Experimental and Numerical Studies on the Efficacy of Water Mist to Suppress Hydrocarbon Fires in Enclosures

fire

Review

Experimental and Numerical Studies on the Efficacy of Water Mist to Suppress Hydrocarbon Fires in Enclosures

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Abstract: Fire is one of the most undesirable events onboard a ship. The engine room is one of the most critical spaces in the ship in terms of fire protection, as it includes machinery, hydrocarbon fuel systems, and different electrical equipment. With the phasing out of Halon 1301 as a fire suppressant over recent decades, there has been an intensive effort to explore the efficacy of water-mist spray in mitigating fires within machinery spaces. This exploration entails a comprehensive investigation through experimental and simulation studies aimed at identifying suppression mechanisms and evaluating their effectiveness. While experimental setups typically encompass measurements of gas temperature, thermal radiation heat flux, oxygen concentration, and fire extinction time, limited attention has been paid to quantifying the heat release rate (HRR), a crucial indicator of fire magnitude. Furthermore, research into shielded fire scenarios remains sparse, despite their significance in maritime fire dynamics. Addressing shielded fires with water mist proves particularly challenging due to the potential obstruction impeding the direct interaction between the fire source and the water droplets. In the existing literature, most of the computational fluid dynamics (CFD) modelling of fires and suppression was performed using a Fire Dynamics Simulator (FDS). Alternate studies were performed using FireFOAM. and very few employed FLUENT and other analogous software codes. In the majority of reported computational studies, the determination of HRR was typically relied upon for its calculation derived from the measured data of fuel mass loss rate. Moreover, certain studies were undertaken for numerical simulations without conducting thorough model validation, either by omitting validation altogether or solely validating against dry fire experiments (i.e., without water-mist suppression). This critical review of the literature has identified several notable research gaps in the context of extinguishing hydrocarbon fires utilising water-mist spray, warranting further investigations. Additionally, this review paper highlights recent advancements in both experimental and numerical investigations pertaining to the efficacy of water-mist fire-suppression systems in enclosed spaces regarding hydrocarbon fires.

Keywords: hydrocarbon fire; water-mist system; experimental studies; CFD modelling; machinery space; heat release rates; suppression efficiency

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1. Introduction

As warships can carry weapons and substantial quantities of liquid fuel on board, the occurrence of unwanted fires is one of the most undesirable events, whether deployed at sea or while harboured. In machinery spaces and other high-fire-risk areas of ships, a liquid-fuel fire may be initiated by a spray leak, or dripping leak, forming a liquid pool. Between 30 and 50% of all fire hazards on merchant ships, in a period of 13 years leading to 1997, have been reported to have occurred in the engine room, of which ~60% were caused by liquid fuels composed of hydrocarbons [1]. Bellas et al. [2], drawing upon data from the ship-classification society Det Norske Veritas, noted that 63% of shipboard fires initiated in engine rooms, and of these incidents, excluding those occurring during yard repairs, 56% were instigated by oil leakages onto hot surfaces. Despite an overall decrease in annual shipping losses throughout the past decade (2011–2020), the incidence of fires aboard container ships has notably risen in recent years [3]. The Allianz Safety and Shipping Review of 2021 [3] revealed a shift from 10% to 20% in the proportion of shipping losses attributed to fire and explosions between 2011 and 2020. Furthermore, the same report identified fire as the second leading cause of ship accidents worldwide. Engine-room fires, as highlighted in the International Maritime Organization (IMO) report [4], represent a significant proportion, accounting for up to two-thirds of all ships' fire incidents. The HMAS Westralia fire incident [5] serves as an example, involving the combustion of diesel fuel in the engine room due to a damaged fuel-line leakage, which persisted for 90 min before smoke clearance. Fuel leakage poses a particularly formidable challenge as it may give rise to pool fires, exacerbating fire size and potential damage to naval vessels, with consequences potentially extending to vessel decommissioning and posing lethal risks, even during peacetime (i.e., through non-combat incidents), as exemplified by the HMAS Westralia incident [5].

Until recently, Halon 1301 (bromo-tri-fluoro methane, CF3Br) and total-flooding carbon dioxide have served as the primary firefighting agents for protecting ships, particularly in machinery spaces and engine rooms [2,6]. Typically, a prescribed threshold concentration of these agents is employed for a designated duration to ensure effective fire suppression. However, halocarbon-based gaseous agents pose risks to both human health and the environment [7]. Upon release into the atmosphere, Halon 1301 molecules initiate the breakdown of ozone molecules, contributing to the depletion of the ozone layer. Recognizing these environmental hazards, the international community established the Montreal Protocol on substances that deplete the ozone layer in 1987 [8], with the goal of phasing out the production and consumption of ozone-depleting substances, including halons. Consequently, these agents have been either phased out or banned for marine applications in Australia since 1994 [9]. Thus, there exists a pressing need to investigate environmentally benign active fire-suppression systems as viable alternatives to halon-based counterparts in both defence and broader maritime industries [10].

Although there exist less hazardous gaseous firefighting agents, they typically necessitate evacuation time prior to agent discharge and demand the continual maintenance of extinguishing concentrations within the compartment to effectively combat hydrocarbon fires. Moreover, the deployment of gaseous agents impedes manual firefighting efforts within the compartment. Water-mist spray emerges as a promising alternative for fighting such high-risk fires, offering cooling, oxygen displacement, and radiation attenuation mechanisms conducive to fire extinguishment. Notably, water mist is already being used in both passenger and naval vessels [11].

In the marine environment, there is a notable preference for fire-suppression system designs to adhere to a goal-based (performance-based) framework rather than a rule-based (prescriptive) approach. Rule-based designs, while historically grounded and often effective, may not consistently optimise factors such as cost, complexity, or extinguishment efficiency. Conversely, goal-based designs necessitate validation against predefined criteria, such as temperature limits, extinguishment times, etc., either through experimental means or computational simulations. Given the significant expense associated with large-scale experimental fire tests, numerical simulation presents a viable alternative for evaluating fire-safety systems via computational modelling. However, it is imperative to conduct benchmark experiments to assess and validate numerical models, also known as computational fluid dynamics (CFD) models, before their application in designing more intricate systems. Validated models can substantially contribute to the early stages of the design lifecycle by facilitating the establishment of optimal designs. By utilising numerical modelling to simulate various design iterations involving nozzle characteristics, spacing, and quantity, a performance-based suppression system can be tailored to suit specific ship configurations and compartments effectively.

The primary objectives of this literature review include the following:

- Exploring conducted experiments and their outcomes to understand the state-of-the-art in fire-suppression mechanisms facilitated by water-mist spray;
- Identifying computational fluid dynamics (CFD) models capable of simulating fire extinguishment, facilitated by water-mist systems.

The objectives of this study can contribute to the formulation of research endeavours with practical implications for real-world scenarios, especially pertinent to maritime safety.

2. Mechanism for Water-Mist Fire Suppression

Water mist is a continuum of water droplets, generally in the size-range between an aerosol (droplet diameter $\cong$ 5 µm) and a fog (10 µm $\leq$ droplet diameter $\leq$ 1000 µm) [12]. The National Fire Protection Association (NFPA) [12,13] has also defined water mist in the fire-suppression field as a spray with a range of particle sizes smaller than 1000 µm. There are five mechanisms associated with the extinguishment of class A (solid) and B (flammable liquid) fires by water mist, which are the following [14]:

- Gas-phase cooling;
- Oxygen displacement and flammable vapour dilution;
- The wetting and cooling of the fuel surface;
- Radiation attenuation;
- Kinetic effects.

Generally, all mechanisms take place to varying extents during the fire suppression of hydrocarbon fires in enclosures.

2.1. Gas-Phase Cooling

A water-mist spray is generated by directing water through a mist nozzle to produce exceedingly fine, atomised droplets. The production of fine droplets results in an augmented surface-area-to-volume ratio compared to conventional water nozzle droplets. Consequently, there is an acceleration in the vaporisation rate of the droplets, facilitated by the absorption of heat from surroundings including the flame, hot gases, the smoke layer, and hot boundaries [15]. This process contributes to a reduction in compartment temperature. Should the temperature descend below the critical threshold necessary to sustain the combustion process, the flames will be extinguished. Additionally, the cooling effect serves to mitigate flame radiation onto the fuel surface, consequently diminishing the rate of fuel pyrolysis or gasification.

In closed environments, the efficacy of water in extinguishing fires surpasses that in open spaces, owing to enhanced vaporisation efficiency attributable to heat confinement and restricted oxygen availability within enclosures [12]. This phenomenon arises from the increased absorption of heat by water mist in enclosed spaces, where heat retention accelerates droplet vaporisation. The resulting steam from vaporised droplets contributes to oxygen depletion within the compartment, thereby curtailing the oxygen supply necessary for fuel combustion. Conversely, in open spaces, the dissipation of heat from the fire occurs more readily, and the fire benefits from a larger and more consistent oxygen supply to sustain combustion.

2.2. Oxygen Depletion and Flammable Vapour Dilution

In a water-mist fire-suppression system (WMFSS), the conversion of water droplets into vapour typically leads to a considerable increase in the total volume occupied by the water-mist droplets, often exceeding three orders of magnitude [12]. This expansion in water volume can subsequently disrupt the entrainment of air into the flame. The reduction in oxygen concentration within a compartment due to the introduction of water mist can be regarded as being dependent on factors such as fire size, pre-suppression period duration, compartment volume, and ventilation conditions within the compartment [15].

Typically, extinguishing a fire becomes feasible when the concentration of oxygen diminishes to a level below the critical threshold required to sustain combustion, known as the limiting oxygen concentration (LOC) [16]. The decline in oxygen concentration can arise from a combination of factors including the following: (a) oxygen consumption by the fire itself, (b) dilution caused by the expansion of the volume occupied by water vapour, and (c) dilution due to the production of combustion byproducts [17]. The processes of oxygen depletion and the dilution of flammable vapours within the fire environment are illustrated in Figure 1.

