights, or vary height numerically without physical validation, so the height-performance relationship within the reviewed range is often interpolated rather than densely measured.
- Each study is generally limited to a single fuel type ([1] gasoline, [2] diesel, [3] wood crib), so fuel-dependent effects on the optimum nozzle height cannot be separated from the reviewed data.
- Compartment geometry, operating pressure, flow rate and detection method differ across studies, so suppression times are not directly comparable between studies and can only be compared qualitatively.
- Only [4] is purely numerical (FDS) and it is not benchmarked against nozzle-height experiments in the same compartment, so its height-dependent trends have not been independently validated against full-scale height variation.
- None of the reviewed studies combine nozzle height and fuel type as co-varied experimental factors, which limits the

ability to generalise findings to mixed-occupancy or mixed-fuel scenarios.

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9. Conclusions

- Water mist fire suppression performance is consistently reduced as nozzle discharge height increases, across tunnel, room and warehouse-scale studies, because droplets lose momentum and the spray cone disperses before reaching the fire.
- Lower nozzle positions favour rapid, direct fire suppression through higher droplet momentum and local water flux; higher positions favour general cooling of the protected space but are slower, and may fail to extinguish the fire without further compensation, as shown for ceiling heights above about 7 m in the FDS study in [4].
- The adverse effect of increased height can be offset by raising operating pressure and flow rate, or by switching from thermal to smoke detection to reduce activation delay.
- Obstruction or shielding of the fire source produces a suppression-time penalty broadly similar in character to that produced by increasing nozzle height, since both increase the effective distance and complexity of the droplet path to the flame.
- Within the literature reviewed in this study, no study was identified that systematically compares the performance of water mist on Class A, Class B, and mixed Class A-B fires under identical experimental conditions, together with nozzle height. The present research therefore aims to address this gap by experimentally investigating the suppression characteristics of water mist across these three fire scenarios at varying nozzle heights, providing a broader understanding of its effectiveness across different fire classes.

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