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A REVIEW OF THE RESEARCH AND APPLICATION OF WATER MIST FIRE SUPPRESSION SYSTEMS – FUNDAMENTAL STUDIES

Zhigang Liu and Andrew K. Kim

ABSTRACT

The progress on the research and application of water mist systems in fire suppression has been substantial over the last decade. To bring this work into focus, a review has been undertaken to identify future developments and potential efficacy improvements for water mist fire suppression systems. This paper, as a first step, provides a review of the fundamental research in water mist fire suppression systems. This includes a review of extinguishing mechanisms and the factors that influence the performance of water mist, such as spray characteristics, enclosure effects, dynamic mixing, the use of additives and methods of generating water mist. Recent studies on the use of computer modelling for the development of water mist fire suppression systems are also reviewed and discussed.

The review shows that the extinguishing mechanisms and the role of spray characteristics in fire suppression have become well understood and identified. Water mist does not behave like a "true" gaseous agent in fire suppression. The effectiveness of a water mist system in fire suppression is dependent on spray characteristics (the distribution of droplet sizes, flux density and spray dynamics) with respect to the fire scenario (shielding of the fuel, fire size and ventilation conditions). Other factors, such as enclosure effect and the dynamic mixing created by the discharge of water mist, also affect the performance of water mist in fire suppression. A combination of experimental and computational modelling studies with validation by fire tests will make the development of water mist systems much more efficient and effective.

1.0 INTRODUCTION

The term "water mist" refers to fine water sprays in which 99% of the volume of the spray is in drops with diameters less than 1000 microns [1]. The use of water mist in fire suppression, compared to the use of gaseous agents and conventional sprinkler systems, has demonstrated advantages including the following:

(1) no toxic and asphyxiation problems;
(2) no environmental problems;
(3) low system cost;
(4) limited or no water damage; and
(5) high efficiency in suppressing certain fires.

The study and description of the fundamental principles of extinguishment of liquid and solid fuel fires by water mist can be traced back to the mid-1950s [2]. Research continued to be carried out during the 1960s and 1970s at university, industry and government research facilities [3-11]. These early studies focused on the extinguishing mechanisms of water mist and the optimum droplet parameters for efficient fire suppression. It was shown that water mist with fine sprays was very efficient in controlling liquid and solid fuel fires, and suppressing hydrocarbon mist explosions [12]. At the same time, however, Halon 1301 and 1211, the most effective chemical fire suppressants ever developed, were introduced. The application of water mist to fire suppression was, therefore, not considered practical until the recent requirement to phase out halon agents due to their negative environmental effects.

Over the last decade, studies on water mist technology have significantly increased. A survey carried out by Mawhinney and Richardson [13] in 1996 indicated that nearly 50 agencies around the world are involved in the research and development of water mist fire suppression systems, ranging from theoretical investigations into extinguishing mechanisms and computer modelling to the development, patenting and manufacturing of mist-generating equipment. These recent studies have shown that water mist technologies have the potential either to replace current fire protection techniques that are no longer environmentally acceptable, or to provide new answers to problems where traditional technologies have not been as effective as desired [13-23].

In order to identify future developments and potential efficacy improvements for water mist fire suppression systems, there is a need to review the progress that has been made on water mist technology over the last few years. This paper, as a first step, provides a review of the fundamental research in water mist fire suppression systems, including mechanisms of extinguishment, spray characteristics, methods of generating water mist and some factors that influence performance of water mist, such as the enclosure effect and dynamic mixing. Recent studies on the use of computer modelling for the development of water mist systems are also reviewed and discussed.

2.0 EXTINGUISHING MECHANISMS

Water has favourable physical properties for fire suppression. Its high heat capacity (4.2 J/g•K) and high latent heat of vaporization (2442 J/g) can absorb a significant quantity of heat from flames and fuels. Water also expands 1700 times when it evaporates to steam, which results in the dilution of the surrounding oxygen and fuel vapours. With the formation of fine droplets, the effectiveness of water in fire suppression is further increased due to the significant increase in the surface area of water that is available for heat absorption and evaporation. Such an increase in the surface area of water is shown in Table 1 for a given volume of water (0.001 m^3).

Water mist in fire suppression, however, does not behave like a “true” gaseous agent. When water is injected into a compartment, not all the sprays that are formed are directly involved in fire suppression. They are partitioned into a number of fractions as follows [24]:

(1) Droplets that are blown away before reaching the fire;

(2) Droplets that penetrate the fire plume, or otherwise reach the burning surfaces under the fire plume, to inhibit pyrolysis by cooling, and the resultant steam that dilutes the available oxygen;
(3) Droplets that impact on the walls, floor and ceiling of the compartment and cool them, if they are hot, or otherwise run-off to waste;
(4) Droplets that vaporize to steam while traversing the compartment and contribute to the cooling of the fire plume, hot gases, compartment and other surfaces;
(5) Droplets that pre-wet adjacent combustibles to prevent fire spread.

Braidech and Rasbash in their early studies [2, 3] identified two mechanisms by which water mist extinguishes fires: displacement of oxygen and heat extraction, resulting from the evaporation of water mist in the area surrounding the fire. Research conducted to date has not altered the accuracy of such extinguishing mechanisms. Recent studies, however, suggest that there are additional mechanisms in fire suppression using water mist. For example, Wighus [25, 26] suggested that a reduction of fuel evaporation is another extinguishing mechanism, together with cooling and diluting of the fire. Mawhinney et al [27, 28] further suggested that radiant heat attenuation, the kinetic effect of water mist on the flame, and fuel vapour/air dilution by entrained air are additional extinguishing mechanisms. They classified the extinguishing mechanisms of water mist in fire suppression as primary and secondary mechanisms [28], which can be summarized as follows:

Primary mechanisms:
(1) heat extraction
  - cooling of fire plume
  - wetting/cooling of the fuel surface
(2) displacement
  - displacement of oxygen
  - dilution of fuel vapour
Secondary mechanisms:
(1) radiation attenuation
(2) kinetic effects

2.1 Heat Extraction (Cooling)

The cooling mechanisms of water mist for fire suppression can be divided broadly into cooling of the fire plume and wetting/cooling of the fuel surface. Flame cooling by water mist is attributed primarily to the conversion of water to steam that occurs when a high percentage of small water droplets enter a fire plume and rapidly evaporate. A fire will be extinguished when the adiabatic flame temperature is reduced to the lower temperature limit, resulting in the termination of the combustion reaction of the fuel-air mixture. For most hydrocarbons and organic vapours, this lower temperature limit is approximately 1600 K (1327°C) [29].