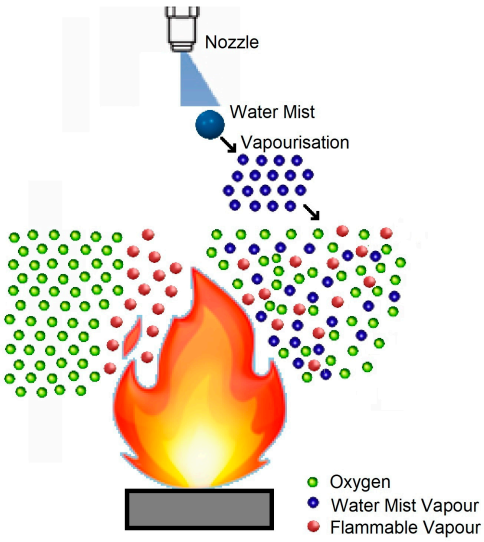


Figure 1. A schematic diagram of oxygen dilution, depletion, and flammable vapour dilution induced by the water-mist vaporisation in a fire environment [18].

2.3. The Wetting and Cooling of the Fuel Surface

The primary extinguishment mechanism for numerous fuels, particularly those that do not produce flammable vapour mixtures above the fuel surface at ambient temperatures—such as solid fuels—is the wetting and cooling of the fuel surface. This process typically entails a decrease in fuel pyrolysis. The suppression of the fire occurs when the temperature of the vapour–air mixture descends below the combustion temperature of the fuel [12].

2.4. Radiation Attenuation

The inclusion of water mist and water vapour can notably diminish the radiant heat flux towards materials situated in close proximity to the fire, thereby hindering the propagation of the fire. The diminished flame temperature resulting from gas-phase cooling contributes to a decrease in radiation feedback to the fuel surface, consequently lowering the rate of fuel pyrolysis. Additionally, the presence of water vapor within the air above the fuel surface can serve as a thermal barrier, absorbing radiant energy and subsequently re-emitting it to the fuel surface at a reduced intensity [16].

In an experimental investigation conducted by Mawhinney et al. [14], it was observed that the application of a water-mist fire-suppression system (WMFSS) could reduce the radiant heat flux of enclosure walls by up to 70%. Furthermore, the study revealed that finer water droplets possess the capability to diminish thermal radiation at a lower water concentration compared to larger spray droplets [19]. The mechanism underlying radiation attenuation facilitated by a water-mist spray is depicted in Figure 2.

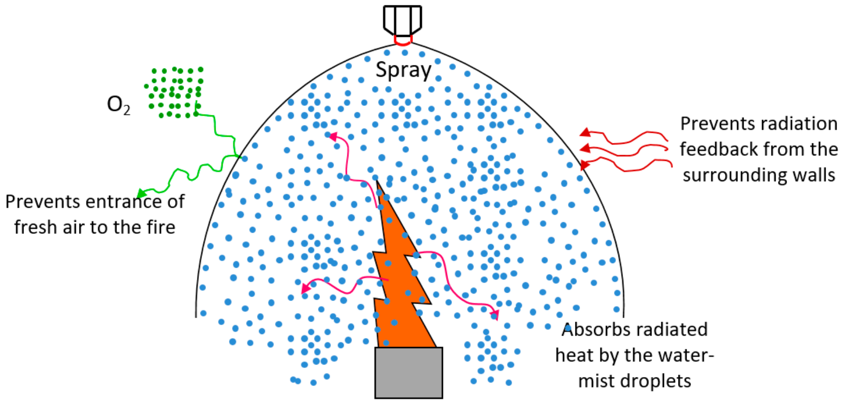


Figure 2. A schematic diagram of attenuation of thermal radiation by water-mist sprays [15].

2.5. Kinetic Effects

Kinetics primarily pertains to the examination of chemical reaction rates, governing processes such as combustion, as well as physical phenomena like vaporisation and condensation. The insertion of water-mist spray can modify the chemical kinetics of a fire by altering the velocity of the flame front within a flammable gas mixture [14]. These kinetic alterations may either intensify the flame or contribute to its extinguishment. Upon initial contact with water mist, the flame may experience intensification due to an accelerated burning rate, potentially induced by the turbulence and entrainment associated with rapid vaporisation at the flame surface [12]. Alternatively, kinetic effects may lead to fire suppression by reducing the reaction rates of burning fuel, facilitated by gas-phase cooling and oxygen depletion/dilution. The insertion of water mist, along with entrained and vitiated gases, can collectively dilute combustible gases. When coupled with flame cooling, this dilution can lead to variations in the combustion rate from its stoichiometric conditions.

3. Literature Review of Maritime Standards

In order to comprehend the current naval standards pertinent to water-mist system evaluation, and to identify prescriptive certification approaches alongside suggesting alternative performance-based methodologies, a comprehensive review of diverse naval water-based fire-suppression standards available in the public domain was conducted. It was noted that the International Maritime Organization MSC/Circ. 1165 [20] and MSC/Circ. 1387 [21] serve as principal standards, offering testing protocols aimed at securing certification for fixed water-mist suppression systems deployed on naval vessels.

The following constitute the primary prescriptive test conditions:

- Engine room volume $\geq$ 500 m^3;
- Floor area $\geq$ 100 m^2, Height $\geq$ 5 m;
- Ventilation: 2 m $\times$ 2 m door;
- Fuel $\geq$ 50 mm on water base;
- 5 to 15 s pre-burn if using heptane as fuel;
- Ambient room temperature of between 10 °C and 30 °C at the start of each test;
- A continuous supply of water $\geq$30 min;
- The water-mist suppression system shall be set up with a 2 m $\times$ 2 m or 3 m $\times$ 3 m nozzle grid to allow for variable test configurations. It is the manufacturer's responsibility to determine the minimum and maximum nozzle-separation distances, specified as "the distance between the nozzle grid and the fuel spray nozzle".

The test-compartment volume dictates the nominal fire size, measured in terms of heat-release rate (HRR), as well as parameters such as fuel tray dimensions, fuel type, and obstruction characteristics, as outlined in Table 1. However, the rationale behind the linear relationship between compartment volume and nominal pool fire size remains ambiguous. This relationship might aim to ensure adequate oxygen supply within larger spaces to sustain larger fires. Additionally, the specification of 0.5 MW for volumes less than 500 m^3 lacks clarity. Back et al. [22] observed that larger fires were comparatively easier and quicker to extinguish than smaller fires due to the greater oxygen consumption and the augmented generation of steam and turbulence. Nonetheless, a fire is deemed sufficiently suppressed by a water-mist spray when it is reduced to a state manageable by human-operated portable systems, defined as having an HRR of less than 1.5 MW or achieving a temperature below 60 °C within 60 s of water-mist spray activation in a large engine room [23].

Table 1. Correlation between compartment volumes and nominal pool fire sizes as well as associated fuel-tray obstruction size [20].

Test Compartment Volume (m^3)	Pool Fire Scenario (Nominal HRR) (MW)	Fuel Tray Diameter (cm)	Fuel Tray Area (m^2)	Size of Obstruction Steel Plate (m × m)
Not specified	0.5	62	0.30	2.0 × 2.0
500	1	83	0.54	2.0 × 2.0
1000	2	112	0.99	2.0 × 2.0
1500	3	136	1.45	2.25 × 2.25
2000	4	156	1.90	2.25 × 2.25
2500	5	173	2.36	2.5 × 2.5
3000	6	189	2.81	2.5 × 2.5

4. Methodology for Reviewing the Academic Literature

To gain insight into recent experimental methodologies relevant to the subject matter, the authors conducted a comprehensive search across multiple databases, including ScienceDirect, Google Scholar, the American Chemical Society (ACS), and the American Society of Civil Engineers (ASCE) Library. The search strategy involved querying keywords such as "suppression of fires by water mist", "suppression of fires by water mist in an enclosure", and "numerical simulation of suppression of fires by water mist", alongside variations thereof. Notably, in the context of fires occurring in the machinery spaces of naval ships, several key characteristics were anticipated: (i) occurrence within ventilated compartments, (ii) the involvement of liquid fuel as a fire source, potentially in conjunction with other fire loads such as accumulated oil/dust, and (iii) the presence of machinery that may act as a shield against the fire. Consequently, the review scope was delimited as follows:

- Inclusion of papers published within the past 15 years (i.e., from 2005 onwards), with any seminal papers with significant citations also incorporated, even if published prior to 2005;
- Focus on compartment fires, with consideration given to fires in open spaces if they involved shielding, given the interest in fire suppression within shielded environments;
- Emphasis on fire sizes exceeding 50 kW, unless specific papers provided critical insights regarding device positioning for measurement purposes;
- Inclusion of studies specifically utilising water-mist spray for fire suppression.

5. Literature Review of Experimental Studies

The experimental studies, along with their corresponding details, are enumerated in Table 2. The table includes the test configurations employed and the parameters measured during these investigations.

Table 2. Test configurations and parameters measured during various experimental studies.

