WATER MIST MONITORING IN LARGE-SCALE FIRE SUPPRESSION RESEARCH: FUNDAMENTAL ISSUES

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INTRODUCTION

Water mist has been widely used in the commercial fire protection sector for several decades. Recent attention has focused on expanding the areas of application for water mist fire suppression systems, particularly on US Navy platforms, to provide protection for areas historically protected with Halon 1301. The research and application issues for water mist are more complicated than those of gaseous agent systems under consideration since water mist does not disperse and diffuse like a gas. Qualifying drops **as** to their effectiveness under various fire scenarios is key to understanding water mist based fire suppression systems. Small drops are effective at following flow streamlines, but may lack the momentum and survival time (shortened by evaporation prior to the fire) to get to the fire. The momentum of large drops does not usually allow them to change direction sufficiently to penetrate highly obstructed areas.

The NRL is conducting research from laboratory to large scale to understand how to better use water as a total-flooding agent. Suppression interactions can be divided into (1) compartment dynamics–generation, transport, hot layer interactions, obstructions; ***(2)*** fire dynamics–convection, drop entrainment; and **(3)** flame dynamics–suppression processes (evaporative cooling, oxygen dilution). The overall objectives of the NRL water mist program are to understand these suppression interactions in order to provide optimized implementation guidance for water mist. Knowledge of the behavior of the water drops in large-scale test environments is critical to this understanding. This paper presents various approaches to obtaining this information and the issues that arise in implementing these approaches for the full-scale fire suppression test environment. While the arguments presented are developed around testing in military ships, many of the considerations and conclusions are applicable to a wide range of fire testing requirements.

TEST CONDITIONS

During and after a fire threat, **US** Navy ships must be able to absorb damage and resume functioning without undo loss of capability. The fire protection system must be able to provide protection against a fast growing, three-dimensional fire. These ships carry large quantities of pressurized and non-pressurized flammable liquids. Fires can be located anywhere in the compartment and can be of several types including cascading, pool, or gaseous non-premixed. Any of these fires can be highly obstructed. Fire control instead of extinguishment with the availability **of** equipped and trained firefighters to conduct the final extinguishment may be an option aboard Navy ships. Rapid compartment reclamation is necessary. The fire suppression system must protect high value assets whose **loss,** particularly in the event of military action, can have very significant implications.

The very first thing that presents itself in real-scale testing is the large size of the test environment. For **all** real-scale tests, a key issue is the spatial distribution of the agent throughout the compartment. For water mist systems, the properties of what can be delivered by the nozzle vary greatly due to the large number of nozzle designs as well **as** the specific nozzle operating conditions. If one wants to understand and compare suppression effectiveness, it is important to characterize the initial properties of the mist **as** it exits the nozzle. This characterization should be performed preferably at a location that is reasonably close to the nozzle exit yet far enough away so as to measure the fully developed mist and not be influenced by the rapidly changing conditions with large spatial gradients that are developing right at the nozzle exit. If the same operating conditions are to be maintained for all tests, a characterization of the mist can be done in the absence of the fire. Several measurements can then provide quantifiable uncertainty for the characteristics of the mist. However, in order to determine the influence of the mist on suppression effectiveness, various mist conditions will more than likely be examined. To fully characterize the mist characteristics for a number of different nozzle configurations and rely on the assumption that the mist characteristics are not changing during the fire tests is a problem. At a minimum, simultaneous measurements to characterize the nozzle output and drop characteristics in the test chamber are necessary.

The most challenging fires to extinguish are small, obstructed fires. These are even more challenging for water mist because of agent dispersal issues. Mist distribution is greatly affected by obstacles, much more so than are gaseous agents. Fire-induced convection currents also play a major role in drop entrainment. Small drops can more easily follow the gas stream trajectories than larger drops leading to a potential segregation of suppression efficient small drops from less efficient larger drops. The heat from large fires can cause significant drop evaporation. Evaporation rates will be lower in small, obstructed fires with lower heat release rates that are often lowered even further by the effect of the mist. Thus, it is important to quantify the drop size and trajectory of the mist near the fire as well as follow the mist drop size as a function of fire test time and conditions.