Rasbash has calculated the efficiency of water for flame cooling [30]. It was found that when all the water is vaporized to steam, the heat absorption required for fire extinction can be halved, in comparison to condensed steam or partly vaporized water. With the formation of fine droplets, the surface area of the water mass and the speed at which the spray extracts heat from the hot gas and flame are significantly increased. As indicated by Kanury [31] and Herterich [32], the rate of vaporization of a droplet depends on: 1) surrounding temperatures; 2) the surface area of the droplet; 3) the heat transfer coefficient; and 4) the relative velocity of the droplet in relation to the surrounding gas. For droplets of $100\ \mu m < d < 1000\ \mu m$, the heat transfer coefficient, H, is directly related to the size of the droplet and can be expressed as [32]:

$$H = \frac{0.6}{d} K \Pr^{1.5} \mathrm{Re}^{0.5} \tag{1}$$

where d is the diameter of the droplet, K is the thermal conductivity of air, Pr is the Prandtl number and Re is the Reynolds number.

Various attempts have been made to establish a design relationship between the fire size and the amount of water needed to cool the fire enough for extinguishment. Wighus [33] introduced the concept of the Spray Heat Absorption Ratio (SHAR) in a study of the extinguishment of propane fires by water mist. SHAR was defined as the ratio of the heat absorbed by the spray (Q_{water}) to the heat released by the fire (Q_{fire}):

$$SHAR = \frac{Q_{water}}{Q_{fire}} \tag{2}$$

It was found that the value of SHAR or the heat absorption rate of water needed for fire extinguishment varied substantially with the fire scenarios encountered, because the efficiency of delivery of water mist into flame was almost unpredictable. For an unconfined propane flame, the value of SHAR was as low as 0.3 under optimum conditions while the value was in the range of 0.6 for more ‘realistic’ machinery space conditions due to small fires in shielded areas.

A fire will also be extinguished when the fuel is cooled below its fire point by removing heat from the fuel surface, or when the concentration of the vapour/air mixture above the surface of the fuel falls below the lean flammability limit due to the cooling. In order to cool the fuel surface, a spray must penetrate the flame zone to reach the fuel surface and then remove a certain amount of heat from the fuel surface at a higher rate than the flame can supply it. It is recognized that heat is mainly transferred from the flame to the fuel by convection and radiation, while fuel cooling by water mist is primarily due to the conversion of water to steam. Thus, the heat rate per unit area that must be removed by water for fire suppression is given by [30]:

$$S_h = (H_f - \lambda_f)\dot{m}_b + R_a - R_s \tag{3}$$

where S_h is heat removed per unit area by water spray, H_f is convective heat transfer from flames per unit mass of fuel entering flames, λ_f is heat required to produce a unit mass of vapour, $\dot{m}_b$ is burning rate per unit area, R_a is other forms of heat transfer to the fuel surface and R_s is heat lost from the surface not included in λ_f (e.g., radiant heat loss).

Fuel wetting/cooling by water mist also reduces the pyrolysis rate of the fuel and prevents re-ignition when the fuel is cooled down. For fuels whose low flash points are above normal ambient temperature, more water sprays are needed to cool the fuel surface, because less heat is required to produce fuel vapour. Also, more water sprays are needed to prevent re-ignition of a hot, deep-seated fire. The wood crib and slab tests carried out by Tamanini [34] showed that the risk of re-ignition is greater for higher water application rates, if spraying is stopped as soon as the flames go out. This is because higher water flow rates extinguish the fire faster, but the fuel remains hot and continues to pyrolize if the water is switched off immediately after extinction.

Fuel wetting/cooling by water mist may be the predominant extinguishment mechanism for fuels that do not produce combustible mixtures of vapour above the fuel surface [35]. The primary combustion reaction with this type of fuels, such as solid fuels, occurs within the carbon-rich zone that forms on the fuel surface. Hence, cooling of the diffusion flame above an established char zone of solid fuel may not be enough to achieve suppression [28]. Water mist must be applied to cool the fuel surface either before a deep char zone has developed, or water droplets must penetrate the char zone to reach the actual interface between the burned and unburned fuel.

2.2 Oxygen Displacement

Oxygen displacement can occur on either a compartmental or localized scale [35]. On a compartmental scale, the oxygen concentration in the compartment can be substantially reduced by the rapid evaporation and expansion of fine water droplets to steam, when water mist is injected into a hot compartment and absorbs heat from the fire, hot gases and surfaces. Calculation results showed that oxygen concentration in a room with a volume of 100 m^3 could decrease approximately 10%, when 5.5 liters of water is completely converted into steam [36].

The reduction of the oxygen concentration in a compartment by water mist is a function of the fire size, the length of pre-burn period, the volume of the compartment and the ventilation conditions in the compartment. As the fire size or the length of the pre-burn period of the fire increases, both the oxygen depletion due to the fire and the oxygen displacement due to the formation of more water vapour caused by high compartment temperatures are increased. This combined effect significantly reduces the oxygen concentration in the compartment and enhances the effectiveness of water mist for fire suppression.

On a localized scale, when the water sprays penetrate into the fire plume and are converted to vapour, the vaporizing water expands to 1700 times its liquid volume. The volumetric expansion of the vaporizing water disrupts the entrainment of air (oxygen) into the flame and dilutes the fuel vapour available for combustion of the fuel. As a result, when the fuel vapour is diluted below the lower flammable limit of the fuel-air mixture, or when the concentration of oxygen necessary to sustain combustion is reduced below a critical level, the fire will be extinguished.

Water vapour as an inert agent in fire suppression has been widely studied. Rosander and Giselsson [36] described the process of extinguishing a fire by the formation of steam as "indirect extinguishment." They recommend a 35% mixture of water in the surrounding gas to extinguish the fire by steam formation. From an analysis of computer modelling, Dlugogorski et al [37] indicated that, for effective suppression, the required concentrations of water vapour in the mixture of flammable gases vary with the surrounding temperatures and reach 36% and 44% for surrounding temperatures of 100°C and 300°C, respectively.