Sl. No.	Publication Details		Compartment Details		Fire Details			Water-Mist Details			Results	
	Authors and Associated Details	Publication Year	Compartment Size (m^3)	Opening Size (m)	Fuel Tray (m)	Fuel Type (Solid/Liquid/Sand Burner) Obstruction, and Suppression Time (s)	HRR (kW)	Nozzle Spacing (m) Number of Nozzles Operating Pressure (bar)	Flow Rate (Lpm)	Mean Droplet Size (μm)	Measured Parameters	Was It Modelled?
1	Back, Beyler et al.; report CG-D-03-99 [24]	1999	10 × 10 × 5	2 × 2 one door	0.7 × 3.5 m	Heptane-pool fire 0.7 × 3.5 m obst.@1.7 m height 490 s	7000	4 × 4 m spacing A cluster of 9 nozzles 8 bar	9 × 15.5 = 140	[1] VMD 100	Temp and Extinction time	Yes (Bellas and Gomez [2])
2	Back, Beyler et al.; report CG-D-03-99 [24]	1999	10 × 10 × 5	2 × 1 two doors	0.74 × 0.74 m	Diesel-pool fire 0.7 × 3.5 m obst. at 1.7 m height 792 s	1000	4 × 4 m spacing 36 single 7 bar	36 × 11 = 396	[1] VMD 390	Temp and Extinction time	Yes (Bellas and Gomez [2])
3	Adiga et al.; Fire Saf. J [25]	2007	3 × 3 × 3 steel-walled compartment	1 supply vent 2 exhaust vent	0.3 m dia	Heptane, Methanol	120 (Heptane) 75 (Methanol)	~1.8 m × 0.6 m	0.66	10	Comb efficiency; Rad and Convec fraction, mass fraction and Extinction time	Yes
4	Beihua et al., J. Fire Sci [26]	2009	3 × 3 × 3	Exhaust fan & 0.2 m-high opening along the wall	0.15 to 0.35 m square pan with 0.025 m increment	Diesel-pool fire No obst 25 to 150 s	8.5~90	Single nozzle operated at different flow rates and pressures	Flow rate varied at 0.53 ~ 0.83	[2] SMD 135	[2] SMD by [4] LDV Temp, O_2, CO_2 and Extinction time	No
5	Xu et al. Thermal Sci, 15(2):353–366; CSIRO [27]	2011	ISO Room 3.6 × 2.4 × 2.4	2 × 0.8 one door	Solid fuel	Wood crib + [5] GRP layer on wall No obst 24, 30, and 14 s for test 1, 2, and 3, respectively	3030 (Test 1) 5409 (Test 2) 1125 (Test 3)	1.4 × 1.9 m spacing 4 single nozzles 17.2 bar	4 × 15 = 60	[2] VMD 100	Temperature O_2 and CO_2 extinction time	No
6	Bystrom et al. Fire Saf J. [28]	2012	9 × 5 × 4.8	2 × 2 m ventilation	Solid fuel	Wood crib No obst 200 s	900	Water application by firefighters	—	—	[6] MLR Temp	Yes
7	Lal et al., spray and comb dyna, 5(3):181–200 [29]	2013	3.6 × 3.5 × 3.1	1.1 × 1.94 door and two 0.4 × 0.3 exhaust fan	0.46 m dia 0.56 m dia 0.66 m dia	Heptane-pool fire No obst 75, 69, 60 s	300, 500, 800	1.63 m dia circ ring– spacing 61 mm 6 single nozzles 2 bar	6 × 1 = 6	[2] SMD 40, 80, 120	[2] SMD by laser-diffraction technique, Temp, O_2, CO, CO_2	No
8	Jenft et al. Fire Safety J. 67:1–12 [30]	2014	4.2 × 4.3 × 3.05	0.3 × 0.4 and a blower	0.35 m dia	Diesel-pool fire No obst 65 s	75	1.2 × 0.9 m spacing 4 nozzles 10 bar	4 × 6.3 = 25.2	[1] SMD 112	MLR Temp O_2	Yes

Table 2. *Cont.*

Sl. No.	Publication Details		Compartment Details		Fire Details			Water-Mist Details			Results	
	Authors and Associated Details	**Publication Year**	**Compartment Size (m^3)**	**Opening Size (m)**	**Fuel Tray (m)**	**Fuel Type (Solid/Liquid/Sand Burner) Obstruction, and Suppression Time (s)**	**HRR (kW)**	**Nozzle Spacing (m) Number of Nozzles Operating Pressure (bar)**	**Flow Rate (Lpm)**	**Mean Droplet Size (µm)**	**Measured Parameters**	**Was It Modelled?**
9	Jeong et al., Korea Inst. of Fire Sci. and Eng. Confer, 2014 [31]	2014	18 × 18 × 16.5	2 × 2 door	0.7 × 3 m	Heptane pool, 0.7 × 3.5 m at 1.75 m height 477 s	—	4 × 3 m spacing 22 nozzles 10 bar	22 × 22.5 = 495	[1] VMD 125	Extinction time	Yes (Ha et al. [32])
10	Zhu et al. J. of Fire Sci. [33]	2015	Room 1- 5 × 6 × 3.6 Room 2- 8 × 6 × 8	8 × 8	1.0 × 1.0 m	Diesel	1810	2 nozzles, 2 m apart Pressure varied	0.74 to 1.75	[2] SMD 53 to 88	Temp, Rad and Extinction time	Yes
11	Chiu and Li, Pro Saf and Env Prot, 98:40–49 [34]	2015	6.05 × 2.43 × 2.5	2.0 × 0.9 door and 2.15 × 0.2 air inlet at a wall	0.63 × 0.63 m	Diesel	113	T1 2 nozzles T2 3 nozzles 1 m spacing	220	No information	Temperature	Yes
12	Zhang et al., App Ther Eng 94:706–714 [35]	2016	3.6 × 1.5 × 0.6	1.5 × 0.2 m vent	0.5 m dia	Ethanol-pool fire, and 0.14 × 0.14 m rubber pad as additional fuel No Obst 60 to 500 s for differ pressure	130	2 different single nozzles, cluster of 7, 20 to 100 bar	2.25 to 10	[2] SMD 200 ~ 350	[2] SMD and droplet velocity by PIV system, MLR, Temp, Rad, O_2, H_2	No
13	White et al. Fire Saf. J. 91:705–713 [36]	2017	2 × 2 × 2 m	Air supplied by a blower	0.05 × 0.5 m burner	Methane	50	Unusual arrangement; 0.5 × 0.75 m opening levelled with fuel area, mist projected upward	NA	[2] SMD 6	[3] DSD by laser, Comb efficiency; mass fraction and extinction time	yes
14	White et al. Fire Saf. J. 92:164–176 [37]	2017	Open *	Open	0.05 × 0.5 m burner	Methane	50	Co-flowing oxidizer with N_2 to reduce O_2 mole fraction	—	—	HRR, O_2 mole fraction, and comb efficiency,	Yes (White et al. [38])
15	Jenft et al. Fire Saf. J., 91:680–687 [39]	2017	4.2 × 4.3 × 3.05	0.3 × 0.4 m ventilation and a 0.3 m dia blower	0.25 and 0.35 m dia	Diesel-pool fire No obst 23 to 437 s for different test conditions	45 to 75 based on different conditions	1.2 × 0.9 m spacing A cluster of 4	4 × 6.3 = 17.2	[1] SMD 112	MLR Fuel-surface Temp	Yes
16	Lee, Nucl Eng and Tech 51: 410–423 [40]	2019	5.4 × 3.1 × 2.4	1.1 × 1.9 m door	0.3 × 0.3 m	Heptane-pool fire No Obst. 2.5 s	244	Single nozzle	22.45	[3] VMD 125	[2] DSD by laser, Extinction time	Yes

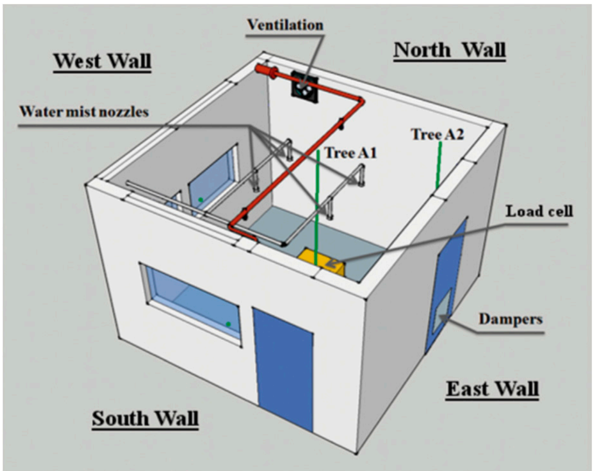
Table 2. *Cont.*

Sl. No.	Publication Details		Compartment Details		Fire Details			Water-Mist Details			Results	
	Authors and Associated Details	**Publication Year**	**Compartment Size (m^3)**	**Opening Size (m)**	**Fuel Tray (m)**	**Fuel Type (Solid/Liquid/Sand Burner) Obstruction, and Suppression Time (s)**	**HRR (kW)**	**Nozzle Spacing (m) Number of Nozzles Operating Pressure (bar)**	**Flow Rate (Lpm)**	**Mean Droplet Size (µm)**	**Measured Parameters**	**Was It Modelled?**
17	Liu et al. Pros Saf Env Prot., IChemE [7]	2020	10 × 6 × 4	Open	0.25 m dia	Propane sand-burner 0.1 m dia, 1.5 m height 35 s in one case	40~72	1 nozzle Pressure was varied from 20 bar to 40 bar	Flow was varied 1.08~1.44	[3] VMD 40	MLR Temperature,	Yes
18	Ren et al., 11th AOSFST [41]	2020	Open *	Open	Solid fuel	16 pallet loads arranged to be two-tiers high. Each pallet load is a corrugated cardboard box sitting on a hardwood pallet. 75 s	T1 1700 T2 1700 T3 1700	T1 and T2 with 4 nozzles at 3 × 3 m spacing T1: 44.8 bar T2: 20 bar T3 with 4 nozzles at 2.6 × 2.6 m spacing T3: 100 bar	T1 3 × 6.1 = 18.3 T2 3 × 4.1 = 12.3 T3 3 × 6.1 = 18.3	[3] VMD T1 177 T2 210 T3 70	HRR, Rad	Yes
19	Bu et al., Ther Sci and Eng Prog 35:101467 [42]	2022	T1 50 × 7.7 × 6.2 T2 19 × 2.8 × 2.7	Exhaust fan 1.5 m/s and 2.5 m/s	0.7 × 0.7 m	Oil-pool fire Obstructed under train seat 60 s	400	2.5 × 5.2 m grid 18 nozzles in 2 rows 50 and 80 bar	18 × 3.5 = 63 to 18 × 13.5 = 243	180	HRR, Temp, Smoke Conc	Yes

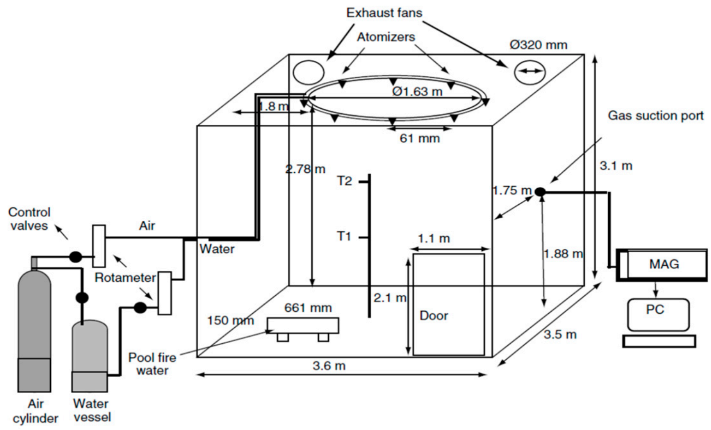
[1] VMD = Volumetric mean diameter, [2] SMD = Sauter mean diameter, [3] DSD = Droplet size distribution, [4] LDV = Laser Doppler velocimetry, [5] GRP = Glass-reinforced polyester, [6] MLR = Mass-loss rate. * The compartment was “open” as it was mentioned by the authors in the article.