A high-pressure water mist system is capable of producing larger quantities of very small (<20 µm diameter), effective drops. However, there are significant advantages to implementing a low-pressure system that provides somewhat larger drops (>200 µm). For these systems, ship impact is reduced as the pumping requirements (space, weight, and power) are reduced or potentially even eliminated if the system can be designed to operate off the firemain. Thus the mist monitoring system must be able to measure a range of drop sizes.

Several techniques can be used to measure drop size and/or drop velocity. In general the uncertainties associated with these techniques are typically low for measuring the individual drops. However, information on the individual drop is secondary to that of the entire aerosol. The fact that there are drops of varying size that must be monitored brings up further requirements and accompanying issues. In particular, the need for a well-defined sample volume must be addressed as well as the issue of missed drops. In order to discuss these issues, several definitions are useful at this point.

DEFINITIONS

Mist—An aerosol is a suspension of either solid particles or liquid drops, or both, in a gas. Smoke, fog, mists, and sprays are all aerosols. Water mists and water sprays are liquid aerosols. Water sprays are generally characterized by a drop size of a mm or greater (e.g., rain drops and drops from water sprinklers) while water mist refers to aerosols with drop sizes less than a mm (e.g., from low-pressure nozzles). Mist with drop sizes < 200 µm are sometimes referred to as fine water mist (e.g., from high-pressure nozzles). A water mist is said to be mono-disperse if all of the drops have the same diameter. Real mists are polydisperse, composed of drops with a range of diameters. Water mists whose average drop size ranges from 100 to 1000 µm have been deemed most suitable for fire suppression [1]. NRL studies in laboratory flames have shown that sufficiently small drops (< 1 µm diameter) are as effective as Halon 1301 on a mass basis at reducing the burning velocity of premixed methane/air flames [2]. Water drops less than 30 µm were found to be more effective than Halon 1301 at reducing the extinction strain rate of methane/air and propane/air non-premixed flames while larger diameter drops were less effective [3].

Mean Diameter — A mean or average drop diameter is sometimes useful for describing the mist and for quantitatively evaluating the suppression effectiveness of different mists. A mean diameter can be selected to provide specific data relating to a particular phenomenon controlling the process under investigation (Table 1). The arithmetic or length mean, D10, is simply the average diameter of the spherical drops. The Sauter Mean Diameter (SMD) is that diameter for a single drop whose ratio of volume to surface area is the same as that ofthe entire aerosol. While D10 and the SMD values can he used to compare the average drop diameters or surface area ratio of various aerosols, they do not relate how those drops are distributed. Aerosols with similar D10s, D30s, or SMDs can have very different size distributions.

TABLE 1. DEFINITION OF MEAN DIAMETERS, NOTATION, AND AREA OF APPLICATION [4].

Name of Mean			
Diameter	Symbol	Notation	Application
Arithmetic or length	D10	$\Sigma N_i D_i / \Sigma N_i$	comparions
Surface area	D20	$(\Sigma N_i D^2_i / \Sigma N_i D_i)^{1/2}$	surface area
Volume	D30	$(\Sigma N_i D^3_i / \Sigma N_i)^{1/3}$	volume controlling
Sauter (SMD)	D32	$\Sigma N D^3 / \Sigma N D^2$	mass transfer

The aerosol can be also be described by defining a mass accumulation diameter such that **all** drops below this diameter make up a certain percentage of the total mass of the aerosol. For instance, $D_{0.5}$ is that drop size such that 50% of the liquid volume is in drops of smaller diameter. The $D_{0.5}$ diameter is also referred to as the mass median diameter (MMD). Other common mass accumulation diameters are for 10%, $D_{0.1}$, and for 90%, $D_{0.9}$. As in the case for the mean diameters, aerosols with similar mass accumulation diameters can have that mass distributed very differently with respect to drop size. A more comprehensive characterization of the mist is required.

