Recent Progress in Methods of Generating Water Mist for Fire Suppression

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Key Words: water mist, characteristics of water mist, fire suppression effectiveness, fire extinguishing mechanisms

Abstract

To prevent the ozonosphere from being destroyed by Halon, it is an urgent task to find out Halon replacement. As one of the replacements water mist have showed broad applications by its advantages: little pollution to environment (not destroying the ozone layer or bring green house effect), extinguishing fire quickly, consuming a small quantity of water and having little damage to the protected objects. The methods of generating water mist strongly influence fire suppression effectiveness, which determine the cone angle, drop size distribution, flux uniformity, and momentum of the generating spray. The traditional water mist nozzle included pressure jet nozzles, impingement nozzles and twin-fluid nozzles. All of them have more or less disadvantages for fire suppression. Therefore, many research institutes and corporations are taking up with innovations in mist generation. This article provided some recent studies in State Key Laboratory of Fire Science (SKLFS) of University of Science and Technology of China. SKLFS have investigated new methods of generating water mist (i.e. effervescent atomization and ultrasonic atomization), and self developed a series of nozzles and developed advanced DPIVS (Digital Particle Image Velocimetry and Sizing) technique. Characteristics of water mist (the distribution of droplet sizes, flux density, spray dynamics and cone angle) produced by these nozzles were measured under different conditions (work pressure, nozzle geometry, etc.) using LDV/APV and DPIVS systems. A series of experiments were performed to study the fire suppression effectiveness in different fire scenario (different kindsof the fuel, fire size and ventilation conditions). The fire extinguishing mechanisms of water mist was also discussed.

1. Introduction

Because of the adverse effects of halogen-based fire suppressing agents on the atmospheric ozone layer, the Montreal Protocol was introduced in 1987 and put forward clear and definite target-Halon fire suppressants will be replaced by the beginning of 21st century. Therefore, from the 1990s the world began seeking for alternative extinguishing agent of Halon. There has been substantial interest in the substitutes such as water sprinkler, CO_2, inert gas and foam. But despite much effort the objective remains to be achieved. During the past decade years, water mist technology has been developed and regarded as a promising substitute because of its advantages: little pollution to environment (notdestroying the ozone layer or bring green house effect), extinguishing fire quickly, consuming a small quantity of water and having little damage to the protected objects(1, 2). Generally water mist is defined as fine water droplets for which the droplet diameter at the thickest part on the surface 1 meter away from the nozzle, $D_{v0.99}$, is less than 1000 mm at the minimum design pressure(3). Water mist have been successfully used to suppress Class A and Class B fires, and it also haswide applications in the protection of special fires in high technology industries such as computer room and aircraft cabin.

This paper, as a first step, reviews characteristics of water mist and the measurement methods, then introduces methods of generating water mist for fire suppression. The studies of fire suppression effectiveness

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and fire extinguishing mechanisms are also reviewed and discussed.

2. Characteristics of water mist

The effectiveness of a water mist system in suppressing a fire is directly related to the spray characteristics produced by the nozzles. Characteristics of water mist can be classified as four main parameters: droplet size distribution, flux density, spray momentum and cone angle(3). These fourmain 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.

2.1 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(4) 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.

The relationship between drop size distribution and extinguishing capacity of a water mist is complex. In general, Class 1 and Class 2 mists are successful at extinguishing liquid fuel pool fires and spray fires without agitation of liquid pool surfaces. Given an appropriate geometry, Class 3 sprays are reported to have extinguished pool fires(5). However, in general, it is difficult to extinguish Class A combustibles with Class 1 sprays, which may not achieve the fuel wetting necessary to penetrate the char layer. Class A can be extinguished with Class 1 mists, however, particularly if the velocity is high, the burning is surgical, or enclosure effects enhance the degree of oxygen reduction.

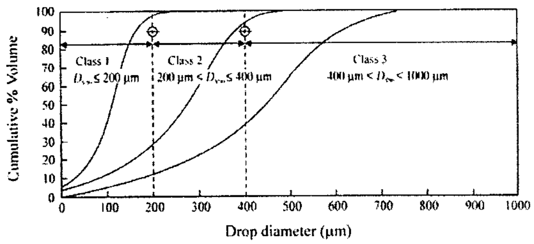


Fig. 1 Classfication of drop size distributions-Class 1, 2 and 3(4)

2.2 Flux Density

Spray flux density refers to the amount of water mist in a unit volume (L/m^3) or applied to a unit area (L/m^3)(3). 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(6). On a localized scale, however, the fire is extinguished only when water mist achieve a minimum flux density. Without sufficient flux density of water mist 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.

2.3 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 vapor into the combustion zone, which dilutes the oxygen and fuel vapor 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 vapor-phase water and air entrained by water mist(7). The momentum of the spray, Mw, can be expressed as follow:

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

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

2.4 Spray Cone Angle

Spray cone angle decides the area that water mist can protect, and influences droplet velocity and spray momentum. It is one of the important water mist characteristics.

2.5 Measurements of Water Mist Characteristics

In order to evaluate the capability of water mist nozzles and research the extinguishing mechanisms of water mist, it is necessary to measure the water mist characteristics. SKLFS applied and developed some measurement techniques.