The primary observations from the documented experimental studies are as follows:

- With the exception of Back et al. [24], Xu et al. [27], Zhu et al. [33], and Ren et al. [41], the majority of studies investigated fire sizes ≤1000 kW (1 MW), with some instances where fire sizes were below 100 kW. Xu et al. [27] and Ren et al. [41] utilised solid fuels for their experiments. Xu et al. [27] reported fires with HRRs of 3030 and 5409 kW in their Tests 1 and 2, respectively. However, questions arise regarding whether the oxygen supply within the enclosure used (an ISO room) could sustain such large fires, particularly those exceeding 5 MW, unless a substantial amount of pyrolysed fuel burned outside the door.
- The majority of experiments were conducted within enclosure volumes not exceeding 50 m^3. Some specific experimental setups are depicted in Figure 3.



(**a**)



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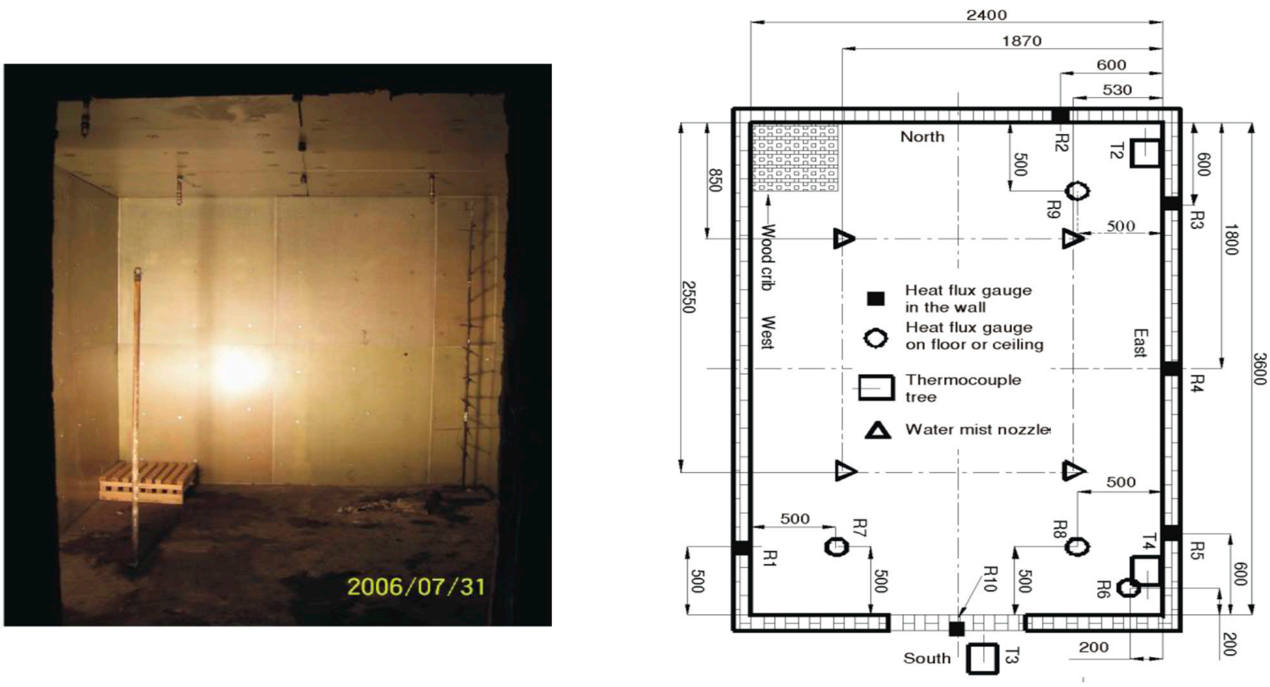

(**c**)

Figure 3. A schematic of some configurations in some experimental studies, (**a**) Jenft et al. [30], (**b**) Lal et al. [29], and (**c**) Xu et al. [27].

- Only Xu et al. [27] (listed as serial 5 in Table 1 and indicated by underline) directly measured the fire size (HRR) using oxygen calorimetry. In most cases, mass-loss rate (MLR) was measured, which was subsequently converted to HRR using the equation HRR = MLR × heat of combustion × combustion efficiency. It should be noted that once water mist is activated, mass measurements include the mass of water. Therefore, HRR during the extinction phase cannot be estimated based on mass-loss measurement;
- The parameters often measured using devices are the following:
  - Gas and fuel-layer temperature;
  - Concentrations of O_2, CO, CO_2, and smoke;
  - Radiation heat flux.

  Additionally, extinction times are recorded through physical observation;
- Mean droplet sizes ranged from 6 to 400 μm, and the water supply working pressures predominantly varied between 70 and 135 bar.
- The suppression of fires using shielding was observed in approximately 30% of experiments;
- Some of these experiments were combined with numerical modelling, some were modelled by other researchers, and some have not been modelled;
- The studies which contained only experiments were mainly aimed at exploring the efficiency of water-mist spray with different water-flow pressures and droplet diameters, for instance, the following:
  - Beihua et al. [26] investigated the extinction limit of diesel-pool fires by water-mist spray based on spray pressure and fire size;
  - Lal et al. [29] investigated varied droplet sizes for the suppression of a n-heptane-pool fire;
  - Zhang et al. [35] examined pressure variations from 20 to 100 bar, with increments of 10 bar, for the suppression of an ethanol-pool fire.

We have identified the following results as major findings relevant to naval applications based on Williams et al. [23]:

- The optimal performing water-mist nozzle was a modified nozzle operating at 70 bar (1000 psi);
- The most effective performance was achieved when nozzles were positioned immediately below the overhead of each level (i.e., deck head or ceiling);
- The recommended nozzle spacing was nominally 2.5 m apart, with an adequate number of nozzles to generate a total water flow of 0.4 Lpm/m^3;
- Extinguishment times were typically under one minute, except for small obstructed fires or instances where forced ventilation was intentionally sustained;
- Compartment temperatures dropped from 500 °C to 50 °C within seconds after mist activation;
- The small residual fires that could not be extinguished by the water mist were easily approached and extinguished using a standard hand-held portable extinguisher. This was considered acceptable, with the criterion specifying a maintained compartment temperature below 60 °C after 60 s from the initial mist discharge.

Williams et al. [23] introduced an extinguishment pass/failure criterion, the black line curve illustrated in Figure 4, as a function of fire size against extinguishing time, considering <1.5 MW (considering the tested fire sizes were very large) to be “contained” and approachable with portable equipment. Notably, the black line curve follows an exponential trend (with R^2 = 0.98), and the profile has been extrapolated as a red line. Additionally, the experimental data from Table 2 are plotted.

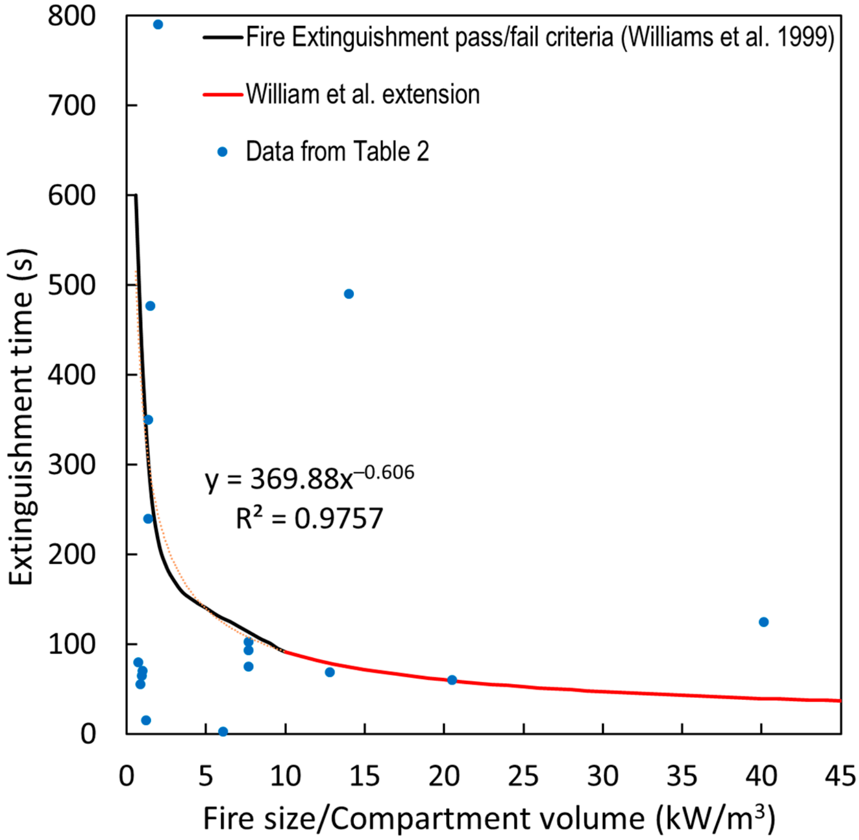

Figure 4. A plot showing the extinguishment pass/failure criteria proposed by Williams et al. [23] and comparison with experimental data. Below the line is considered a pass criterion.