Histogram — A simple and practical method for displaying drop size information is to plot a histogram where the number of drops in a defined size bin is plotted for that bin. In practice, the minimum size plotted is dictated by the physical limitation of the instrument settings. A water mist histogram (obtained with a phase Doppler interferometer as discussed below) is presented in Figure 1. The mean diameters defined in Table 1 for this mist are indicated. In the limit of smaller bin size, the histogram becomes a frequency or size distribution.

Distribution — Since water drops of different sizes can exhibit different suppression effectiveness, information on the range of drop sizes or size distribution is necessary to compare the suppression performance of different mists and to make valid comparisons between experimental observations and modeling predictions. Several mathematical expressions for size distributions have been proposed although each of them has some shortcomings. The expression to use is the one that best characterizes the relevant properties of the mist under study. Two commonly used expressions are one describing the drops as a Gaussian distribution and another expressing this distribution by a mass accumulation [5]. The single expressions cannot adequately describe bi- or multi-modal distributions and linear combinations of the different single expressions are sometimes used.

The Gaussian or normal distribution with respect to the natural logarithm (lognormal) of the diameter is often sufficient to fit observed experimental drop size distributions.

$$N(d) = [0.399/(s*d)] \exp\{-[\log(d) - \log(dmn)]2/2s2\}$$

where d_{mn} is the number geometric mean drop diameter D10 and s is the corresponding standard deviation describing the spread in the distribution. The mass accumulation expression or the Rosin-Rammler distribution equation describes the aerosol distribution by relating it to the volume of liquid contained in all drops below a given diameter d. The Rosin-Rammler expression is

$$N(d) = (b/a^b) d^{b-4} \exp\{-(d/a)^b\}$$

where a and b are constants related to a mean diameter and the spread, respectively. Note that each expression has two parameters to describe the distribution. One advantage of using the Rosin-Rammler expression is that all of the representative diameters (e.g., $D_{0.1}$, $D_{0.5}$, etc.) can be related to each other through the spread.

Mathematical descriptions of the histogram (Figure 1) are presented (Figure 2) with a lognormal fit (dashed line) and a Rosin-Rammler fit (solid line). Although both expressions qualitatively describe the mist, the lognormal expression is a better match for this mist in both the peak position and the spread in the distribution.

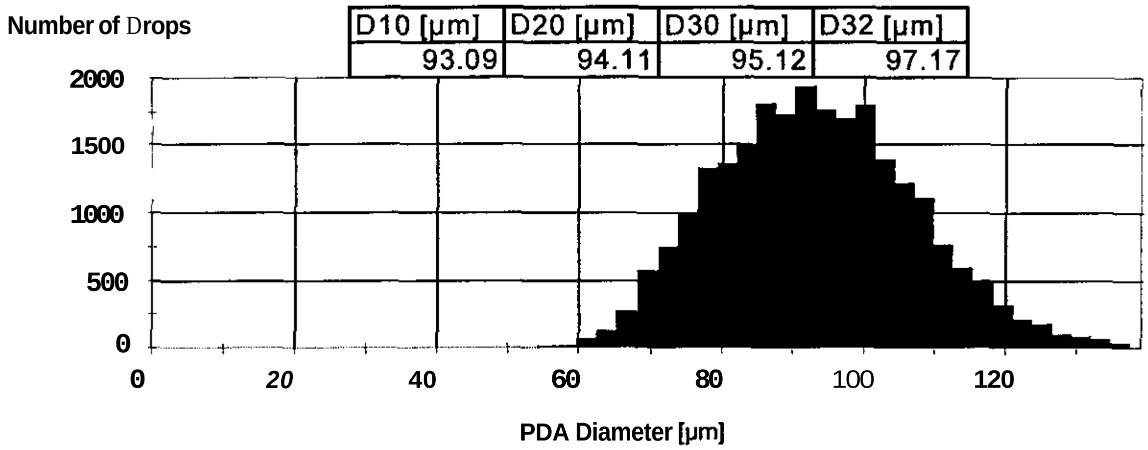

Figure 1. Water mist size histogram and values of the mean diameters defined in Table 1.