2.5.1 The LDV/APV system

The system is based on the light scattering theory of non-conductive spherical particles and the characteristic of the water mist, scheming optical path of the Laser Doppler Velocimetry or the Adaptive Phase Doppler Velocimetry system (LDV/APV).

The system contains the following major components: a laser light source, a light separation optics, a light transmitting optics, a light collecting optics, two photodetectors, a signal processing electronics, a external data input devices, a computer, Software and a traversing systems. Fig. 2 is typical results of a small pressure nozzle measured by the LDV/APV system.

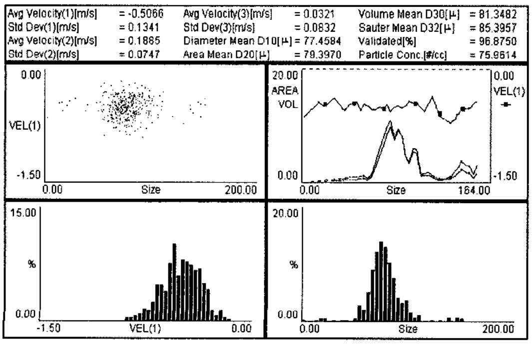

Avg Velocity(1)[m/s] = -0.5066
Std Dev(1)[m/s] = 0.1341
Avg Velocity(2)[m/s] = 0.1885
Std Dev(2)[m/s] = 0.0747
Avg Velocity(3)[m/s] = 0.0321
Std Dev(3)[m/s] = 0.0832
Diameter Mean D10[μ] = 77.4584
Area Mean D20[μ] = 79.3970
Volume Mean D30[μ] = 81.3482
Sauter Mean D32[μ] = 85.3957
Validated[%] = 96.8750
Particle Conc.[#/cc] = 75.9614

Fig. 2 Measurement results by LDV/APV system (0.02 m away from the exit orifice, 1.2 MPa)

2.5.2 The DPIV systems

Particle image velocimetry (PIV) is one of the methods of PLV(pulse laser velocimetry) and the flow field velocity distribution can be determined based on many methods and processes. DPIV is just the digital form of PIV technology, that is, DPIV uses charge-coupled device (CCD) camera to obtain the particle images. Therefore, the images can be directly stored and analyzed by computer with a frame grabber, thus the film interpretation process is not needed. Generally speaking, the DPIV technology has the merits of simple, real-time measurements, etc. Especially, the DPIV technology avoids the ambiguity of particle displacement through the cross-correlation analysis of two small areas within two sequential images(8).

2.5.3 The DPIVS technology

Although DPIV method has been well developed on fundamentals and technology realization and it has been applied as a very effective diagnostic method within recent years, it can only determine the velocity field. SKLFS developed advanced DPIVS (Digital Particle Image Velocimetry and Sizing) technique based the DPIV method.

The fundamentals of this developed field diagnostic method for particle size measurement mainly include two processes, one is to obtain the particle images based on their forward scattering through a CCD camera perpendicular to the light sheet and the illumination of the particle field with the sheet; the other is to analyze the particle images and obtain the size distribution with many image processing methods, such as the image emendation, image smoothing, de-noise, element division and limited corrosion, etc. The hardware system of this extending method is similar to DPIV, but the former uses a laser light sheet perpendicular to the mean direction of the flow, and the image manipulation method is quite different from the latter. The former method mainly focuses on recognition and analysis of a single particle, but the latter is mainly focused on the statistical analysis of more tracing particles within the inquiry area(9). Fig. 3 and 4 give a schematic system of the principle

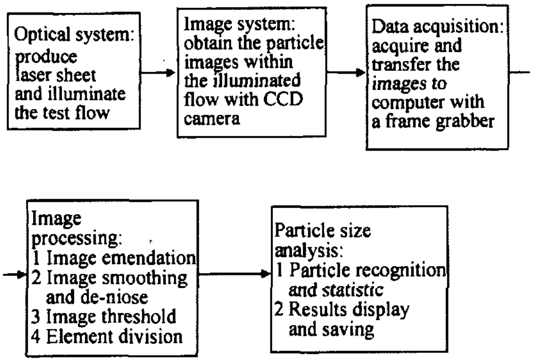


Fig. 3 Schematic system of the field diagnostic method on particle size measurement

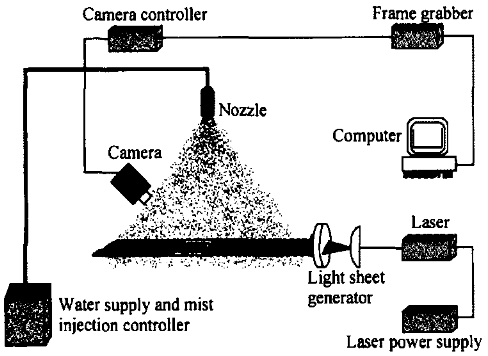


Fig. 4 Schematic system for water mist droplet size measurement

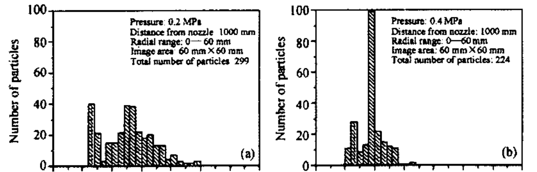


Fig. 5 Measurement results of droplet size distribution by DPIVS

and hardware with the extended method.