In Figure 4, it is evident that in the majority of experimental instances, a pass criterion is met, indicating that extinguishment times fall below the profile recommended by Williams et al. [23] and its extension. Nevertheless, it is to be noted that the experiments presented in Table 2 encompass diverse ventilation conditions, which can be a factor in attaining rapid extinguishment.

6. Literature Review of Numerical Modelling

6.1. CFD Modelling Technique

As conducting full-scale experiments in enclosed spaces is time-consuming and expensive, computational fluid dynamics (CFD)-based fire models can be considered an alternative method to predict the physics of fire and water-mist interaction in enclosures [43]. In order to accurately predict the conditions required for extinguishment, the combustion chemistry, combined with thermodynamics and fluid dynamics, need to be modelled in detail.

Generally, the compartment geometry is imported into the CFD software and discretised using three-dimensional meshes (also known as the grid resolution). CFD models can calculate the fire environment within the control volume by numerically solving the conservation equations (mass, energy, momentum, diffusion, species, etc.) within each mesh cell. Solving these equations is accomplished by using finite difference, finite element, or boundary-element methods. The enormous number of computations performed during these modelling exercises is time-consuming and requires powerful computational machines. Nowadays, as greater computer-processing power becomes available at lower costs, CFD-based fire models are increasingly used in all aspects of fire safety engineering. An important feature of CFD simulation is that it can be used to explore complicated fire scenarios multiple times, with minor changes in the scenario, as required. However, it is important to examine the accuracy of the CFD model before using it for the design and analysis of fire-suppression systems. The results of a numerical model need to be verified by using analytical solutions and/or be validated against the experimental test results [44].

Currently in CFD modelling, water-mist drop transportation and tracking are being performed using either Eulerian or Lagrangian formulations. While both use a fixed grid, the Eulerian formulation assumes the drops pass through (drops and gases travel at different velocities), whereas the Lagrangian formulation considers the droplets and gases to be a single homogeneous mixture. The appropriate formulation will depend on the spray characteristics of the nozzle as well as on the application. For example, the transport of larger drops may be better predicted using an Eulerian formulation, whereas smaller drops may be better predicted using a Lagrangian Particle-Tracking (LPT) model. To make matters more complicated, a specific technique may work better closer to the nozzle (the near field) and lose accuracy in the far field [12].

Generally, turbulent flows generated by the water-mist spray can be represented by eddies with a range of lengths and time scales. The entire range of eddies can be directly resolved using the Direct Numerical Simulation (DNS) approach; partially resolved using Large Eddy Simulation (LES), which directly resolves large-scale eddies and models small eddies; or completely modelled by employing the Reynolds Averaged Navier–Stokes (RANS) approach. Thus, LES allows for the usage of much coarser meshes and longer time steps compared to DNS. It is impractical to apply DNS for real-world engineering problems dealing with high Reynolds number flows due to its extreme computational cost [45]. In contrast, RANS models cannot capture the details of unsteady transient phases observed in fire dynamics; the large-scale flow; and combustion features [45–48], as RANS models include sub-models and coefficients that are configuration-dependent and require careful calibration work. The wide variety of configurations found in fire problems makes this calibration work a daunting and almost impractical task [15].

LES needs much coarser meshes and longer time steps compared to DNS and finer meshes than those used for RANS computations. Since RANS models cannot capture features of the transient phases and spray structure such as droplet collisions and coalescences, LES can be applied to overcome these limitations [45–48]. The interest in LES has become amplified over the past decade, and LES has now displaced RANS as the dominant CFD approach for spray and fire simulations [49].

The FDS User Guide [50] suggests that for simulations involving buoyant plumes, mesh resolution (a measure of how well the flow field is resolved), should be governed by a non-dimensional expression $D^*/\delta x$, where D^* is a characteristic fire diameter as defined in Equation (1):

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

where ρ_∞, c_p, and T_∞ are the density, specific heat, and temperature of ambient air, respectively, $\dot{Q}$ is the HRR of fire and g is the gravitational acceleration. The ratio between D^* and grid size, dx, should be between 4 and 16 for LES and when the HRR is prescribed. $D^*/\delta x$ can be very large if the HRR is not prescribed.

Some of the CFD programs currently in use include the Fire Dynamics Simulator (FDS), FireFOAM, and FLUENT, which are capable of characterising water-mist applications [12]. With a validated model, a parametric study can be conducted to explore the effect of different factors in suppressing fires by water-mist sprays. The factors may include the location of the fire, obstruction to the fire, water-injection pressure, type of nozzles (such as single-orifice nozzle, multi-orifice nozzle, etc.), number of nozzles, and the size of the droplets.

6.2. Previous Studies Using CFD Modelling

There exist numerous studies in the literature focused on CFD modelling, with Table 3 providing a comprehensive list of papers involving numerical investigations. Only studies meeting the specified criteria outlined in Section 4 have been included and presented in the table. The following are the key observations extracted from those studies:

- Predominantly, investigations were conducted utilising the FDS, with fewer instances employing FireFOAM and a scant number employing FLUENT and other codes;
- The vast majority of simulations used the Eddy Dissipation Concept (EDC) as the combustion model; the Lagrangian–Eulerian-mist model (Lagrangian for the liquid phase and Eulerian for the gas phase); and a Radiation Transport Equation (RTE) model for radiation. Adiga et al. [25] employed Lagrangian and Eulerian separately for mist simulation. FDS versions prior to version 6 utilised a mixture-controlled combustion model;
- For extinction modelling, FDS uses Critical Flame Temperature (CFT); whereas FireFOAM uses the Damkohler number (Da). This will be discussed further;
- While FDS employed a default set of heat- and mass-transfer equations for evaporation, FireFOAM offered multiple options for this process;
- Except for serials #6, 7, 9, 14, and 16 in Table 3 (highlighted with blue font), the HRR was prescribed in the model either based on experimental data or calculated HRR obtained from the mass-loss rate. Some special techniques for the prescribed HRR used are as follows:
    - In serials #3 and 8, Jenft and co-workers adopted a methodology wherein the HRR in the numerical model was determined based on the experimental MLR in the absence of water-mist spray application. The HRR calculation relied on the measured MLR before the introduction of water-mist spray, and during mist application, the HRR was adjusted to follow an exponential reduction trajectory through some correlations. The reduction factors were estimated considering the characteristic time to suppression, defined as the duration for the HRR to diminish to zero in accordance with the experimental suppression time;
    - In serials #10, 11, and 12, the HRR growth was prescribed as a t^2 function, with the peak value derived from theoretical computations. The post-activation of the spray and the decay of the HRR were simulated by incorporating an extinction coefficient for fire suppression. This coefficient was iteratively adjusted within the model to synchronize the numerical suppression time with the experimental counterpart.
- In some instances, model validation was omitted, as exemplified by the investigations detailed in serials #11 and 12 of Table 3. In serial #11, the study explored the impact of door aspect ratio (door width/height) and opening ratio (reduced area/original area) on fire suppression using the FDS. Conversely, serial #12 examined the influence of the distance between the fire and the nozzle;
- In some instances, validation procedures entailed dry-fire tests, conducted without the application of water-mist spray, followed by subsequent explorations of parametric effects using the model. In serial #3 of Table 3, investigations delved into the influence of early and late applications of water spray on fire suppression times, examined both experimentally and via numerical simulations utilising FDS. Serial #17 involved a sensitivity analysis for FDS, wherein variations in extinction coefficient, droplets per second (DPS), and peak heat release rate (HRR) were assessed for their impacts on the rate of HRR reduction and suppression duration. In serial #18, the efficacy of water mist in suppressing shielded fires was investigated by altering the height and dimensions of obstructions, alongside estimations of suppression time, HRR, and temperature;

With the exception of the investigations detailed in serials #5, 13, 16, and 18 of Table 3, fire-suppression scenarios were simulated without the presence of shielding.

The details of some of the numerical studies, which have been presented in Table 3, along with their respective limitations and research gaps, are presented in the following sections.

Table 3. Numerical configurations and predicted parameters during various CFD studies.

Sl. No.	Publication Details		Experiment Modelled	Computational Model Details						Model Application Details						Results	
	Authors and Associated Details	Publication Year	This Serial Is from Table 2	Software Name	Turbulence Model	Mist Model	Combustion Model	Radiation Model	Evaporation Model	Grid Size (mm)	HRR Prescribed?	D*/dx	[1] SA	[2] DPS	Computational Resources	What Parameter Compared (HRR, MLR, Temp, O_2, Rad)	Was the Fire Suppressed?
1	Adiga et al.; Fire Saf. J [25]	2007	Serial 3	FLUENT	k-epsilon	Lagrangian Discrete-Phase Model (DPM), Eulerian Dense Gaseous (DG)	none	none	default	72.5	Yes	5	default	default	No record	Temp, Extinction time	100 deg C gas temp reduction = suppression
2	Bystrom et al. Fire Saf J. [28]	2012	Serial 6	FDS 5.5.3	LES	Lagrangian–Euler	Mixture-fraction with [3] CFT extinc	[4] RTE	default	50 100	Yes	18	default	default	No record	MLR Temp	Fire was suppressed by firefighter
3	Jenft et al. Fire Saf. J. 67:1–12 [30]	2014	Serial 8	FDS 5.5.3	LES	Lagrangian–Euler	Mixture-fraction with CFT extinction	RTE	default	50	Yes	6.8	default	default	No record	Extinction time Temp O_2	HRR was forced to reduce to zero by using a MLR-reduction factor at the activation of spray based on the experimental extinction time.
4	Zhu et al. J. of Fire Sci. [33]	2015	Serial 10	FDS 6.1.1	LES	Lagrangian–Euler	[5] EDC with CFT extinction	RTE	default	100	Yes	12	500	50,000	No record	Rad, [6] CNF, Temp	No suppression modelled
5	Chiu and Li, Pro Saf and Env Prot, 98:40–49 [34]	2015	Serial 11	FDS (version not reported)	LES	Lagrangian–Euler	Unclear as version unknown	RTE	default	120 × 50 × 40 cells (not a square grid)	No information (seems that prescribed)	—	default	default	No record	Extinction time, Temp	Suppression of fire claimed based on temperature reduction. However, no HRR or flame extinction was reported either in experiment nor in simulation
6	White et al. Fire Saf. J. 90:72–86 [38]	2017	Serial 14	FDS 6	LES	Lagrangian–Euler	[5] EDC with CFT extinc	RTE, with simplification using the concept of GRLF [7]	default	5	No	58	default	NA as dilatation of O_2 with N_2 used	40 processors UMD Deepthought2 HPC cluster. 1 Sim, 30 s = 1080 CPU hours using Intel Ivy Bridge E5-2680v2 2.80 GHz processors.	Temp, O_2, and Comb efficiency	Yes, combustion efficiency was reduced with dilution of O_2 and matched with the exp data
7	White et al. Fire Saf. J. 91:705–713 [36]	2017	Serial 13	FireFOAM	Epsilon ε model	Lagrangian–Euler	EDC with Damkohler number (Da)-based extinction	RTE	Ranz–Marshall	4	No	17	—	1,000,000	100 processors UMD Deepthought2 HPC cluster. 1 Sim = 15,000 CPU hours using Intel Ivy Bridge E5-2680v2 2.80 GHz processors.	Comb efficiency; O_2 mass fraction and Extinc time	Yes; qualitative comparison
8	Jenft et al. Fire Saf. J. 91:680–687 [39]	2017	Serial 15	FDS 6	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	50	Yes	7	default	default	No record	Temp O_2	The same is serial #3