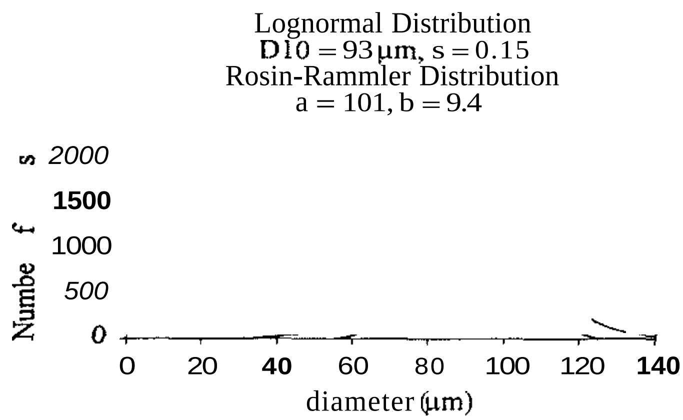

Figure 2. Lognormal (dashed line) and Rosin-Rammler (solid line) expressions fit to the water mist histogram (Figure 1) resulting in the indicated parameters.

MIST MONITORING SYSTEM REQUIREMENTS

In deciding what to measure, it helps to consider which is more important—drop sizing information or drop number density. The answer helps to guide the selection of the measurement system. In fire suppression system design the minimum amount of agent required to guarantee fire suppression is a key quantity. For water-based agents this means knowing the volume or mass of liquid water required. When measuring particles, deriving a mass or volume by assuming particles as equivalent spheres is sometimes questionable. For liquid aerosols, the assumption of sphericity is less of a stretch.

To emphasize the impact of a size distribution uncertainty or number density accuracy in the determination of total water mass, consider an equal number of 10 µm diameter and 100 µm diameter drops in a mist. The entire volume of the smaller drops is only 0.1% of the total volume of liquid. Not counting any of the small drops would not significantly alter the volume determination. Not counting 1000 of the smaller drops would be equivalent to missing only one large drop. For total water mass information, accurate drop size distribution with valid number densities for the largest drops is more important than overall number density. In fire suppression, smaller drops are more effective on a mass basis. Thus, to understand water mist fire suppression effectiveness, it is important to have accurate drop information delivered to the fire, including (1) drop size distribution, **(2)** drop velocity, and **(3)** drop size weighted, water mass flux. **For** modeling, information on the mist properties at the boundaries is required.

The earlier discussion on test conditions outlines several requirements necessary to be able to successfully characterize the mist drops. Many of these are common to aerosol diagnostics in general and to the characterization of spray systems in particular [6]. There are several requirements for a water mist monitoring field instrument suitable for testing under real-scale suppression conditions (listed below). Satisfying **all** of these requirements in the same instrument is tricky; however, employing optical approaches with fast detectors, electronics, and computers makes the task more feasible.

Water mist monitoring field instrument requirements suitable for fire suppression testing are **as** follows:

1. Capable of measuring both size and velocity
2. Quantifiable sample volume
3. Suitable dynamic range (with minimal configuration changes)
4. Capable of continuous data collection
5. Appropriate for mist and fire test conditions
    a. Non-intrusive (non-destructive)
    b. Flexible data collection (wider drop size distributions require longer data collection times; must balance speed **and** accuracy)
    c. Accurate (easily validated/calibrated)
    d. "Hardened" to withstand fire environment
    e. Mobility to allow sampling at different locations

Several sizing techniques are capable of making solid particle size measurements, though many of them require extractive analysis. The "fragile" nature of liquid drops makes most extractive methods problematic. Techniques that rely on in-situ drop collection followed by direct or indirect analysis methods (e.g., drop collection on specially prepared slides [7]) **are** less practical for real-scale fire suppression testing. However, the need to validate and/or calibrate the field instrument easily may well benefit from one of the techniques.

The requirement for both non-intrusive and non-destructive further limits the choices for a suitable field instrument. Most of the remaining requirements are best achieved using an optical based measurement approach. Those appropriate for the current task can be grouped into three general types according to the principle of operation: diffraction, phase Doppler, and imaging.