Figure 5 shows the measurement results of droplet size distribution within a water mist with different pressures by the extended DPIV method.

2.5.4 Water mist field visualization technology

SKLFS set up an image acquisition system. It contains a Studio DC10plus board made by Pinnacle Systems Inc. and a CCD camera made by Korea Saerim Inc. Water mist field can be visualized by this system and the spray cone can be obtained.

3. Methods of generating water mist

Methods to generate water mist range from simple to elaborate. For fire suppression purposes, the choice of method is narrowed by the facts that the mass flow rates and velocities needed to be effective are beyondthe capacity of some methods. The methods that are practical for fire suppression systems are those that break up water into drops smaller than 1,000 microns, at mass flow rates and spray velocities appropriate for full-scale fire scenarios, which can be protected against plugging and which reliably sustain that flow as long as is required. The economics of providing the stored energy, or installing special pumps and piping systems, are also determinants in selection of a mist-generating technology for a given application.

3.1 Traditional methods

In general, water mist nozzle designs involve one of three basic principles: (1) impingement of a jet of water on a deflector (impingement), (2) expulsion of a high-velocity jet from an orifice (pressure jet), and (3) using compressed air or nitrogen to shear water into fine spray (twin-fluid or air-atomizing nozzles). All three methods have been used by manufacturers of spray nozzles for many years.

These three types of nozzles work under different operating pressures and can produce different spray characteristics. NFPA 750(4) defines three pressure regions for water mist generating technologies: low, intermediate and high pressure systems. Low pressure systems operate at pressures of 1.2 MPa or less, intermediate pressure systems operate at pressures greater than 1.2 MPa and less than 3.4 MPa, and high pressure systems operate at pressures greater that 3.4 MPa.

3.1.1 Impingement nozzles

Impingement nozzles, operated with a single fluid,

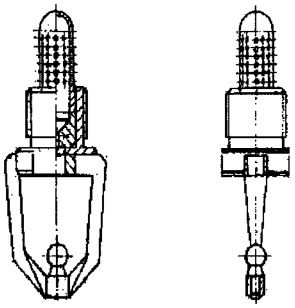


Fig. 6 Impingement nozzle

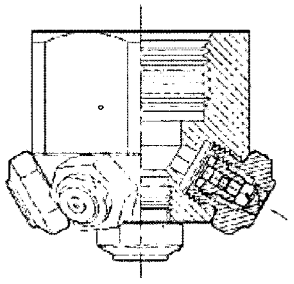


Fig. 7 Pressure jet nozzle(13)

consist of a large diameter orifice and a deflector(3). 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 is from low to intermediate pressures(3). Fig. 6 shows one type of impingement-style nozzle used in water mist systems.

The design of this type of nozzle is relatively simple and its manufacturing cost is less than that for nozzles that require precise machining. However, the test revealed that impingement nozzles have a limited axial spray projection distance, because of the energy lost as the jet strikes the deflector. A slight tilt in the deflector plate will skew the spray distribution in one direction. Deflector supports can cause shadow effects, and irregularities in the impingement surface can magnify to large irregularities in the impingement surface can magnify to large irregularities in the spray distribution.

3.1.2 Pressure jet nozzles

Pressure jet nozzles work by pushing a jet of water through a relatively small-diameter orifice at a high velocity. As the jet leaves the orifice, complex physical events occur, involving the fluid viscosity, and the jet diameter and velocity relative to the air(10). The break-up of the thin jet of water into droplets can be enhanced by inserting swirl devices in a chamber inside the nozzle, to impart a rotation to the jet as it emerges from the orifice. If water is pushed through a narrow slot instead of a circular orifice, the jet takes the form of a sheet, which becomes unstable and disintegrates into droplets. The orifice diameter for this type of nozzle ranges from 0.2 mm to 3 mm(3). The operating pressures range from low pressure (0.5 MPa) to high pressure (27.2 MPa)(3, 11).

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(12). 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.

3.1.3 Twin-fluid nozzles

Twin-fluid nozzles operate with compressed air and water. They consist of an air inlet, water inlet and internal chamber(3, 10). 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(10, 14). 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 0.3 MPa to 1.2 MPa)(3, 11).

Twin-fluid nozzles have been widely used in industrial spray systems for many years(3, 10). 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.

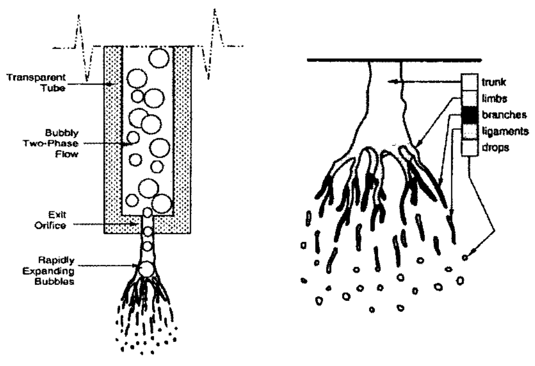
The primary disadvantage of the twin-fluid water mist system is the system's cost, since it requires two supply lines for air and water and the storage of a sufficient quantity of compressed air(3, 11). Its spray momentum is also relatively low due to its low discharge pressure, in comparison with those types of nozzles with high discharge pressures, which could affect its effectiveness against fire challenges.