The impact of oxygen dilution by water mist on fire suppression is strongly dependent on the properties of the fuel [28]. This is because the minimum amount of free oxygen required to support combustion varies with the type of fuel. For most hydrocarbon fuels, the critical oxygen concentration for maintaining combustion is approximately 13% [29]. For solid fuels, the critical oxygen concentration required for combustion is even lower.

2.3 Radiant Heat Attenuation

When water mist envelops or reaches the surface of the fuel, water can act as a thermal barrier to prevent further heating by radiation of the burning fuel surface as well as non-burning surfaces [38-40]. Also, water vapour in the air above the fuel surface acts as a gray body radiator that absorbs radiant energy, and re-radiates it to the fuel surface at a reduced intensity. Blocking radiant heat by water mist stops the fire from spreading to unignited fuel surfaces and reduces the vaporization or pyrolysis rate at the fuel surface.

Experimental tests conducted at the National Research Council of Canada [27] showed that the radiant flux to the walls of a test compartment was reduced by more than 70% by the activation of the water mist system. The calculation conducted by Log [40] also showed that given a spray load of 100 g/m^3 and a 1 m path length, a spray on the borderline between Class 1 and Class 2 ($D_{v0.1}$= 100 µm and $D_{v0.9}$ =200 µm) is capable of blocking about 60% of the radiant heat from a black body at the temperature of 800^{o}C.

It has been shown that the attenuation of radiation depends very much on drop diameter and mass density of the droplets. A given volume of water will provide a more efficient barrier against radiation if it is made up of very small droplets in a dense spray, than a dilute spray with larger droplets. The calculation carried out by Ravigururajan and Beltran [38] showed that, to achieve the same radiation attenuation at the object temperature of 650 K, the mass density of the 100 micron droplets had to be 10 times larger than that of the 10 micron droplets. The wavelength of the radiation, however, is also important in determining the radiation attenuation of water mist. The spray will absorb more radiation if the droplet diameters are close to the wavelength of the radiation.

For non-burning fuel, water droplets wet the fuel surface, preventing further heating by radiation and reducing the risk of ignition. In order to prevent ignition of the non-burning fuel by radiation, the minimum water flow required can be calculated by using the following equation [24]:

$$\frac{F_m}{A_s} = \frac{\varepsilon \times \sigma \times \phi \times (T_r^4 - T_s^4) - I_c}{H_{vap}} \tag{4}$$

where F_m is minimum water flow rate, A_s is fuel surface area, ε is emmissivity of the radiator, σ is Stefan-Boltzman constant, ϕ is view factor to the fuel bed, T_r is mean absolute temperature of the radiation source, T_s is mean absolute temperature of the surface, I_c is critical radiation intensity required for piloted ignition and H_{vap} is heat of vaporization of water.

2.4 Kinetic Effects of Water Mist on Flames

Experimental tests carried out by Mawhinney [41], and Jones and Thomas [42] showed that when "under-designed" water mist systems failed to extinguish a liquid fuel pool fire, the heat release rate of the fire was higher than that of a fire without the suppression by water mist. Mawhinney [1] indicated that the increase in the heat release rate of the fire may result from kinetic effects of water mist on flames.

A momentary increase in the liquid pool fire size was also observed at the beginning of the water mist discharge in the case of successful fire extinguishment [43, 44]. This increase in fire size, however, is attributed to the enlarged flame surface caused by the impingement of water sprays, as water mist impinged the pool flame and increased the mixing area between the oxidizer and the fuel.

Suh and Atreya [45, 46] conducted both experimental and theoretical studies on the effect of water vapour on the combustion of the fuel-air mixture. Their studies showed that, although the fire extinguishment by water is mainly due to the physical effects, the addition of water vapour to the fuel-air mixture could result in an increase in the flame temperature, CO_2 production rate and O_2 depletion rate as well as a decrease in CO and soot production rate. These effects are due to the water vapour enhancing chemical reactions inside the flames. As the water vapour concentration is increased in the flame, the OH radical concentration increases, resulting in an increase in flame temperature and CO_2 production rate. After the addition of approximately 30% of the water vapour in the fuel-air mixture, however, the chemical enhancement of the flame by water vapour was not observed and the flame temperature began to decrease.

3.0 FACTORS THAT AFFECT WATER MIST PERFORMANCE

It has been recognized that although all the extinguishing mechanisms of water mist are involved to some degree in fire extinguishment, only one or two mechanisms play a predominant role [28]. Which suppression mechanism is dominant, depends on the characteristics of the water mist, fire scenarios, compartment geometry and ventilation conditions. Many other factors, such as the enclosure effect, dynamic mixing created by water mist discharge, types of water mist systems applied (total or local application) and the use of additives and discharge modes, have important impacts on the effectiveness of water mist in fire suppression [35, 47, 48].

3.1 Water Mist Characteristics

The effectiveness of a water mist system in suppressing a fire is directly related to the spray characteristics produced by the nozzles. Rasbash [30], in his early study, gave a detailed list of the important parameters of water sprays for fire suppression. These are:

(1) mean flow rate per unit area in the fire region;
(2) distribution of flow rate in and about the fire area;
(3) direction of application;
(4) droplet size and distribution;
(5) entrained air velocity; and
(6) droplet velocity relative to entrained air, flame velocity, and fuel types.

Although these important spray parameters can be used to describe the characteristics of water mist in fire suppression, they can be further broadly classified as three main parameters: droplet size distribution, flux density and spray momentum [1]. These three main parameters of water mist not only directly determine the effectiveness of the water mist for fire suppression but also potentially determine the nozzle spacing as well as the ceiling height limitation for a given installation.

3.1.1 Droplet Size Distribution

Droplet size distribution refers to the range of droplet sizes contained in representative samples of a spray or mist cloud measured at specified locations. NFPA 750 [49] has divided the droplets produced by a water mist system into three classes to distinguish between "coarser" and "finer" droplet sizes within the 1000 micron window. The classifications are: Class 1 mist has 90% of the volume of the spray ($D_{v0.9}$) within drop sizes of 200 microns or less; Class 2 mist has a $D_{v0.9}$ of 400 microns or less; and Class 3 mist has a $D_{v0.9}$ value larger than 400 microns.