Diffraction Method — Diffraction based systems are capable of providing size information (either mass **or** volume) of an aerosol. The experimental layout is fairly simple (Figure **3). A** coherent light source and a two-dimensional detector (e.g., a linear array of detectors or a charge coupled device - CCD - camera) are needed. The laser light is directed **at** the detector passing through the sample volume containing the aerosol. Laser light diffracts around individual drops in the aerosol (Fraunhofer diffraction). The light intensity pattern falling on the camera is a superposition of **all** of the single drop diffraction patterns. By deconvoluting the diffracted intensity from the ensemble of drops, the mass or volume distribution can be derived. Diffraction methods do not rely on a spherical drop or particle, although the determination of volume or mass must assume some shape. The ease of set-up and essentially no calibration requirement make diffraction methods attractive.

Diffraction methods lack the spatial resolution of other optical approaches. They essentially measure everything that lies in the beam path. Because they rely on diffraction, higher power laser sources are needed. Diffraction methods also do not provide velocity information, and thus cannot provide flux information directly. Although the lack of velocity information is an issue, diffraction methods can provide drop size distribution and density information. From these an effective mass flux can be estimated for well-characterized flows.

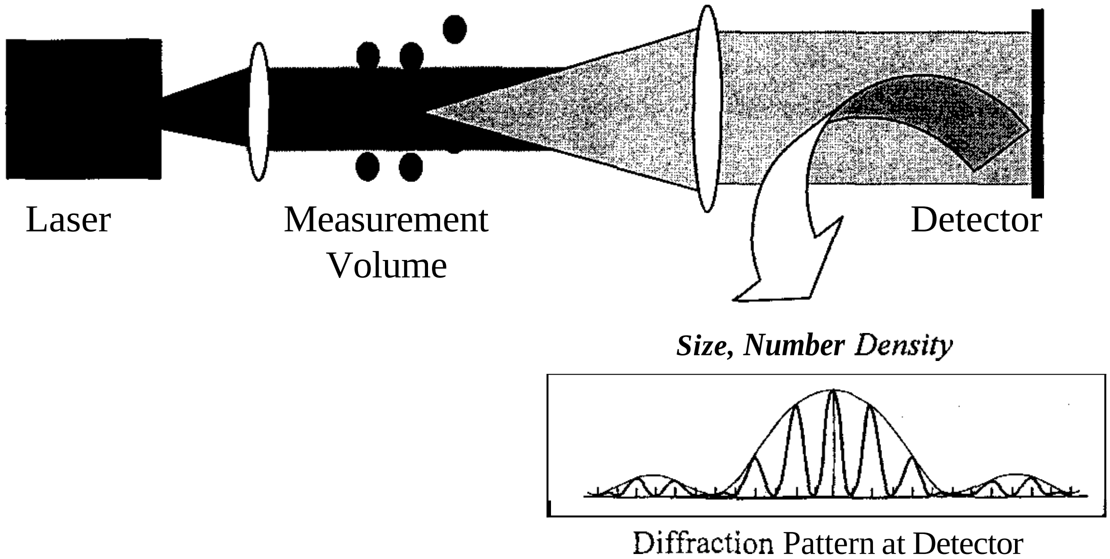

Figure 3. Schematic diagram for diffraction based particle sizing.

Phase Doppler Method — Phase Doppler Interferometry (PDI) is a well-established technique that can measure both size and velocity for a single drop. Measurement times can be as short as one microsecond so that statistically significant size histograms can be generated in one second. Drop sizes from ~1 μm to several mm can be measured, although not with a single system configuration. PDI drop sizing relies on the phase difference between two signals originating from the same point and arriving at two spatially separated detectors. Each signal is generated by a drop passing through a set of parallel grating lines produced from the overlap of coherent laser beams. The technique is shown schematically (Figure 4) with a representation for the ellipsoidal "grating" measurement volume. PDI determined diameters are only strictly valid for spherical drops. A third detector providing a second phase difference is used to check the sphericity requirement.