3.2 Research of SKLFS in mist generation

As the three general methods of generating water mist each has some disadvantages, innovations are going on by many research institutes. The innovations are intended to improve efficiency, or to optimize some spray characteristics such as mass flow rate, spray velocity, drop size distribution, or cone shape, for use in fire suppression applications. SKLFS have self-developed some kinds of nozzles, include traditional nozzles, investigated new methods of generating water mist especially effervescent atomization and ultrasonic atomization and used different kinds of nozzles in fire suppression.

Effervescent atomization. Effervescent atomization is a method of twin-fluid atomization that involves bubbling a small amount of gas into the liquid before it is ejected from the atomizer. The technique of bubbling gas directly into the liquid stream inside the atomizer body is essentially different from other methods of twin-fluid atomization(either internal or external mixing) and leads to significant improvements in performance in terms of smaller drop sizes and/or lower injection pressures. Furthermore, the amount of atomizing gas required is considerably less than what is employed in all other twin-fluid atomization techniques(15).

The principle of effervescent atomization has been investigated experimentally by Lefebvre and Sojka and their coworkers. Roesler(16) and Lefebvre(17, 18) conducted experiments to visualize both the two-phase flow inside an effervescent atomizer as it approaches the exit orifice and the near-nozzle liquid break-up mechanism. They observed that the bubbly two-phase mixture formed in the effervescent nozzle evolves as it flows towards the nozzle exit and may be in a bubbly, slug or annular flow regime inside the discharge orifice. With bubbly flow, the bubbles discharged from the orifice are immersed in the liquid jet. On leaving the orifice the bubbles experience a sudden pressure relaxation and expand rapidly, thereby shattering the liquid into drops, as shown schematically in Fig. 8(a). When the atomizer is operating in the slug flow regime, the rapidly expanding gas slugs similarly break up the liquid. In the annular flow regime the central gas core created by the coalescence of individual gas bubbles expanded rapidly and broke up the annular sheath into a ring of ligaments. The near-nozzle structure in this regime resembled a tree with the annular liquid sheath forming a hollow trunk and the ligaments forming branches. An artist's interpretation of this is presented in Fig. 8(b).



(a) (b)

Fig. 8 Schematic of the atomization mechanism(15)

Effervescent atomization has been used successfully in a number of applications since its inception over ten years ago. Now it has been used in gas turbine combustors, consumer products, furnaces and boilers, internal combustion (IC) engines and incinerators, but has been rarely applied in fire suppression. SKLFS designed an effervescent atomizer and conducted a series of experiments to study fire suppress-

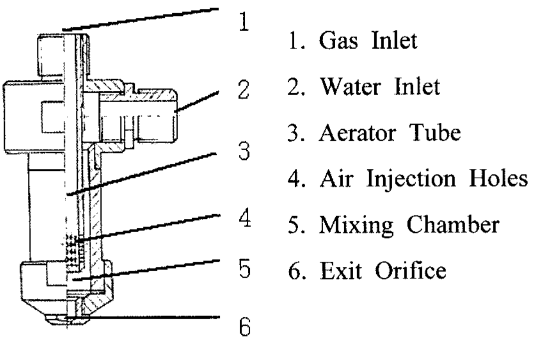


Fig. 9 Schematic diagram of the effervescent atomizer

Table 1 Time of extinguishing kerosene fire

Water Pressure/MPa	Distance/cm	Extinguish Time/s
0.15	110	3
	130	4
	150	4
0.23	110	4
	130	8
	150	6
0.39	110	4
	130	8
	150	6

Table 2 Time of extinguishing ethanol fire

Water Pressure/MPa	Distance/cm	Extinguish Time/s
0.15	110	30
	130	43
	150	63
0.23	110	15
	130	25
	150	48
0.39	110	8
	130	12
	150	15

ing effectiveness of water mist produced by effervescent atomizer. The schematic diagram of the effervescent atomizer is shown in Fig. 9. It consists of four main components: liquid and gas supply ports, a mixing chamber where the gas is bubbled into the liquid stream, and an exit orifice. The overall length of the atomizer is approximately 120 mm. The mixing chamber diameter is 30 mm. Four rows of twelve holes, each 1mm in diameter, are used for injecting nitrogen into the mixing chamber. The exit orifice includes seven exit holes, each 1 mm in diameter, one in the center and the others distributes symmetrically around it.

The characteristics of water mist produced by the effervescent atomizer, such as drop size distribution, velocity distribution and flux density were measured by a LDV/APV system. When the operation water pressure was 0.35 MPa and the operation nitrogen pressure was 0.45 MPa, at 1 m away along the nozzle axis the axial mean velocity is about 1.15 m/s and the radial mean velocities are about 0.15 m/s and 0.22 m/s respectively. And under above conditions the volume mean diameter is approximately 55 μm. The water flow rate is 7.1×10^{-6} m^3/s under 0.25 MPa operation water pressure and 0.30 MPa operation nitrogen pressure.

Fire extinguishing experiments were performed in a 3mx3mx3m confined space. A 0.18 m diameter pan with a lip height of 0.05m was used for the ethanol and kerosene pool fire tests. Table 1 and Table 2 respectively give the extinguishing time which the water mist required to extinguish kerosene and ethanol pool fire. They indicate that water mist extinguishes kerosene pool fire very quickly, in no more than 8 seconds. More time was required to extinguish ethanol fire, but the fire was suppressed immediately after the water mist was injected. Therefore, it has a good future that applied effervescent atomizer in fire suppression technology.