In theory, small droplets are more efficient in fire suppression than large droplets, because of their larger total surface area available for evaporation and heat extraction. They are more effective in radiation attenuation [38]. Also, small droplets have longer residence times, allowing them to be carried by air currents to remote or obstructed parts of an enclosure. They can exhibit more gaseous-like behaviour and superior mixing characteristics. However, it is very difficult for small droplets to penetrate into the fire plume and to reach the fuel surface due to the drag and the hydrodynamic effect of the fire plume. Fine droplets with low momentum are easily carried away from the fire by air currents. In addition, more energy is required to produce fine droplets and transfer them to the fire.

Large droplets can penetrate the fire plume easily to provide direct impingement, and to wet and cool the combustibles. However, large droplets have smaller total surface areas available for heat extraction and evaporation. The capability of water mist in suppressing obstructed/shielded fires is reduced as the size of the droplets is increased. As well, large droplets with high velocities can cause liquid fuels to be splashed, resulting in an increase in fire size.

A wide range of experimental tests under different fire conditions [50, 51] was carried out to identify the optimum droplet size for fire suppression. Andrews [52] summarized the optimum droplet sizes suggested by various authors, as shown in Table 2. It can be seen that the optimum size of droplets for fire suppression is strongly dependent on many factors, such as the properties of the combustibles, the degree of obstruction in the compartment, and the size of the fire. The droplet size distribution that is most effective in extinguishing one fire scenario will not necessarily be the best for other scenarios. There is no one-size distribution to fit all fire scenarios. Actually, the performance of water mist with a well-mixed distribution of fine and coarse droplets is better than that with a uniform droplet size [1, 41]. Furthermore, any changes in fire size, spray velocity (momentum) and enclosure effects will change the optimum droplet size for fire suppression.

3.1.2 Flux Density

Spray flux density refers to the amount of water spray in a unit volume (Lpm/m^3) or applied to a unit area (Lpm/m^2) [1]. On a compartmental scale, the increase in the flux density will reduce the compartment temperature but will have little effect on the oxygen concentrations in the compartment [47]. On a localized scale, however, the fire is extinguished only when water sprays achieve a minimum flux density. Without sufficient flux density of water sprays to remove a certain amount of heat from a fire or to cool the fuel below its fire point, the fire can sustain itself by maintaining high flame temperature and high fuel temperature.

Since water mist does not behave like a “true” gaseous agent, it is difficult to establish the "critical concentration" of water droplets required to extinguish a fire (i.e., the minimum total mass of water in droplets per unit volume or per unit area for fire suppression) [1, 21, 52]. The amount of mist reaching the fire is determined by many factors. These include the spray momentum and angle, shielding of the fuel, fire size, ventilation conditions and compartment geometry.

In addition, current spray technology and corresponding nozzle allocation in the compartment cannot provide a uniform flux density of the spray. The flux density distribution of water mist within a single nozzle spray cone is non-homogeneous. Some types of nozzles for the production of water mist concentrate a high percentage of the water spray into the centre of the cone area while other types of nozzles may have less water mist concentration at the centre area [41, 47]. When spray cones from a group of nozzles overlap, the flux densities at any point are also different from those observed with a single nozzle due to the dynamics of spray interaction.

Andrews [52] has compared the minimum flow rates required for extinguishing solid fuel fires suggested by 19 authors. It was found that these minimum flow rates varied widely with application conditions and no "critical concentration" of water sprays could fit all applications.

3.1.3 Spray Momentum

Spray momentum refers to the spray mass, spray velocity and its direction relative to the fire plume. The spray momentum determines not only whether the water droplets can penetrate into the flame or reach the fuel surface, it also determines the entrainment rate of surrounding air into the fire plume. The turbulence produced by the spray momentum mixes fine water droplets and water vapour into the combustion zone, which dilutes the oxygen and fuel vapour and increases the extinguishing efficiency of water mist in fire suppression. The spray mass defined in the momentum of the spray, therefore, not only includes the mass of liquid-phase water but also includes the mass of vapour-phase water and air entrained by water mist [35]. The momentum of the spray, M_w, can be expressed as follow:

$$M_w = (m_{wl} + m_{wv} + m_{wa}) \times V_w \qquad (5)$$

where m_{wl}, m_{wv}, and m_{wa} are mass of liquid-phase water, vapour-phase water and air entrained by mist, respectively, and V_w is associated to the velocity vector of water mist.

Water spray momentum is determined by many factors. These include droplet size and velocity, discharge pressure and cone angle, the spacing of nozzles, ventilation conditions and the compartment geometry [35]. In addition, the spray momentum will gradually decrease, as fine water droplets travel through hot gas and the droplet velocity and size are reduced due to gravitational and drag forces on the droplets with the evaporation [53]. The distance (X_o) from the nozzle which water droplets must travel before falling in the air, is determined by spray momentum and discharge cone angle (ϑ) [53].

When water droplets fall in the air due to gravitational force, the maximum falling distance of the droplets is mainly controlled by droplet size and surrounding temperature, before they disappear into the hot gas due to the evaporation. Such maximum falling distance (X_{fall}), without considering the upward velocity produced by the fire, is given by [53]:

$$X_{fall} = 2000\frac{D_o L\rho}{2K_g \Delta T C_2} \qquad (6)$$

where D_o is the droplet diameter, L is the Latent heat of vaporisation, ρ is the surrounding density, ΔT is the temperature difference between the droplet and surroundings and C_2 is the coefficient.

Table 3 lists the typical falling distances for droplets with different sizes at different surrounding temperatures [53]. The falling distances are significantly reduced with the droplet size and with the increase in the surrounding temperature. Hence, with a high ceiling, the momentum of fine water droplets will become very small before they reach the fire. Such fine water sprays with low momentum will not penetrate the strong upward fire plume to reach the region of the fuel surface, resulting in failure to suppress the fire.