The grating line spacing is determined by the laser wavelength and beam-crossing angle. Passage of the drop through the grating generates a Doppler burst pattern containing the drop 1-D velocity information perpendicular to the fringes. 2-D and 3-D velocity information can be obtained but requires additional hardware to generate the respective gratings and detectors to generate and record the signals. The grating fringe spacing must be reasonable for the drop size in order to determine a valid burst pattern and provide the corresponding velocity. For closely spaced lines and large drops, there may not be sufficient modulation in the signal to qualify as a valid burst. Large spacings and small drops may not provide enough modulations for the phase shift validation. PDI signals can originate from light reflected from the drop surface or refracted through the drop. The angle of the refracted light exiting the drop is dependent on the liquid index of refraction that must be known. Although the reflected light does not depend on the index of refraction, its signals are generally much weaker. The choice of scattering angle will determine which scattering mode is dominant. If a single scattering mode is dominant, then there will be a linear correlation of the drop diameter with the phase difference. If more than one scattering mode significantly contributes to the signal, the phase angle/diameter relationship will not be linear. Typically, the first order refraction mode from the water drop measured at 30 deg (Figure 4) is used.

Uncertainty in the PDI size determination associated with the scattering angle and refractive index are generally less than a few percent. Because of the finite range for the detector, and the nonlinear dependence of the scattering intensity on the drop size, the usable dynamic range dictates a drop size dependent precision in the determination of the sizes. Additional potential limiting factors are the laser power,

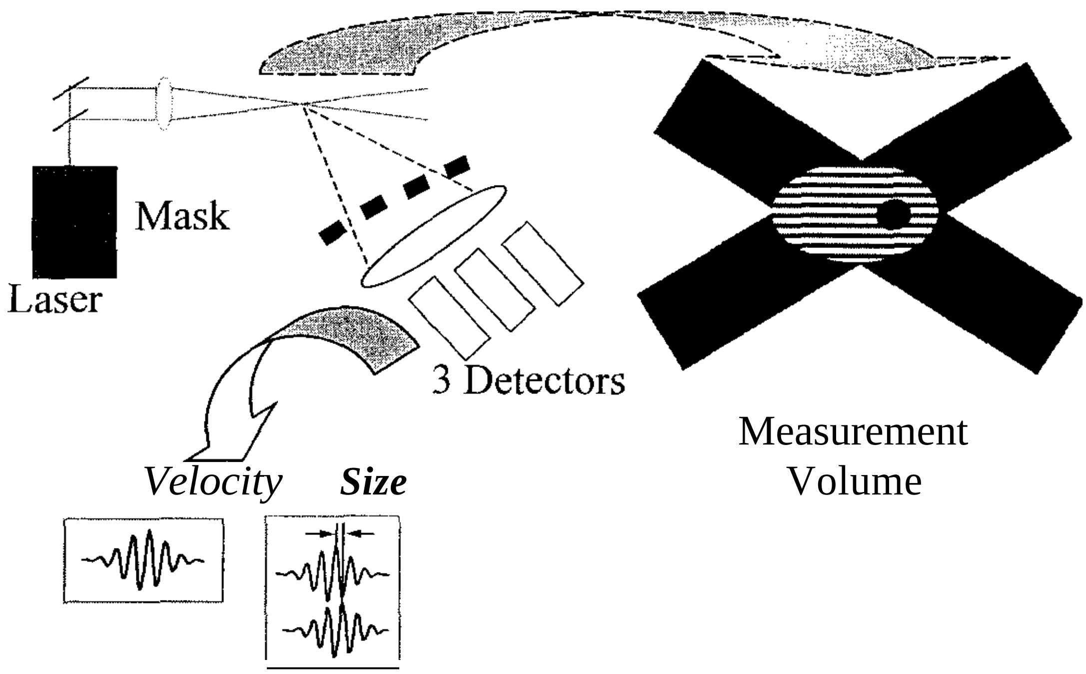

Figure **4.** Schematic diagram for 1-D phase Doppler Interferometry.