3.2.1 Ultrasonic atomizers

When a liquid is introduced onto a rapidly vibrating solid surface, a checkerboard-like wave pattern appears in the film that forms as the liquid spreads over the surface. As the amplitude of the surface vibration is increased, the wave crest height in the film also increases. It was demonstrated by Lang(19) that atomization occurs when the amplitude of the vibrating surface increases to the point where the wave crests in the film become unstable and collapse. This causes a mist of small drops to be ejected from the surface.

More recent opinion favors a capillary wave theory based on the observation that the mean drop size produced from thin layers of liquid on an ultrasonically excited plate is proportional to the capillary wavelength on the liquid surface. This implies that the mean drop size should be related to the ripple wavelength, which in turn is controlled by the vibration frequency. The results of experiments tend to support this hypothesis. For example, Lang(19) found that

$$D=0.34\lambda=0.34\left(\frac{8\pi}{\rho_L F}\right) \tag{1}$$

which is in close agreement with Lobdellís theoretical value of 0.36λ obtained from considerations of drop formation from high-amplitude capillary waves(20).

Another capillary wave theory was developed by Peskin and Raco(21) in terms of Taylor instability. They found that the atomization process is governed by several nondimensional parameters. The drop size is seen to be a function of frequency and film thickness. For films of large thickness, their analytical result reduces to

$$D=\left(\frac{4\pi^3\sigma}{\rho_L\omega_0^2}\right)^{1/3} \tag{2}$$

3.3 Comparison among different kinds of nozzles

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(3). 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.

Impingement nozzles can produce Class 2 and Class 3 sprays with coneangles between 60° and 120°(3). However, the spray momentum is relatively low, because of the energy lost as the jet strikes the deflector. These nozzles have been widely used to control Class A fires as well as fire scenarios where large droplets are required to extinguish fires(3). They have demonstrated good extinguishing performance for use in ship cabins and crew areas and in residential buildings(22, 23). 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(11, 22), where enclosure effects make spray momentum less critical.

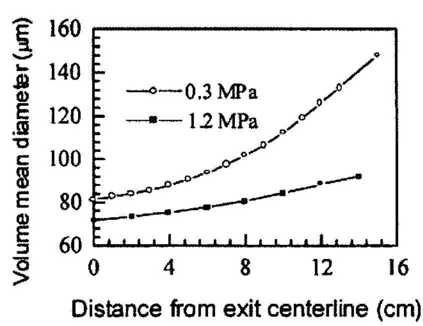


Fig. 10 The radial distribution of the volume-mean diameter of water mist

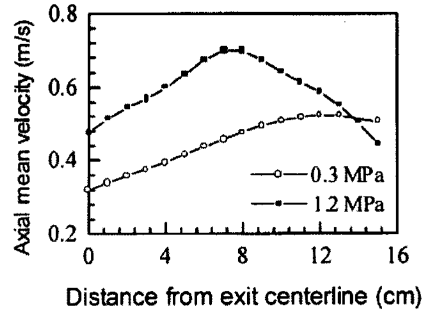


Fig. 11 The radial distribution of the axial-mean velocity of water mist

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 mass flow rates vary from 1L for a single nozzle to 45L for a multi-orifice assembly. The spray cone angle produced by pressure jet nozzles is between 20° and 150°. The size and distribution of droplets produced by a pressure jet nozzle are mainly determined by the discharge pressure used. Fig. 10 and 11 are the distribution of the diameter and velocity of water mist produced by a pressure jet nozzle respectively. They

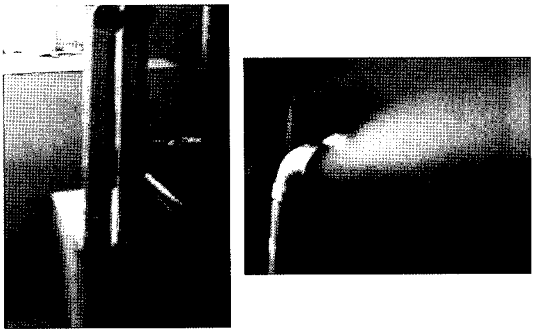


Fig. 12 Ultrasonic water mist generator

were measured by the LDV/APV system at 20 cm away along the nozzle axis. Fig. 15 shows 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. 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(11) and Class A fires in ship cabins and crew areas(24). Their performance for the protection of electronic equipment has also been evaluated(25).

The cone angle of twin-fluid 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(26).

A most useful attribute of the ultrasonic atomizer is its low spray velocity. This makes it an easy matter to entrain the spray in a moving stream and convey the drops in a controlled manner as a uniform mist. Another asset of the ultrasonic nozzle is its ability to provide very fine atomization. It can produce water mist of which diameter is smaller than 10 μm, i.e. ultra-fine water mist. This kind of water mist is used for small-scale fire extinguishing experiment, e.g. in cup burner and small wind tunnel. Now SKLFS is investigating applying ultra-fine water mist as total flooding agent to extinguish pool fire and cable fire. Fig. 12 shows an ultrasonic water mist generator used by SKLFS for fire suppression.