To avoid having the mist (and the water vapour) carried away by the fire plume, the momentum of the mist must be at least equal in magnitude, and opposite in direction, to the momentum of the fire plume [35]. This relationship is given by:

$$M_{wy} \geq M_{fy} \qquad (7)$$

where M_{wy} and M_{fy} are the 'y' component of water mist and fire plume momentums, respectively.

The fire plume momentum, M_f, can be expressed as follow [35]:

$$M_f = (m_{fp} + m_{fg} + m_{fg}) \times V_f \qquad (8)$$

where m_{fp}, m_{fg}, and m_{fa} are mass of combustion products, fire gases and air entrained by the fire plume, respectively, and V_f is associated to the velocity vector of the fire plume.

Spray momentum is also particularly important for zoned water mist fire suppression systems and for fires with a high degree of obstruction. For such fire challenges, water mist must be directly discharged onto the fire and extinguish it by flame and fuel cooling. Recent experimental tests conducted by Kim et al [54], for the protection of electrical equipment by water mist, showed that effective fire suppression was achieved only by exercising rigorous control over spray direction by laying out nozzles to suit the physical arrangement of the obstructions or structural elements.

3.2 Enclosure Effects

When a fire occurs in an enclosed compartment, the room is heated and the oxygen concentration in the compartment is gradually reduced. In addition, the hot gases from the fire tend to concentrate near the ceiling. With the discharge of water mist downward from ceiling level, a maximum amount of water is converted to vapour and displaces oxygen and fuel vapour around the fire, as fine water droplets quickly absorb heat from their hot surroundings [55]. The capability of the compartment to capture heat and confine combustion products and water vapour has an important impact on the extinguishing performance of water mist, which is described as "enclosure effects" in fire suppression [1, 35, 56]. With enclosure effects, it is possible to extinguish even shielded fires with low-momentum sprays in heavily obstructed compartments. The flux density required for extinguishment can be as much as 10 times lower than that required for unconfined and well-ventilated fires [57].

The degree of "enclosure effects" in fire suppression is mainly dependent on the fire size in relation to the compartment size. 'Large' and 'small' fires are defined loosely in terms of whether the fire will affect the average temperature and oxygen concentrations in the compartment within the activation time of the water mist system [28]. A 'large' fire reduces the ambient oxygen concentration to the point that the combustion efficiency of the fire is reduced, prior to introducing water mist. A 'large' fire also releases more heat in the compartment to evaporate the fine water droplets, and further reduces the oxygen concentration in the compartment. With the enclosure effect, the main extinguishing mechanism of water mist for 'large' fires is oxygen displacement. Test results have shown that, in a compartment with large fires, small fires in a cabinet with a low ventilation rate were also extinguished by water mist due to the depletion of oxygen in the compartment by fires and steam. The extinguishing times were significantly reduced with the increase in the fire size [43, 47].

For a 'large' fire challenge, the use of a Total Compartment Application (TCA) Water Mist System can quickly extinguish fires with low flux densities. This is because the use of a TCA water mist system maximizes the benefits of oxygen depletion and fuel vapour dilution for fire suppression by combining vitiated combustion products with a large amount of water vapour.

When the fine droplets are discharged into a very hot enclosure due to the existence of large fires, however, the rapid cooling by water mist will result in an overall negative pressure inside the compartment, because the hot air or gases contract faster than the steam can expand [26, 43]. The very high negative pressure produced could cause some damages to the compartment, such as the implosion of double-glazed windows, and lead to fresh air being drawn into the room [26, 43]. The cooling effect of water mist on the room pressure must be carefully assessed when designing a system for a "large" fire challenge.

With 'small' fires in the compartment, however, less heat and combustion products are released. The reduction in oxygen concentration and the increase in gas temperature in the compartment are small prior to the activation of the water mist system [43]. The "enclosure effect" no longer has important effect on the extinguishing performance of water mist, because less heat, water vapour and vitiated gases are available for confinement. The extinguishment of a 'small' fire by water mist will depend almost entirely on direct fire plume or fuel cooling. Water mist must be discharged directly on the fire. For 'small' fire challenges, the use of a Local Application (LA) water mist system might extinguish the fire more efficiently.

3.3 Dynamic Mixing

During water mist discharge, strong dynamic mixing is produced in the compartment, as the discharge of water mist entrains surrounding gases and pushes the combustion products and water vapour in the hot layer near the ceiling downward to mix with the gases near the floor of the compartment [43]. The dynamic mixing created by water mist discharge reduces oxygen concentration in the lower portion of the compartment and increases the convective mixing of mist, water vapour and combustion gases near the fire, resulting in the enhancement of the mist's extinguishing capability. The gas concentrations (O_2, CO_2, CO, etc.) and temperatures throughout the compartment tend to be uniform after water mist discharge.

Test results showed that a water mist system in which the nozzles were directly below the compartment's overhead had a better extinguishing performance than a system whose nozzles were 2 m below the overhead or whose nozzles were vertically installed on the side wall [58]. This is because the water mist system whose nozzles were near the ceiling could effectively produce more water vapour in the hot layer and redirect the vitiated gases and water vapour near the ceiling back to the fires by dynamic mixing. Test results also showed that a water mist system that could produce strong dynamic mixing in the compartment performed better against fires under ventilation conditions than a system that could not produce strong dynamic mixing, leading to short extinguishing time and less water required for fire suppression [59]. Another example is a water mist system developed by Marioff for the protection of a gas turbine enclosure where only two nozzles are installed in the compartment, one located near the ceiling and the other located near the floor [60]. It is claimed that such a configuration can increase the dynamic mixing in the compartment and enhance the extinguishing capability of water mist.

Recent research showed that the cycling discharge, i.e., the on/off action of water spray discharge, could substantially improve the efficacy of water mist in fire suppression [43, 61]. In comparison with the continuous application of mist, the use of the cycling discharge mode achieved rapid extinguishment and used less water. In some cases, the water requirement was one-third and the time to extinguish the fire was one-half that of the continuous discharge. The use of cycling discharge also improved the water mist's capability against fires under ventilation conditions [59]. One important factor for the improvement of the mist's extinguishing capability was that using the cycling discharge created a strong recurrent dynamic mixing in the compartment [61], increasing the convective mixing of mist, water vapour and combustion gases near the fire.