Table 3. *Cont.*

Sl. No.	Publication Details		Experiment Modelled	Computational Model Details						Model Application Details						Results	
	Authors and Associated Details	Publication Year	This Serial Is from Table 2	Software Name	Turbulence Model	Mist Model	Combustion Model	Radiation Model	Evaporation Model	Grid Size (mm)	HRR Pre-scribed?	D*/dx	[1] SA	[2] DPS	Computational Resources	What Parameter Compared (HRR, MLR, Temp, O_2, Rad)	Was the Fire Suppressed?
9	Vilfayeau et al., Combustion Institute 36, 3287–3295 [51]	2017	No experiment	FireFOAM3	Epsilon model	Lagrangian–Euler	EDC with Damköhler number based extinction	RTE	Ranz–Marshall	4 8 16	No	70 35 18	default	default	14 s simulation, Used 40 processors Linux cluster, 1500 h CPU time.	Flame-cooling and evaporation-cooling power: Comb efficiency; HRR	Flame extinction was achieved by the Model when mist entrained into the flame-base region
10	Lee, Nucl Eng and Tech 51: 410–423 [40]	2019	Serial 16	FDS 6.3.2	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	50	Yes	11	default	1000~5,00,000	No record	Extinction time, Temp, O_2	HRR prescribed as t^2 with calculated peak value. The HRR after spray activation was modelled using an extinction coefficient.
11	Lee, Annals of Nucl Ener 136:107021 [52]	2020	No experiment	FDS 6.4.0 and CFAST 7.1.1 (two-zone model)	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	22	Yes	24	default	50,000	No record	Temp, Suppression time	HRR prescribed as t^2 with calculated peak value. Extinct coeff. was varied to match experimental suppression time.
12	Lee and Moon, Annals of Nucl Ener 144 [53]	2020	No experiment	FDS 6.5.2	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	40	Yes	10	default	5000	No record	Temp, Suppression time	Same as serial #9
13	Liu et al., Pros Saf Env Prot., IChemE [7]	2020	Serial 17	FDS 6.3.2	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	100	Yes	3.5	default	default	No record	Temp, O_2	HRR was prescribed
14	Bellas and Gomez, Fire Tech [2]	2020	Serial 1	FDS 6.7.0	LES	Lagrangian–Euler	EDC with CFT extinc	RTE	default	100	No	21	default	default	11 meshes, 2 core per mesh; 22 × 18 h CPU core time for a 240 s simulation	Temp, O_2	HRR was reduced to 1000 kW, but not completely suppressed.
15	Bellas and Gomez, Fire Tech [2]	2020	Serial 2	FDS 6.7.0	LES	Lagrangian–Euler	EDC with CFT extinction	RTE	default	50/100	Yes	19	default	default	11 meshes, 2 core per mesh; 22 × 18 h CPU core time for a 240 s simulation	Temp, O_2	HRR was prescribed
16	Ren et al., 11th AOSFST [41]	2020	Serial 18	FireFOAM3	k equation	Lagrangian–Euler	EDC with Da-based extinction	RTE	reactive volume fraction (RVF) model	25.4	No	46	default	default	No record	HRR, Rad	The numerical results followed the experimental trend, but fire was not suppressed.
17	Ha et al., Nucl Eng and Tech 53: 1157–1166 [32]	2021	Serial 9	FDS 6.5.2	LES	Lagrangian–Euler	EDC with CFT extinction	RTE	default	50	Yes	4.5	default	5000	No record	Extinction coefficient (EC),Temp, Suppression time	Extinction coefficient was used

Table 3. *Cont.*

Sl. No.	Publication Details		Experiment Modelled	Computational Model Details						Model Application Details						Results	
	Authors and Associated Details	Publication Year	This Serial Is from Table 2	Software Name	Turbulence Model	Mist Model	Combustion Model	Radiation Model	Evaporation Model	Grid Size (mm)	HRR Prescribed?	D*/dx	[1] SA	[2] DPS	Computational Resources	What Parameter Compared (HRR, MLR, Temp, O_2, Rad)	Was the Fire Suppressed?
18	Hamzehpour et al., WMC, Spain [54]	2022	Serial 8	FDS 6	LES	Lagrangian–Euler	EDC with CFT extinction	RTE	default	50	Yes	7	default	default	No record	Temp O_2	Yes, The validation was on a dry test, without the application of water mist.
19	Bu et al., Ther Sci and Eng Prog 35:101467 [42]	2022	Serial 19	SIMTEC developed by Lund Uni	LES	Lagrangian–Euler	EDC	RTE	default	200	Yes	3.3	default	default	No record	Temp, Smoke Conc	HRR was prescribed

[1] SA = solid angle [2] DPS = droplet per second [3] CFT = Critical Flame Temperature [4] RTE = Radiation Transport Equation [5] EDC = Eddy Dissipation Concept. [6] CNF = cumulative number fraction. [7] GRLF = global radiation loss fraction.

Zhu et al. [33] is the earliest literature resource found in this review to use the FDS's EDC combustion model. However, they prescribed the HRR with estimated growth and extinction periods (based on the fuel-burning time and variation trend of measured radiative heat flux). They conducted an extensive sensitivity study of grid size for mass, momentum, and species transport, a solid angle for radiation transport, and droplets per second of water mist. Similarly, Lee and Moon [53], with the absence of any experimental data, assumed the fire growth to be a function of t^2 and the peak HRR based on the theoretical burning rate. They carried out a numerical study on the effect of horizontal distance between a water-spray nozzle and a fire on fire suppression using FDS version 6.5.2. In other studies by Lee and co-workers [40,52] similar assumptions for HRR were used without presenting any experimental data. Lee et al. [40] also proposed a simple calibration method to determine the extinguishing coefficient, yielding the fire-suppression time closest to that measured by experiments to use as the FDS input parameters. However, this correlation was proposed on a single extinguishment time in the experiment.

Jenft et al. [39] treated liquid fuel as solid fuel and used the Arrhenius relationship [55] to model pyrolysis instead of the evaporation model in FDS. They introduced an additional term to force the pyrolysis rate down to zero below the ignition temperature. White et al. [38] incorporated provisions into FDS to prevent spurious re-ignition and yield extinction and validated the developed FDS model with the fire extinction of a methane-diffusion flame when oxygen concentration was depleted by supplying additional N_2. Bellas et al. [2] used FDS 6.7.0 to simulate seven experiments representing International Maritime Organization-approved water-based fire-suppression in machinery spaces [21], including five with spray fires (four with diesel oil and one with heptane) and two heptane-pool fires with both exposed and obstructed fire configurations. Although fire suppression was predicted, there was no experimental HRR or MLR data available to compare. Only the temperature reduction was compared.

Vilfayeau et al. [51,56] investigated the mechanisms that control flame cooling efficacy in water-mist spray using FireFOAM, and concluded that maximum suppression is obtained when mist droplets are entrained into the flame-base region. However, they did not compare the numerical results with any experimental measurement. Moreover, they used a monodispersed spray (spray consisting of a single size of droplet) of water mist. Ren et al. [57] performed a series of numerical simulations, using FireFOAM, for deep-seated solid-fuel fires in a rack-storage configuration in an open space. Water mist was used for the suppression of the fire in the experiment and numerical simulations. The numerical results followed the experimental trend to some extent; however, the fire was not completely extinguished in the simulation. White et al. [36] employed FireFOAM to analyse the water-mist suppression effects on a buoyant, turbulent, methane-fuelled diffusion flame with the Damköhler number (Da)-based extinction model. Da-based extinction models [58] incorporate additional physics to account for chemical time scales and aerodynamic quenching effects and are computationally expensive. White et al. [36] qualitatively modelled the suppression of fire by water mist.

The suppression of shielded, or obstructed, fires with water mist is typically challenging, as the fire receives radiation feedback from the obstruction, and the obstruction blocks the direct path between the fire and water droplets. Owing to the complexity of fire-extinguishing processes, fire scenarios where flames are shielded by obstacles adds another layer of complexity in the modelling of water-mist suppression [7]. The shielding of fire is very common, for instance, in the engine room of a marine vessel, under a seat in a train, in warehouses under a package, or within a multilayer storage rack. Liu et al. [7] performed a small-scale study on the effect of shielding a fire (using a propane sand-burner) and its suppression both experimentally and numerically. The laser light visualisation of the fire and mist interaction in the experiments revealed that the performance of mists in bypassing an obstacle depends on the size of fire, the diameter of droplets, and the position of the obstruction. In their case, the mist spray with droplets of 40 μm VMD was able to extinguish a 40 kW fire, whereas it failed to suppress a 75 kW fire. Liu et al. also modelled the interaction between shielded fire and water mist by using FDS 6.3.2. The simulation was found to underestimate the temperature drop for the cases with higher block ratio (diameter of water-mist spray projecting to the fuel surface with the obstacle/diameter of the fuel tray).