4. Fire suppression effectiveness

Lots of small-scale and full-scale experiments were performed in SKLFS to study the interaction between water mist and different kinds of fire in different fire scenario. The kinds of fuel include diesel, kerosene, ethanol, solid red pine, polymethyl methacrylate (PMMA) and polyvinyl chloride (PVC). The kinds of fire include liquid pool fire and liquid spray fire. And the influences of obstruction and vent were also studied.

4.1 Small-scale experiments

Small-scale experiments were conducted to investigate the mechanisms and rule of water mist suppression. In these experiments cup burner, wind tunnel and cone calorimeter were used. Fig. 13 is a schematic of the interaction experimental apparatus. The experiment was performed in the 0.6m×0.6m×0.7m glass-walled enclosure of the cone calorimeter. Water mist was generated by a single pressure nozzle and the cone angle was 60°. Fig. 2, 10 and 11 show the distributions of the droplet diameter and velocity of

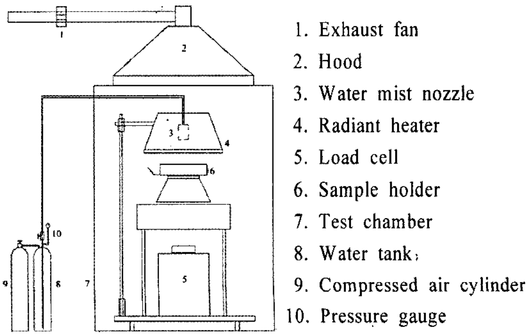


Fig. 13 Schematic of the experimental apparatus

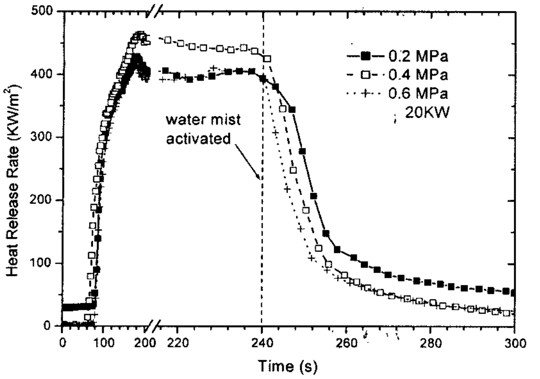


Fig. 14 Heat release rate of PMMA before and after the start of water mist application

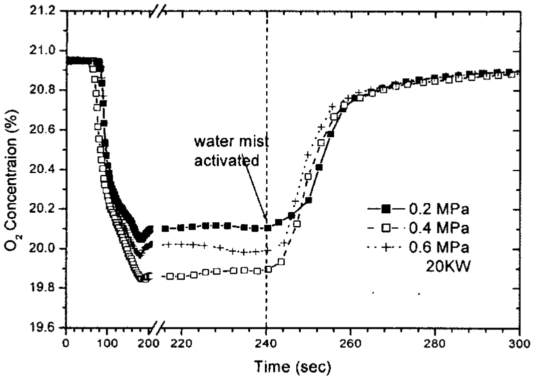


Fig. 15 O_2 concentration with and without water mist application

the mist. The fuel sample was located on the sample holder, and there was a 20 kW/m^2 radiant conical heater over the sample to keep the combustion stable. The solid fuel samples size were both 10 cm×10 cm×1 cm, PMMA weighed 115 g and red pine weighed 100 g with 8% water content$^{(27,28)}$.

Figure 14 and 15 shows the heat release rate of the PMMA samples and oxygen concentration in the exhaust gases for a period of approximately two-and-a-half minutes after activation of the water mist. The heat release rate of PMMA fires decreased rapidly under water mist application. The oxygen concentrationin the exhaust gases decreased after burning and increased after discharging water mist. As observed from Fig. 18, the system will be more effective in fire control when operating under higher pressure than operating under lower pressure.

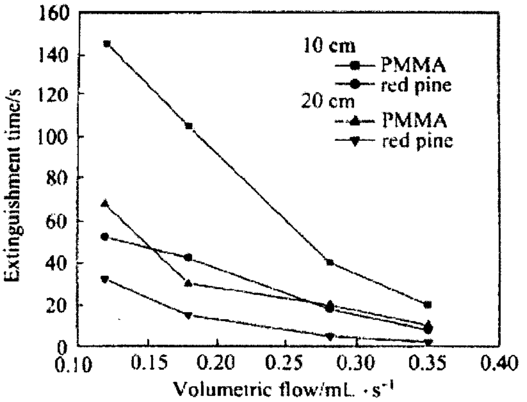


Fig. 16 Average extinguishment time versus volumetric water flow for red pine and PMMA

Figure 16 shows the extinguishment time as a function of water flow. In Fig. 16, the extinguishment time decreases with increasing water volumetric flow. The extinguishment time is much longer for PMMA fires than for red pine fires because the gasification rate of red pine decreases due to char formation during the 120s preburn before water application. And the time required for extinguishments generally deceases with increasing water application rate, irrespective of the nozzle distance from the burning surface. The extinguishment time appears to approach an asymptotic value as the water flow rate increases. At low water flow, the extinguishment time decreases when the nozzle is positioned further from the sample surface. On the contrary, at the high water flow, the extinguishment time appears to be independent of the distance between the nozzle and the sample surface.