The degree of dynamic mixing in the compartment created by water mist discharge is determined by spray characteristics (e.g., spray momentum, velocity), the nozzle characteristics (pressure, cone angle), the spacing of nozzles, the nozzle configuration in the compartment, the ventilation conditions and the compartment's volume. The ability to influence convective mixing in a compartment is a design parameter that can be deliberately worked into the design of a water mist system [35]. However, it is not clear yet how to design a water mist system that achieves the optimum dynamic mixing in the compartment. This may be achieved by the application of a computational fluid dynamics (CFD) field model.

3.4 Water Mist with Additives

Using additives in the water mist system or combining water mist with inert gases and gaseous agents may improve the efficacy of water mist in fire suppression through chemical or physical means. It may also affect the droplet vaporization and generation processes by reducing surface tension or acting as a wetting agent.

Recent test results showed that water mist made with "sea water" (2.5% by weight sodium chloride solution) and the addition of a low percentage of a film-forming agent (e.g., 0.3% AFFF) greatly improved the effectiveness of water mist for suppressing hydrocarbon pool fires [62]. Water mist with "Firestop 107" was also effective for suppressing spill fires in bilge areas that were sheltered from the water sprays or for extinguishing a fire that pure water mist was unable to extinguish [25].

With the proper additives in water, not only the problem of freezing water could be avoided but also the fire suppression effectiveness of water mist could be improved [63-65]. This increases the potential application of water mist for the protection of aircraft engine nacelles and combat vehicles.

In addition, water mist systems can be combined with other gas agents for fire extinguishment. Test results showed that the firefighting capabilities of a water mist system could be increased by substituting nitrogen or other inert gases for air as the second fluid [1, 21].

When water mist was used in conjunction with a gaseous agent, such as FM-200 and Halon 1301 [66], the use of water mist, whether initiated at the same time, prior to or later than the discharge of gaseous agents, could enhance the performance of the gaseous agents in preventing re-ignition of the combustibles. The combination of a gaseous agent with water mist also significantly reduced the level of acid decomposition products generated in a fire. The initiation of the water mist system one minute prior to agent discharge limited HF generation to a peak value of 200 ppm, compared to values over 4000 ppm for tests without the discharge of water mist. As well, the overhead temperature was reduced from over 250°C to less than 60°C in less than 5 seconds from water mist discharge initiation. For comparison, the overhead temperature over the same interval dropped only 50°C with agent discharge alone.

The use of additives in water mist and the addition of chemicals or a combination of inert gases/liquids with water mist, however, increase the operating cost and equipment corrosivity as well as the level of toxicity, in comparison to plain water [1]. In some cases, if most of the droplets are deflected away from the fire, the chemical suppression effectiveness of the additives would be minimized. Furthermore, the reduction in water evaporation rate by additives would impose an additional penalty, because, for a given time, less water vapour would be generated and entrained into the adjacent fire for suppression [67]. These factors must be considered in evaluating water mist systems with additives or combinations of inert gases/liquids with water mist.

3.5 Methods of Generating Water Mist

In general, water mist generating systems can be divided into three basic categories based on the atomizing mechanisms used to produce the fine droplets: impingement nozzles; pressure jet nozzles; and twin fluid nozzles [1]. Any other type of nozzle is a combination of these three basic types.

These three types of nozzles work under different operating pressures and can produce different spray characteristics. NFPA 750 [49] defines three pressure regions for water mist generating technologies: low, intermediate and high pressure systems. Low pressure systems operate at pressures of 12.0 bar (175 psi) or less, intermediate pressure systems operate at pressures greater than 12.0 bar (175 psi) and less than 34.0 bar (500 psi), and high pressure systems operate at pressures greater that 34.0 bar (500 psi).

The choice of the water mist generating method could influence factors such as spray characteristics, cost-effectiveness and reliability of the system. The method of generating water mist also affects the suppression capability of the system but it is not the only factor [1]. Matching the spray characteristics of drop size distribution, flux density and spray momentum to the fire hazard plays a more important role in fire suppression.

3.5.1 Impingement Nozzles

Impingement nozzles, operated with a single fluid, consist of a large diameter orifice and a deflector [1]. They include standard sprinklers and nozzles used in traditional water spray and deluge systems. Small droplets can be produced as a high velocity jet of water from the large diameter orifice strikes a deflector and breaks up. The shape of the deflector and the jet velocity determine the size of drops and their distribution, the cone angle, flux density and spray momentum.

Operating pressures for impingement nozzles range from low to intermediate pressures [1]. These nozzles can produce Class 2 and Class 3 sprays with cone angles between 60° and 120° [1].

The design of this type of nozzle is relatively simple and its manufacturing cost is less than that for nozzles that require precise machining. Impinging jet nozzles, however, have limited axial spray penetration momentum. As the jet strikes the deflector, the velocity of the spray is greatly reduced and randomized and may not be increased by increasing the nozzle pressure. The deflector supports also cause irregular flux distribution because of shielding.

Impingement nozzles have been widely used to control Class A fires as well as fire scenarios where large droplets are required to extinguish fires [1]. They have demonstrated good extinguishing performance for use in ship cabins and crew areas and in residential buildings [18, 68]. The impingement nozzle has also been effective in extinguishing a wide variety of hydrocarbon pool and spray fires that might occur in a machinery space [18, 69], where enclosure effects make spray momentum less critical.

3.5.2 Pressure Jet Nozzles

Pressure jet nozzles, operated with a single fluid, consist of small diameter orifices or swirl chambers [1, 69]. When a high velocity jet of water leaves the orifice, the sheet or thin jet of water becomes unstable and disintegrates into fine droplets.

The orifice diameter for this type of nozzle ranges from 0.2 mm to 3 mm [1]. The nozzle can have multi-nozzle heads that operate at relatively low pressures. The mass flow rates vary from 1 Lpm for a single nozzle to 45 Lpm for a multi-orifice assembly. The operating pressures range from low pressure (5.1 bar) to high pressure (272 bar) [1, 69]. The spray cone angle produced by pressure jet nozzles is between 20° and 150°.