Hamzehpour et al. [54] conducted a study on the performance of water mist in the suppression of a shielded fire by using FDS 6 (only the main version of FDS was mentioned, the sub-version or release number was not mentioned). They varied the height and size of the obstruction and estimated the time of suppression, HRR, and temperature. The authors used the same compartment geometry and properties of the model as in the experimental data by Jenft et al. [30]. The authors also prescribed the HRR in the numerical model based on the experimental MLR before the application of water-mist spray, and, during the mist application, the HRR was guided towards an exponential reduction through some correlations so that the numerical suppression time matched with that of the experiment measurement. In the case of the suppression of the shielded fire in the study, the FDS was not able to extinguish the fire when the obstruction size was higher than about three times the top surface area of the fuel package.

Chiu and Li [34] conducted a series of full-scale fire-suppression experiments using self-made mist spray nozzles in a wind-generator scenario, in which the sheltering conditions of two fire sources located under containers were considered. The experimental study found that the water-mist system was capable of suppressing the fire effectively with the wind generation even when the fire was sheltered. Chiu and Li also performed a numerical study using the FDS, and the results showed that the declining trends in the fire temperature in the numerical experiment and actual experiment were relatively close. However, none of the experimental studies involving shielding included the measurement of the HRR during the suppression phase of the fire, and so the HRR was prescribed in the numerical simulation.

It is important to note that HRR is the key parameter to characterise the growth and, in particular, the suppression of fire [29]. Suppression involves modelling the dynamics of the physical behaviour of the suppression agent, especially the tiny droplets of water mist, as well as modelling the complex interactions of fire, the suppression agent, and the surrounding environment. In most of the studies presented in Table 3, the validation of HRR either was not conducted or the model was validated only with dry tests (without the application of water-mist spray). Therefore, the capabilities of CFD models to simulate HRR accurately should be tested. Moreover, further studies are required on the extinguishment of shielded fires under different situations, both experimental and numerical, with the measurement and simulation of HRR. This will help to understand the mechanism of the suppression of shielded fire and also to evaluate the capability of the current models in this aspect.

6.3. Sensitivity of Numerical Parameters for FDS

Grid size is the most common numerical parameter used for sensitivity studies in CFD modelling. The simulation domain is divided into a large number of grid cells and governing equations are solved in every cell during every time step. In order to be certain that the results of fire scenarios are not significantly impacted by the choice of grid resolution, a grid-convergence analysis is usually performed. Grid convergence analysis is a process of gradual refinement [59], where the same simulation is run multiple times with a gradually smaller cell size and a key metric is measured. As cell size decreases, smaller and smaller changes in the chosen metric should be observed. In FDS, grid cells can only be of cuboid shape as they use the finite difference method. However, FLUENT can use tetrahedral, hexahedral, polyhedral, pyramid, or wedge cells (or a combination of these), and it uses the finite volume method.

In FDS, the radiation equation is solved in finite-volume grid and the domain used is divided into a number of solid angles. While almost all researchers use the default 100 solid angles, Zhu et al. [33] conducted a sensitivity study and found that 500 solid angles were required to obtain a converged solution.

For the radiation absorption coefficient, by default FDS uses a grey gas model. This is suitable for sooting fires like those involving heptane. There is a more computationally expensive model available known as the wide band model (often called the Box Model in the radiation literature). This model is only recommended when the fuel produces relatively non-sooting fires, such as one involving ethanol. However, heptane fires can be tested with the wide band model, as various band limits for "N-HEPTANE" are available in FDS.

For modelling water mist, an important parameter is the number of droplets injected per second. Once again, the vast majority of researchers use the default value, and Zhu et al. [33] conducted a sensitivity study in which 50,000 droplets per second (defined as PARTICLES_PER_SECOND) was found to be needed to obtain a converged solution.

Solving detailed turbulence is computationally very expensive. FDS has three different options:

- Large Eddy Simulation (LES);
- Very Large Eddy Simulation (VLES);
- Simplified Very Large Eddy Simulation (SVLES);

LES is computationally more expensive and can provide more accurate results. SVLES is the least expensive and the results are not expected to be as accurate as those generated in LES mode. In between lies VLES.

The FDS has two types of EXTINCTION models. When the SVLES turbulence model is used, the default extinction model is 'EXTINCTION 1'. However, in all other modes, 'EXTINCTION 2' should be used. The difference between the two models is that for 'EXTINCTION 1', only the cell temperature and oxygen concentration are considered because detailed thermo-physical gas species' properties are not invoked, as they are in the 'EXTINCTION 2' model.

7. Concluding Remarks

This literature review highlights the state of the art in the numerical modelling of the suppression of fires using water-mist spray, which was subsequently validated by experiments. Water-mist spray has demonstrated efficacy as a suppression agent in extinguishing pool fires due to various extinguishment mechanisms, its non-toxic attributes, and minimal water consumption. The effectiveness of water mist in the suppression of shielded fires is of special interest, as it is a very common event in the engine room of a marine vessel.

Research gaps in modelling the suppression of fires using water-mist spray have been identified, which warrant further investigation. Particularly, (i) performing benchmark experiments on the growth and suppression of shielded fire with the measurement of HRR, (ii) investigating the capability of the CFD models to simulate fire growth and the extinguishment of fire by water-mist spray without prescribing the HRR, and (iii) identifying the trade-off between accuracy and computational-resource requirement to conduct CFD-based modelling.

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References

1. Charchalis, A.; Czyż, S. Analysis of fire hazard and safety requirements of a sea vessel engine rooms. *J. KONES Powertrain Transp.* **2011**, *18*, 49–56.
2. Bellas, R.; Gómez, M.A.; González-Gil, A.; Porteiro, J.; Míguez, J.L. Assessment of the Fire Dynamics Simulator for Modeling Fire Suppression in Engine Rooms of Ships with Low-Pressure Water Mist. *Fire Technol.* **2020**, *56*, 1315–1352. [CrossRef]
3. Allianz. *Safety and Shipping Review 2021*; Allianz Global Corporate & Specialty SE: Munich, Germany, 2021.
4. IMO. *Global Integrated Shipping Information System (GISIS)*; International Maritime Organization (IMO): London, UK, 2019.
5. Kennett, S.R.; Gamble, G.I.; Li, J. *Modelling of the HMAS Westralia Fire*; DSTO-TR-0698; Defence Science and Technology Organisation (DSTO): Melbourne, Australia, 1998.
6. Darwin, R.L.; Williams, F.W. The Development of Water Mist Fire Protection Systems for U.S. Navy Ships. *Nav. Eng. J.* **2000**, *112*, 49–57. [CrossRef]
7. Liu, Y.; Wang, X.; Liu, T.; Ma, J.; Li, G.; Zhao, Z. Preliminary study on extinguishing shielded fire with water mist. *Process. Saf. Environ. Prot.* **2020**, *141*, 344–354. [CrossRef]
8. Montreal-Protocol. The Montreal Protocol on Substances that Deplete the Ozone Layer. Available online: https://ozone.unep.org/treaties/montreal-protocol-substances-deplete-ozone-layer/text (accessed on 5 January 2024).
9. Department of Environment and Energy. *Australian Halon Management Strategy 2019*; Department of Environment and Energy, Australian Government: Canberra, Australia, 2019.
10. Burch, I. *Water Mist for Ship Machinery Spaces*; DSTO-TR-1852; Maritime Platforms Division, Defence Science and Technology Organisation: Victoria, Australia, 2006.
11. Farrell, K.; Hassan, M.K.; Hossain, M.D.; Ahmed, B.; Rahnamayiezekavat, P.; Douglas, G.; Saha, S. Water Mist Fire Suppression Systems for Building and Industrial Applications: Issues and Challenges. *Fire* **2023**, *6*, 40. [CrossRef]
12. Mawhinney, J.R.; Back, G.G., III. Water mist fire suppression systems. In *SFPE Handbook of Fire Protection Engineering*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 1587–1645.
13. *NFPA 750*; Standard for Water Mist Fire Suppression Systems. NFPA: Quincy, MA, USA, 2010.
14. Mawhinney, J.; Dlugogorski, B.; Kim, A. A closer look at the fire extinguishing properties of water mist. *Fire Saf. Sci.* **1994**, *4*, 47–60. [CrossRef]
15. Mahmud, H. *Simulation of the Suppression of Fires Using Water Mists*; Victoria University: Melbourne, Australia, 2016.
16. Julien, C.; Mauger, A.; Vijh, A.; Zaghib, K. Lithium batteries. In *Lithium Batteries*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 29–68.
17. Back, G.G., III; Beyler, C.L.; Hansen, R. A quasi-steady-state model for predicting fire suppression in spaces protected by water mist systems. *Fire Saf. J.* **2000**, *35*, 327–362. [CrossRef]
18. Ghiji, M.; Novozhilov, V.; Moinuddin, K.; Joseph, P.; Burch, I.; Suendermann, B.; Gamble, G. A review of lithium-ion battery fire suppression. *Energies* **2020**, *13*, 5117. [CrossRef]
19. Dembele, S.; Wen, J.; Sacadura, J.-F. Experimental study of water sprays for the attenuation of fire thermal radiation. *J. Heat Transf.* **2001**, *123*, 534–543. [CrossRef]
20. *MSC/Circ 1165, Revised Guidelines for the Approval of Equivalent Waterbased Fire-Extinguishing Systems for Machinery Spaces and Cargo Pump Rooms*; International Maritime Organisation: London, UK, 2005.
21. *MSC/Circ.1387. Revised Guidelines for the Approval of Fixed Water-Based Local Application Fire-Fighting Systems for Use in Category a Machinery Spaces*; International Maritime Organisation: London, UK, 2010.
22. Back, G.G.; Beyler, C.L.; Hansen, R. The Capabilities and Limitations of Total Flooding, Water Mist Fire Suppression Systems in Machinery Space Applications. *Fire Technol.* **2000**, *36*, 8–23. [CrossRef]
23. Williams, F.; Beck, G., III; DiNenno, P.; Darwin, R.; Hill, S. *Full-Scale Machinery Space Water Mist Tests: Final Design Validation*; Navy Technology Center for Safety and Survivability: Washington, DC, USA, 1999.
24. Back, G.G.; Beyler, C.L.; DiNenno, P.J.; Hansen, R.L. *Full-Scale Water Mist Design Parameters Testing*; CG-D-03-99; Coast Guard Research and Development Center: Groton, CT, USA, 1999; p. 294.
25. Adiga, K.C.; Hatcher, R.F.; Sheinson, R.S.; Williams, F.W.; Ayers, S. A computational and experimental study of ultra fine water mist as a total flooding agent. *Fire Saf. J.* **2007**, *42*, 150–160. [CrossRef]
26. Beihua, C.; Guangxuan, L.; Zhen, H. Extinction Limit of Diesel Pool Fires Suppressed by Water Mist. *J. Fire Sci.* **2009**, *27*, 5–26. [CrossRef]
27. Xu, Q.; Griffin, G.J.; Que, X.; Cao, L.; Yong, J.; Preston, C.; Bicknell, A.D.; Bradbury, G.P.; White, N. Suppress flashover of GRP fire with water mist inside ISO 9705 Room. *Therm. Sci.* **2011**, *15*, 353–366. [CrossRef]