4.2 Full-scale experiments

In order to evaluate the fire suppression effectiveness of water mist systems, a series of full-scale experiments were performed. Full-scale experiments are not simply magnifying small-scale experiments. There are many different fire phenomena in full-scale experiments. These experiments include simulating applications of water mist systems in library, kitchen and marine machinery spaces.

Figure 17 is the schematic of a full-scale experiments carried out under the exhaust hood of a fan-

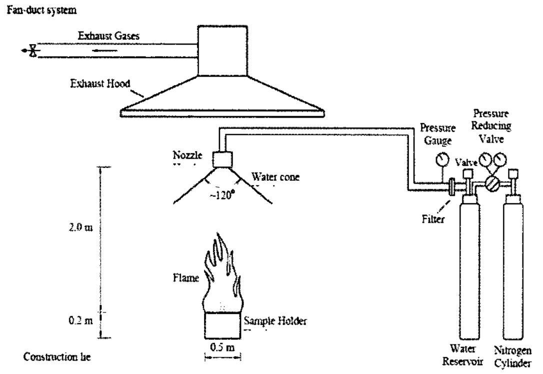
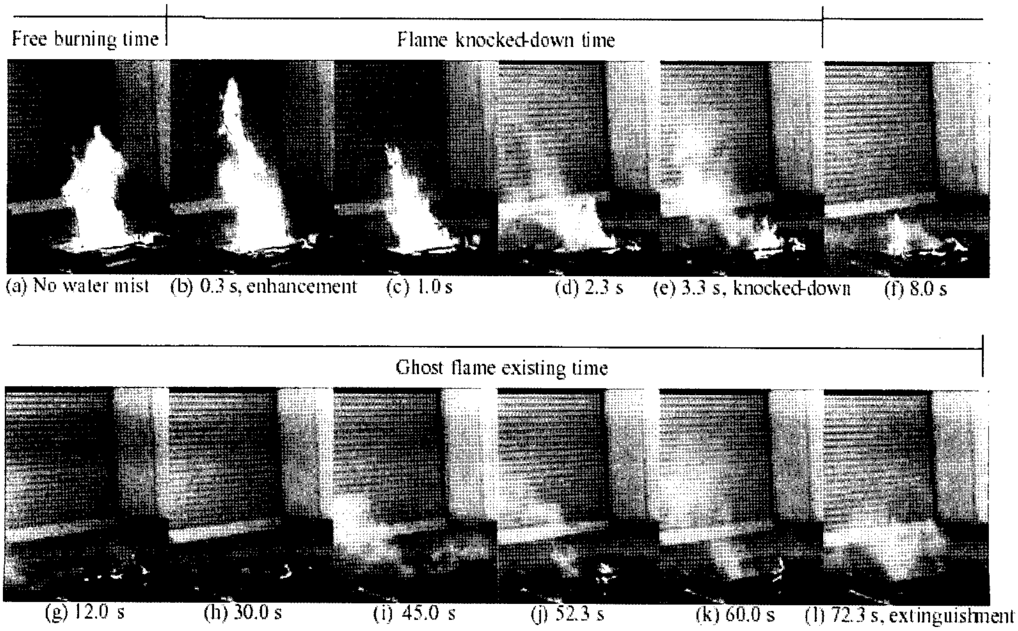


Fig. 17 Schematic of the experimental apparatus

duct system in an oxygen consumption calorimeter. A PMMA sample of size 500 mm by 500 mm and 10 mm thick was placed horizontally on the sample holder at a height of 20 cm above the floor. Water mist was discharged from a pressure jet nozzle, placed at 2.0 m above the sample surface. The water mist consisted of sub-sprays was injected from the seven heads on the nozzle to form a solid water cone. The initial angle of the water mist near the nozzle exit was about 120°. The droplet size and velocity were measured by the LDV/APV system at the cross-section 1.0 m away from the nozzle exit. The volume mean diameter was about 200 μm near the spray centerline and 300 μm near the envelope edge. The mean downward velocity was about 2 ms^{-1} near the centerline and 1 ms^{-1} near the envelope edge. The water flux was measured by collecting water with containers placed on the floor 2.0 m away from the nozzle exit. The water flux increased with the operating pressure, ranging from 1 to 5 $l\mathrm{Min}^{-1}\mathrm{m}^{-2}$ near the centerline.

When the water spray was discharged to reach the flame, an instant flare-up was observed as shown in Fig. 18 and 19. Both the flame size and the radiation heat flux increased. Lasting for only several seconds for this small fire, the flame size was reduced and then knocked down to the sample surface. This short period measured when applying water mist is defined in this paper as the flame knocked-down time. The remaining flame was perturbed by the applied water spray with the flame luminosity significantly reduced. As the spray continued to deliver to the PMMA sample surface, a water layer would be formed first. The layer would then spread and wet the horizontal sample surface. For operating pressure lower than 0.2



(a) No water mist (b) 0.3 s, enhancement (c) 1.0 s (d) 2.3 s (e) 3.3 s, knocked-down (f) 8.0 s

(g) 12.0 s (h) 30.0 s (i) 45.0 s (j) 52.3 s (k) 60.0 s (l) 72.3 s, extinguishment

Fig. 18 PMMA fire under water mist application (operating pressure: 0.2 MPa, time: start from discharging water mist)