Pressure jet nozzles can produce fine droplets, wide spray angles and good spray projection. Using a multi-orifice assembly can further increase cone angle and flux density of pressure jet nozzles. The size and distribution of droplets produced by a pressure jet nozzle are mainly determined by the discharge pressure used. Droplet sizes become finer as pressure increases. The droplet momentum and flux density of pressure jet nozzles are also increased by increasing the operating pressure [35]. However, there is an upper limit, at which point any further increase in pressure has little effect on the drop size distribution but may only increase mass flow rate or momentum.

Pressure jet nozzles have been widely used to suppress a variety of fires, including Class B fires in machinery spaces and in gas turbine enclosures [69, 70] and Class A fires in ship cabins and crew areas [71]. Their performance for the protection of electronic equipment has also been evaluated [72]. It has been shown that pressure jet nozzles with high discharge pressures are effective in suppressing fires under various fire scenarios and can reduce the effect of ventilation on fire suppression [43]. However, the advantage of working with high pressures must be weighed against the cost of operating a high pressure system, which may require special pipes and pumps.

3.5.3 Twin-Fluid Nozzles

Twin-fluid nozzles operate with compressed air and water. They consist of an air inlet, water inlet and internal chamber [1, 73]. The sheet of water formed in the chamber is sheared by the compressed air and becomes unstable and disintegrates into droplets.

After the droplets exit the nozzle, the high turbulent jet can cause a second atomization of droplets, resulting in the further improvement of the droplet size distribution [73, 74].

The discharge pressures of water and atomizing medium (air) from a twin-fluid nozzle are separately controlled. Both water and atomizing medium lines operate in the low pressure regime (from 3 bar to 12 bar) [1, 69]. The cone angle of this type of nozzle varies between 20° and 120°. The droplet sizes produced by a twin-fluid nozzle are Class 1 and Class 2 sprays.

Drop size distribution, cone angle, spray momentum and discharge rates can be efficiently controlled using twin-fluid nozzles. Also, the compressed air discharged from twin-fluid nozzles can carry small water droplets into the combustion zone in sufficient quantities while producing strong turbulence to mix droplets with fires. Both effects increase the effectiveness of twin-fluid nozzles in fire suppression [75].

Twin-fluid nozzles have been widely used in industrial spray systems for many years [1, 73]. They have good reliability, are less likely to clog due to their larger orifice sizes and are easy to maintain due to their low operating pressure. Twin-fluid nozzles can also substitute gaseous halon alternatives or inert gases for air as the atomizing fluid. The twin-fluid water mist system operates in the low pressure range, so that commonly available pipe fittings and valves can be used. One twin-fluid water mist fire suppression system has been listed by Factory Mutual for use in turbine enclosures [76].

The primary disadvantage of the twin-fluid water mist system is the system's cost, since it requires two supply lines for air and water and the storage of a sufficient quantity of compressed air [1, 69]. Its spray momentum is also relatively low due to its low discharge pressure, in comparison with those types of nozzles with high discharge pressures, which could affect its effectiveness against fire challenges.

Recently, the National Research Council of Canada carried out a series of full-scale tests to compare the extinguishment performance of a single-fluid/high pressure water mist system and a twin-fluid/low pressure water mist system [43]. The single-fluid/high pressure water mist system had 70 bar of discharge pressure and its total water discharge rate was 78 Lpm. The twin-fluid/low pressure water mist system had 5.78 bar of discharge pressure for water and 5.57 bar for air and its total water discharge rate was 70 Lpm. Test results showed that the use of the twin-fluid pressure water mist system could not extinguish some fires that could be extinguished by the single-fluid/high pressure water mist system. The changes in the ventilation conditions in the room had a stronger influence on the extinguishing performance of the twin-fluid water mist system than on the single-fluid/high pressure water mist system.

3.5.4 Other Methods of Mist Generation

New methods of mist generation are still being developed by manufacturers. One such method is 'Flashing of super-heated liquid'. This method produces ultra-fine droplets (aerosol sized, 20 micron) when superheated liquid is released suddenly from a pressurized container. The ultra-fine droplets are then distributed widely throughout the compartment. It is assumed that the fire will be easily extinguished, when the ultra-fine droplets are quickly converted into high water vapour concentration, thus reducing the oxygen concentration in the compartment. Tests have demonstrated that this method is effective in quenching dust explosions [10]. For fire suppression, however, this method, due to its insufficient mass of water, is difficult to extinguish a fire in an electric cabinet or a cable fire in underfloor area by passive entrainment in the flames [1, 77]. In addition, it is difficult to control the projecting direction of water mist produced by 'Flashing of super-heated liquid'. In comparison with other mist generating methods, 'Flashing of super-heated liquid' was not as successful in extinguishing fires that occurred in electronic facilities [72].

Other new mist generating methods include a nozzle that combines the principles of pressure jets and impingement nozzles; a pressure jet nozzle that injects nitrogen into the water line; and an impulse spray used as a hand-held portable extinguisher [1]. It was reported that these new mist generating methods could enhance fire suppression effectiveness, compared to the conventional methods [1].

4.0 THE DEVELOPMENT OF COMPUTER MODELLING FOR WATER MIST FIRE SUPPRESSION SYSTEMS

Since current studies of water mist fire suppression systems have shown that the relationship between a fire scenario and the characteristics of the water mist system is not well enough understood to apply a "first principles" approach to the design of water mist systems, the evaluation of the performance of a water mist system for a specific application, until now, has been based on full-scale tests [28, 35]. This results in delays and high costs in the development of water mist fire suppression systems.

Computer modelling is a relatively new method for the study of water mist fire suppression systems [78, 79]. This type of analysis can provide insights into many of the fundamental suppression processes that occur between water mist and fuel-air mixtures. The behaviour of water mist under different fire suppressing conditions can be understood and assessed effectively using computer simulations. Computer modelling is also becoming better defined and much easier to carry out, in comparison to full-scale fire tests [79]. A combination of laboratory and numerical studies with validation by fire tests, will make the development of water mist systems much more efficient and effective.

There are two categories of computer models which have been used to study water mist fire suppression systems: quasi-dimensional computational models with detailed kinetics and computational fluid dynamics (CFD) field models with simple kinetics [79]. For quasi-dimensional computational models, the computational domain is divided into one zone or multiple zones according to the combustion phenomena being simulated. Detailed chemical kinetics are incorporated into the model to describe the elementary reaction steps of fuel-air mixtures. Quasi-dimensional computational models can provide detailed information on the chemical interaction between fire and water mist, including the breakdown of reaction chains, the suppression of active species and the production of combustion by-products (CO_2 and CO). Less computer power is required for quasi-dimensional computational models than for CFD models.