detector gain setting, and S/N ratio. These combined effects typically limit the uncertainty **for** a PDI size determination to at least 0.5% of the full-scale reading. Velocity uncertainties depend on the processor settings, primarily the need to divide the velocity space into a finite number of bins. Binning depends on the size range to be measured, which depends on the optical configuration used. In addition to the dependence on processor settings, uncertainties in the velocity determination depend also on the instrument A/D resolution, fringe spacing uncertainty, and sampling frequency and could be as high **as** $\pm$ *25%.*

The mass **flux** determination relies on the drop size, velocity, and the probe volume. The drop number density also relies on the probe volume. However, the probe volume is drop size dependent, requiring a correction for both number density and mass **flux.** The dynamic range for a single PDI system configuration is typically 40:1. This value depends on several factors including the optical system, laser power, detector gain and dynamic range, and system S/N ratio [4]. Obtaining accurate size information becomes a compromise between the size resolution desired and the range of drop sizes that can be determined.

Imaging Method—Capturing an image **of** the drops can often be more informative than just providing sizing and velocity information about the mist. Drop imaging techniques have been used extensively to study and understand sprays and spray formation and development [8]. The application of an imaging system for water mist fire suppression tests has now been demonstrated and is presented at this meeting [9]. In its basic form, an imaging configuration is fairly simple (Figure 5). It consists of a light source and a recording medium, either photographic **film** or more typically CCD cameras. The light source is normally a laser to provide sufficient spectral brightness in a short time period to "freeze" the motion of the drop. Drops can either be back illuminated in shadow method, **as** indicated in Figure 5, or illuminated from the front. The shadow method is most often used **as** the drop size dependent back-reflected light can complicate data collection. In shadow method, drop images appear as dark spots on a light background. 2-D velocity information in the image plane can be determined from timing drop exposure "tracks" or by double pulsing the light source, creating two images of the same drop displaced according to their velocity and the illumination time delay. Both images can be in the same camera frame or in subsequent frames. Software algorithms are employed to correlate the images permitting both speed and trajectory information. Some algorithms even permit rejecting false shadows that remain in the same location frame after frame (e.g., a drop or particle on a lens or window).

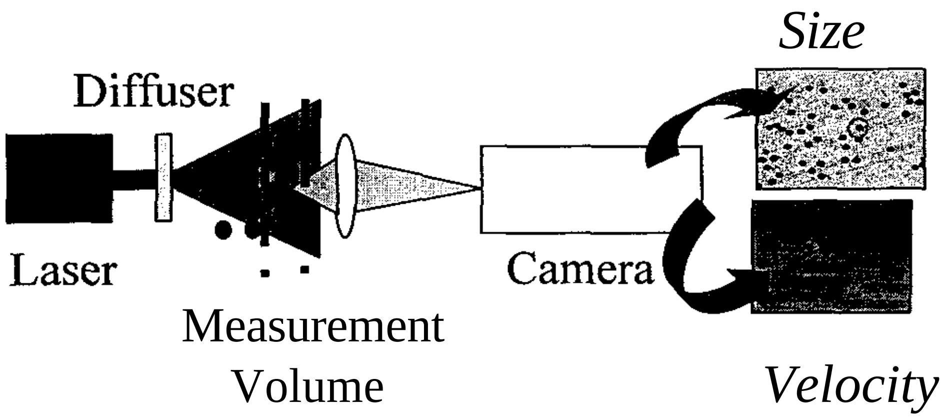

Figure **5.** Schematic of imaging method for size and velocity determination.

Unlike PDI, imaging techniques can he used for particles or non-spherical drops. Drop size imaging is the microscopic analog of Particle Image Velocimetry (PIV). PIV is used primarily to monitor bulk gas or liquid flows and relies on much smaller seed particles. Since size resolution is not desired, larger areas ($\geq$ 1m x 1m depending on the spectral brightness of the laser source and the collection optics) can be characterized.