28. Byström, A.; Cheng, X.; Wickström, U.; Veljkovic, M. Full-scale experimental and numerical studies on compartment fire under low ambient temperature. *Build. Environ.* **2012**, *51*, 255–262. [CrossRef]
29. Lal, S.; Gupta, M.; Kushari, A.; Kapoor, J.C.; Maji, S. Suppression of Pool Fire in a Large Enclosure with Water Mist. *Int. J. Spray Combust. Dyn.* **2013**, *5*, 181–200. [CrossRef]
30. Jenft, A.; Collin, A.; Boulet, P.; Pianet, G.; Breton, A.; Muller, A. Experimental and numerical study of pool fire suppression using water mist. *Fire Saf. J.* **2014**, *67*, 1–12. [CrossRef]
31. Jeong, H.J.; Gwak, J.H.; Kim, H.Y.; Park, M.H.; Jeong, J.H. Fire verification experiment study of water mist fire extinguishing system for fire suppression in diesel generator room. In Proceedings of the Korea Institute of Fire Science and Engineering Conference; Korea Institute of Fire Science and Engineering: Seoul, Republic of Korea, 2014; Volume 2014, pp. 103–104.
32. Ha, G.; Shin, W.G.; Lee, J. Numerical analysis to determine fire suppression time for multiple water mist nozzles in a large fire test compartment. *Nucl. Eng. Technol.* **2021**, *53*, 1157–1166. [CrossRef]
33. Zhu, P.; Wang, X.; Wang, Z.; Cong, H.; Ni, X. Experimental and numerical study on attenuation of thermal radiation from large-scale pool fires by water mist curtain. *J. Fire Sci.* **2015**, *33*, 269–289. [CrossRef]
34. Chiu, C.-W.; Li, Y.-H. Full-scale experimental and numerical analysis of water mist system for sheltered fire sources in wind generator compartment. *Process. Saf. Environ. Prot.* **2015**, *98*, 40–49. [CrossRef]
35. Zhang, P.; Tang, X.; Tian, X.; Liu, C.; Zhong, M. Experimental study on the interaction between fire and water mist in long and narrow spaces. *Appl. Therm. Eng.* **2016**, *94*, 706–714. [CrossRef]
36. White, J.P.; Verma, S.; Keller, E.; Hao, A.; Trouvé, A.; Marshall, A.W. Water mist suppression of a turbulent line fire. *Fire Saf. J.* **2017**, *91*, 705–713. [CrossRef]
37. White, J.P.; Link, E.D.; Trouvé, A.; Sunderland, P.B.; Marshall, A.W. A general calorimetry framework for measurement of combustion efficiency in a suppressed turbulent line fire. *Fire Saf. J.* **2017**, *92*, 164–176. [CrossRef]
38. White, J.P.; Vilfayeau, S.; Marshall, A.W.; Trouvé, A.; McDermott, R.J. Modeling flame extinction and reignition in large eddy simulations with fast chemistry. *Fire Saf. J.* **2017**, *90*, 72–85. [CrossRef]
39. Jenft, A.; Boulet, P.; Collin, A.; Trevisan, N.; Mauger, P.-N.; Pianet, G. Modeling of fire suppression by fuel cooling. *Fire Saf. J.* **2017**, *91*, 680–687. [CrossRef]
40. Lee, J. Numerical analysis on the rapid fire suppression using a water mist nozzle in a fire compartment with a door opening. *Nucl. Eng. Technol.* **2019**, *51*, 410–423. [CrossRef]
41. Ren, N.; Meredith, K.V.; Yu, H.Z.; Zhou, X.; Wang, Y.; Dorofeev, S.B. Water Mist Fire Suppression Modeling of Rack Storage Fires in Open Space. In *Proceedings of the 11th Asia-Oceania Symposium on Fire Science and Technology, 22–24 October, Taipei, Taiwan*; Wu, G.Y., Tsai, K.C., Chow, W.K., Eds.; Springer: Singapore, 2018; pp. 767–779.
42. Bu, R.; Yang, H.; Xie, Y.; Zhao, W.; Fan, C.; Guo, Z.; Zhou, Y. Application of the high-pressure water mist system in a railway tunnel rescue station. *Therm. Sci. Eng. Prog.* **2022**, *35*, 101467. [CrossRef]
43. Abu Bakar, A.S.; Cran, M.; Wadhwani, R.; Moinuddin, K.A.M. Characterisation of pyrolysis and combustion parameters of charring materials most frequently found in buildings. *J. Therm. Anal. Calorim.* **2020**, *139*, 2985–2999. [CrossRef]
44. Moinuddin, K.A.; Nguyen, T.D.; Mahmud, H. Designing an experimental rig for developing a fire severity model using numerical simulation. *Fire Mater.* **2017**, *41*, 871–883. [CrossRef]
45. Gorokhovski, M.; Herrmann, M. Modeling primary atomization. *Annu. Rev. Fluid Mech.* **2008**, *40*, 343–366. [CrossRef]
46. Bong, C.H. Numerical and Experimental Analysis of Diesel Spray Dynamics Including the Effects of Fuel Viscosity. Ph.D. Thesis, University of Tasmania, Tasmania, Australia, 2010.
47. Kaario, O.; Vuorinen, V.; Hulkkonen, T.; Keskinen, K.; Nuutinen, M.; Larmi, M.; Tanner, F.X. Large Eddy Simulation of High Gas Density Effects in Fuel Sprays. *At. Sprays* **2013**, *23*, 297–325. [CrossRef]
48. Vuorinen, V.; Yu, J.; Tirunagari, S.; Kaario, O.; Larmi, M.; Duwig, C.; Boersma, B.J. Large-eddy simulation of highly underexpanded transient gas jets. *Phys. Fluids (1994-Present)* **2013**, *25*, 016101. [CrossRef]
49. Trouvé, A.; Wang, Y. Large eddy simulation of compartment fires. *Int. J. Comput. Fluid Dyn.* **2010**, *24*, 449–466. [CrossRef]
50. McGrattan, K.; Miles, S. Modeling fires using computational fluid dynamics (CFD). In *SFPE Handbook of Fire Protection Engineering*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 1034–1065.
51. Vilfayeau, S.; Myers, T.; Marshall, A.W.; Trouvé, A. Large eddy simulation of suppression of turbulent line fires by base-injected water mist. *Proc. Combust. Inst.* **2017**, *36*, 3287–3295. [CrossRef]
52. Lee, J. Numerical analysis of how ventilation conditions impact compartment fire suppression by water mist. *Ann. Nucl. Energy* **2020**, *136*, 107021. [CrossRef]
53. Lee, J.; Moon, J. Numerical analysis of the effect of horizontal distance between a water mist nozzle and ignition source on reduction in heat release rate. *Ann. Nucl. Energy* **2020**, *144*, 107560. [CrossRef]
54. Hamzehpour, A.; Verda, V.; Borchiellini, R. CFD Modeling of Water Mist Systems for Suppressing Shielded fires in Enclosures Using FDS. In Proceedings of the 21st International Water Mist Conference, Madrid, Spain, 9–10 November 2022.
55. McKeen, L.W. Introduction to Permeation of Plastics and Elastomers. In *Permeability Properties of Plastics and Elastomers*, 4th ed.; McKeen, L.W., Ed.; William Andrew Publishing: Norwich, NY, USA, 2017; pp. 1–19.
56. Vilfayeau, S. *Large Eddy Simulation of Fire Extinction Phenomena*; University of Maryland: College Park, MD, USA, 2015.
57. Ren, N.; Zeng, D.; Meredith, K.V.; Wang, Y.; Dorofeev, S.B. Modeling of flame extinction/re-ignition in oxygen-reduced environments. *Proc. Combust. Inst.* **2019**, *37*, 3951–3958. [CrossRef]

58. Lecoustre, V.; Narayanan, P.; Baum, H.R.; Trouve, A. Local extinction of diffusion flames in fires. In *Fire Safety Science-Proceedings of the Tenth International Symposium*; University of Maryland: College Park, MD, USA, 2011; Volume 10, pp. 583–595.
59. Roache, P.J. Perspective: A Method for Uniform Reporting of Grid Refinement Studies. *J. Fluids Eng.* **1994**, *116*, 405–413. [CrossRef]