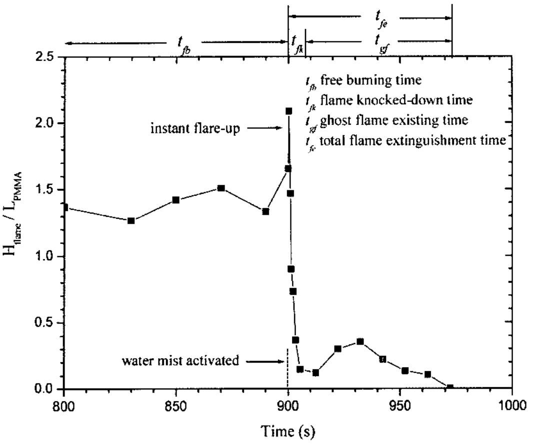


Fig. 19 Ratio of flame height over sample length versus time from ignition (operating pressure: 0.2 MPa)

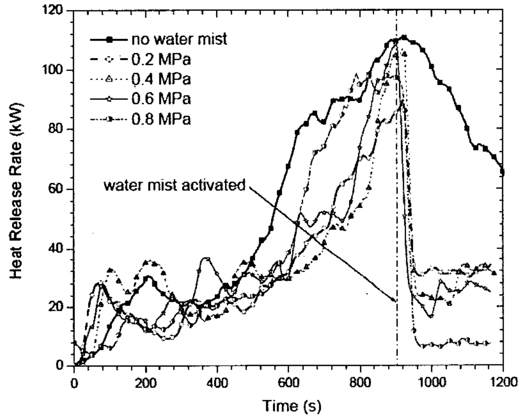


Fig. 20 Heat release rate of PMMA fire with and without water mist application

MPa, small ghost flames (the flame changes positions from one place to another) were observed at the edge of the sample. However, the flame size would be gradually reduced if water mist is kept on discharging. Eventually, the fire would be extinguished under continuous water application.

The total extinguishment time in this paper refers to the time from discharging water mist to the permanent disappearance of visible flame above the sample surface. Based on the 'frame-by-frame' analysis on the images of the flame structure, the ratio of the flame height over the sample length before and after the action of water mist at operating pressure 0.2 MPa is shown in Fig. 19. The heat release rates and production rate of smoke under various operating pressure are shown in Fig. 20 and 21.

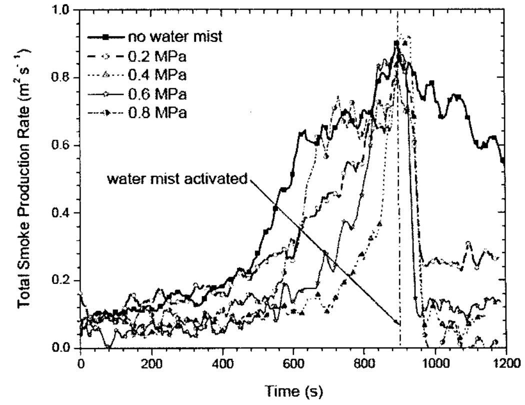


Fig. 21 Smoke production rate of PMMA with and without water mist application

4.3 Extinguishing mechanisms

The mechanisms that act together to extinguish fire can be described as three primary and two secondary mechanisms[(29)]. The primary mechanisms are: (1) heat extraction, (2) oxygen displacement, and (3) blocking of radiant heat. There are two secondary mechanisms that play a role in extinguishment, but it is difficult to quantify their importance. These are (1) vapor/air dilution and (2) kinetic effects.

4.3.1 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.

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 vapor/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(30).

4.3.2 Oxygen displacement

On a localized scale, when the water sprays penetrate into the fire plume and are converted to vapor, 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 vapor available for combustion of the fuel. As a result, when the fuel vapor 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.

4.3.3 Blocking radiant heat

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. Also, water vapor in the air above the fuel surface acts as a gray body radiator that absorbs radiant energy, and reradiates 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.

4.3.4 Kinetic effects of mist on flames

A liquid pool fire is sometimes intensified by the application of water spray. A "flare-up" often occurs in the first second of contact with the water mist, and it is evident in some fire tests that the burning rate in increased for longer periods. In many cases, the flare-up is followed by a quick knockdown and extinguishment of the flames. If the spray dynamics are insufficient to bring about extinguishment, the fire will continue to burn violently in spite of the mist.

5. Summary

As one of the Halon replacement water mist fire suppression systems have been received considerable attentions among international fire science research by its advantages. The effectiveness of a water mist system is dependent on water mist characteristics with respect to the fire scenario (shielding of the fuel, fire size and ventilation conditions).

Spray characteristics decided by the methods of generating water mist should match fire scenarios. The traditional water mist nozzles have more or less disadvantages and for some special situations they can not suppress fire effectively. Therefore, the innovations are proceeding in many research institutes and corporations. Effervescent atomization and ultrasonic atomization were investigated in SKLFS. Results showed that effervescent atomizer has simple geometry and produce smaller droplet by using less atomizing gas than other twin-fluid nozzle. It can also use gas fire extinguishing agent as atomizing media to obtain good effectiveness. Water mist produced by ultrasonic nozzle has many advantages for protecting electric appliance room especially for the computer rooms.

However, 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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