Although photographic film can be used to record images, data collection options are more limited. CCD cameras provide greater flexibility. These cameras can be digital or analog. Digital recording demands large amounts of data storage if the raw images are saved. This limits the time for continuous data collection. Images can be processed either on-line or off-line. On-line image processing can generally store only a few images but a large amount of drop information. Off-line processing requires that the raw images he stored. Analog cameras with tape storage (usually superVHS) offer the advantage of long data collection times (several hours). Acquiring the raw images and performing off-line data reduction is an added time expense but can be an advantage. Repeated data reduction using different fitting parameters can sometimes identify issues with the data collection or point out systematic problems.

Drops ranging in size from a few microns to several mm may be imaged; however, the camera optics must he changed to cover specific discrete ranges. The measurement region that can be imaged depends on the magnification, but it is typically 1 mm^2 for detecting ~ 4 to 300 μm diameter drops. Similar to microscope optics, imaging magnification factors must he greater than one, which requires that the distance of the drops from the focusing lens be much shorter than the distance of the image from the lens. In practice this means that the sample volume must lie fairly close to the collection lens.

Size calibration for an imaging system is fairly straightforward. The accuracy for size measurements as well as for velocity are controlled by the lens focusing system, the media resolution (photographic grain limit or camera pixel resolution), and the determination of degree of focus. Since the data obtained are a mixture of in-focus and out-of-focus drop images, image reduction schemes must be employed to decide which images **are** in focus and then render sizes. The degree of focus impacts both the location of the drop edges and also the determination of the measurement volume.

The uncertainty in the measurement volume is the largest source of uncertainty for imaging detection. Both the drop number density and mass flux determination are impacted by this uncertainty. The measurement volume does depend on the size of the drop hut fortunately, computers can aid in eliminating the human bias in the decision making. The key to achieving a reasonable accuracy lies in the calibration and validation processes.

IN-SITU ISSUES

The working distance from the measurement region for a diffraction or phase Doppler instrument can be greater than for an imaging instrument. Even so, since the mist might be monitored throughout a fairly large test room, at least the collection optics and detector for each of the monitoring systems will be required to function inside the test compartment, exposed directly to the mist and fire environment. Water-tight enclosures are required for the detection hardware (lenses, camera, etc.) and for the laser and associated optics. **In** addition, because ofthe heat generation by the laser inside the enclosure, and the rise in test chamber ambient temperature, the enclosures must also be cooled and purged with dry air to avoid condensation inside the enclosures. Because optical access is necessary for each of the techniques considered here, each will have similar issues: purging the outer windows, condensation abatement possibly through heating of the window, and thermal sensitivity ofthe optical alignment.

Obscuration of the both the laser light and signal will adversely affect each of the techniques. Laser beam attenuation in a water suppressed test environment from smoke, water spray, or water mist for a near infrared beam can be greater than 99% during a fire suppression test [I0]. The impact is less problematic for the imaging techniques because the laser light is very diffuse. Successful drop imaging and size and velocity determination have been demonstrated in water mist suppressed fire tests [9].

CONCLUSIONS

There is a need to quantify the characteristics of water mist during real-scale fire suppression tests to understand the suppression process and give design guidance for water mist-based suppression systems. The size of individual water drops **as** well **as** the size distribution within the mist must be measured to evaluate the mist suppression properties. Knowledge of the drop size-weighted water mass flux near the fire is necessary to be able to quantify the amount of water getting to the tire. Many measurement systems were evaluated for obtaining the necessary mist information. Consideration of the test conditions and technical details are presented for three of the most applicable approaches: diffraction methods, phase Doppler methods, and imaging methods. Water mass flux determinations have the highest uncertainty regardless of technique, and such determinations are complicated by uncertainties in the drop velocity (compared to the relatively small size uncertainty), drop density, and drop size dependent probe volume. No one technique satisfies **all** of the instrument requirements, although imaging methods appear to hold the greatest promise. For well-characterized test conditions, proper attention to accuracy details, and careful calibration of the measurement volume, valid information can be obtained. Initial results using an imaging system illustrate the applicability of this technique to water mist fire suppression tests.

The water mist characterization approaches and their relative merits presented here **are** based on the need to test in Navy shipboard applications. The results are also relevant to **a** broader range **of** application and will lead to more optimized implementation of water mist suppression systems in the future.

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