Suh and Atreya [46] used a Sandia Chemkin-based opposed flow diffusion flame code to study what occurs inside the flame and how the combustion reaction changes as water vapour is added to the flame. The reaction mechanism used for a diffusion methane flame was a C2-full mechanism that consisted of 177 chemical reactions with 32 species. Other studies based on quasi-dimensional computational models have revealed that water mist in fire suppression mainly displays the physical extinguishing mechanism of an inert agent [37] and that the cooling effect from droplet vaporization plays an important role in flame inhibition [80]. The concentration of water vapour for effective diluting is also obtained by the application of such computer models [37].

For CFD models, the computational domain is divided into a large number of small control volumes that are used to trace the extinguishing processes. CFD models can provide detailed information on the physical interaction between fires and water mist, the fire spread, the distribution of spray droplets in the compartment, and the mass and heat transfer between the fire and sprays. CFD models can be used to study the fire extinguishment by water mist on a laboratory scale or on a full scale in a compartment [79].

Recently, the Naval Research Laboratory has developed and applied a numerical model to study the combustion of methane-air diffusion flames and their inhibition by water mist on a laboratory scale [81]. They have considered a two-continuous formulation, wherein the gas properties and the droplet properties are each described by equations in the Eulerian form. In this approach, the droplet properties are treated as if they were continuous in the domain with the gaseous properties. This model provides a detailed understanding of droplet dynamics in a 2-D flow field for the study of the impact of droplet diameter, spray velocity and injection characteristics on mist entrainment into a diffusion flame and flame suppression on a laboratory scale. The relative contribution of various suppression mechanisms has been identified by this model.

A number of studies using CFD models for full-scale fire suppression research have been carried out by Hadjisophocleous, Mawhinney and their coworkers [78, 82-86]. They studied the liquid pool fire extinguishing process in open spaces and in a compartment with various obstacles, and fire suppression by water mist in an aircraft cabin. During 3-D calculations, water sprays are treated using a Lagrangian tracking model. Individual droplets are tracked from their point of injection until they evaporate. The model calculates the combustion of the liquid fuel in the compartment, the injection and flow of the fine water droplets and the interaction between the water droplets and the hot gases. The impact of the number of nozzles, the amount of water used, the droplet size and the location of the nozzles on fire extinguishment are studied. The predicted results show good agreement with the corresponding experimental values.

CFD computer modelling was also used to develop a water mist nozzle. CFD Research Corporation [74] used a computer model to design twin-fluid nozzles that can produce a water spray that sustains its high initial velocity over a long distance.

The results obtained with CFD modelling demonstrate that it is a promising tool for analyzing the complex physical phenomenon of fire suppression by water mist. It extends the understanding of the relationships between the parameters of water mist systems and fire scenarios. The potential for CFD modelling as a research and design tool is now being recognized by both research and commercial agencies [12, 35]. The current CFD models, however, require significant computer power. This requirement could increase the cost and time needed for the development of water mist systems. Additionally, in order to improve the accuracy of CFD modelling, a more comprehensive knowledge of spray characteristics and fire models is required [79, 86].

5.0 SUMMARY

The extinguishing mechanisms of water mist systems have been identified as: cooling of the fuel and flame, displacement of oxygen and fuel vapour, and radiant heat attenuation, with additional kinetic effects. Although all of these mechanisms are involved to some degree in fire extinguishment, only one or two mechanisms play a dominant role in any specific fire suppression scenario.

Water mist does not behave like a "true" gaseous agent in fire suppression. The effectiveness of a water mist system in fire suppression is dependent on spray characteristics (the distribution of droplet sizes, flux density and spray dynamics) with respect to the fire scenario (shielding of the fuel, fire size and ventilation conditions). Other factors, such as the enclosure effect and the dynamic mixing created by the discharge of water mist, also affect water mist performance in fire suppression.

Due to the complex extinguishing processes, the relationship between a fire scenario and the characteristics of a water mist system is not well enough understood to apply a “first principles” approach to the design of a water mist system. A combination of laboratory and computational modelling studies with validation by fire tests, is needed to make the development of water mist systems much more efficient and effective.

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Table 1: The Variation of Surface Area of Water with Droplet Size (Volume of Water 0.001 m^3)

Droplet Size (mm)	6	1	0.1
Total Number of Droplets	8.8 x 10^3	1.9 x 10^6	1.9 x 10^9
Total Surface Area (m^2)	1	6	60

Table 2: Comparison of Optimum Droplet Size for Fire Extinguishment [52]

Author	Date	Droplet Size (μm)	Notes
Braidech & Neale	1955	300 – 350 100 – 150 150 – 300	Applied vertically down Applied horizontally Low flash point, immiscible fuel
Herterich	1960	350	
Yao & Kalelkar	1970	< 350 4000 – 5000	For gas layer cooling For plume penetration
Vincent et al	1976	310	Gas explosion suppression
Beyler	1977	> 1000	Penetration and prewetting of fires larger than 250 kW
Pietrzak & Patterson	1979	200 – 300	Flame/gas layer cooling
Rasbash	1985	400	High flash point, immiscible fuels
Kaleta	1986	300 – 900	Optimum depends on gas layer temperature
Osaka	1988	250 – 300	Hand-held fog nozzle
Tour & Andersson	1989	300	TA Fogfighter nozzle, hand-held
Marioff	1991	60	Pressure fog nozzle

Table 3 Typical Falling Distance of Droplets with Droplet Sizes at Different Surrounding Temperatures [53]

	D_o (Droplet Diameter, μm)					
T_g (^{o}C)	1	10	50	100	500	1000
400	1.5 pm	15 nm	9.1 μm	146 μm	2.5 m	9.9 m
600	0.88 pm	9 nm	5.5 μm	87 μm	1.5 m	6.0 m
800	0.63 pm	6 nm	3.9 μm	63 μm	1.1 m	4.3 m
1000	0.49 pm	5 nm	3.0 μm	49 μm	0.8 m	3.3 m