WATER MIST VISUALIZATION AND DROPLET SIZE ANALYSIS IN LARGE-SCALE FIRE SUPPRESSION RESEARCH

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ABSTRACT

The Navy Technology Center for Safety and Survivability (NTCSS) is investigating water spray and water mist fire suppression systems for use in shipboard compartments. Water spray and water mist systems currently being tested include low-pressure [10 bar (150 psi)] water spray, with drop sizes on the order of 1000 μm or less, and high-pressure [138 bar (2000 psi)] water mist, with drop sizes on the order of 100 μm or less. The NTCSS is evaluating a laser-based particle/droplet visualization system at the Naval Research Laboratory-Chesapeake Bay Detachment (NRL-CBD) facility to simultaneously determine droplet size distribution and velocity at two positions in a 28 m^3 (1000 ft^3) fire suppression test compartment. The goal is twofold: (1) determine what mist/spray properties—drop size distribution, velocity, and number density—at the fire result in the most effective fire suppression; and (2) determine what mist/spray properties at the nozzle are required to provide the most effective spray/mist at the fire. Issues regarding implementation and limitations of the visualization system, including system protection, performance verification and sampling considerations are discussed.

INTRODUCTION

The effectiveness of water mist and water spray for fire suppression has been reported throughout the 1990s [1-5]. These sources report the ability of water mist and water spray to (a) extinguish large, and to some extent small, obstructed fires; (b) scrub smoke; and (c) cool compartments **all** with minimal environmental impact. The performance of water mist and spray systems in terms of size distribution, number density, and velocity has not been reported in intermediate to large-scale fire suppression scenarios specifically with regard to the quantities of "wet" oxygen and water vapor. Furthermore, the fate of water drops as they move from a nozzle, through the hot layer, to the tire and into the flame sheet has not been characterized, much less optimized, with respect to fire suppression effectiveness. To support such an effort, the NTCSS surveyed and evaluated technologies available for drop size distribution, number density, and velocity determinations **[6]**. The result **was** acquisition of a commercial particle/droplet image analysis system from Oxford Lasers Ltd. [7] to complement instrumentation already present at the small- and intermediate-scale fire research test facility **at** NRL-CBD. This paper discusses adaptations to the system for fire suppression testing, initial phases of installation and performance evaluation.

PRINCIPLES OF OPERATION

GENERAL DESCRIPTION

The system installed at NRL-CBD employs two, pulsed-diode lasers emitting **808** nm light. Laser optics diffuse the laser light, back-illuminating a "probe volume." Drops in the probe volume obscure the light. Two charge-coupled device (CCD) cameras (one digital and one analog output) image the drop shadows. Image analysis software calculates drop size at a rate of 15 frames per second (fps) and 30 fps for the digital and analog cameras, respectively. By varying camera optics, drops in discreet ranges from 5 to **5000 μm** may be imaged. For velocity determinations, the laser may be pulsed twice per camera frame, obtaining two images of the same drop in each frame. The image analysis software calculates the distance between the two drop images, determining both speed and velocity. Furthermore, the capability to pulse the laser up to 4 times per frame while monitoring real-time images enables flow visualization. The images from the digital camera system are analyzed real-time while the analog camera output is recorded to videotape. Post-test, the analog data are played back into the system for analysis. Recorded analog data may be reanalyzed using varying system settings (run time, rejection parameters, correction factors) to optimize data quality.

SYSTEM DETAILS

The lasers employed by the system are 200 Watt, class 4, pulsed-diode lasers operating at 808 nm with a user definable pulse duration ranging from 1 - 80 μs. The laser may be pulsed one to four times per camera frame with a user-defined pulse separation.

The digital camera is an 8-bit, monochrome, one megapixel camera operating at 15 fps. A frame synchronization signal is generated by the camera and used to synchronize the laser pulse through the laser controller. The analog camera employed is a black and white camera that collects approximately 0.3 megapixel images at a rate of up to 30 fps. The analog video output has a frame-synchronization signal superimposed on it, which is stripped from the video signal using a "sync stripper." The stripped signal is routed to the laser controller to trigger the laser at the beginning of the frame (Figure 1).

The control console houses the laser controllers, CPU, sync stripper, VCR, a black and white monitor, *two* CRTs, and power for the entire system. Output from either the digital or analog camera may be displayed live on the 2nd CRT. During analysis using both systems, the digital camera output is displayed at 1 fps on the 2nd CRT, while the analog camera output is displayed real-time on the black and white monitor and simultaneously recorded to the VCR.

CAMERA AND LASER PROTECTION

Both cameras and lasers require protection from the harsh environments expected during the water mist and water spray fire suppression testing. The systems will be located at times in the hot layer and as close to the fire as possible. Stainless steel enclosures have been constructed to protect the cameras and lasers from heat, water, and combustion products. Each enclosure is a modified 15.2 x 15.2 x 61 cm (6 x 6 x 24 inch) stainless steel cable trough. The front and back of each enclosure are 19 x 19 cm (7.5 x 7.5 inch) stainless steel faceplates. The front plates of each enclosure have a 6.4 cm (2.5 inch) circular opening to which 0.64 cm (0.25 inch) thick borosilicate glass is attached using both a high-temperature, silicone, adhesive-sealant and an aluminum disk fastened to the front plate. A 4.5 cm (1.75 inch) diameter hole in each aluminum disk allows laser light to exit each laser enclosure and enter each camera enclosure. The back of each enclosure is outfitted with a nitrogen inlet and outlet, a cooling water inlet and outlet, and quick-connect electrical connections. The nitrogen purge is used to create a positive pressure within each enclosure to protect it from compartment air infiltration. Cooling water is circulated through a heat exchanger made from 0.64 cm (0.25 inch) diameter, refrigeration-grade copper tubing. The quick-connect electrical connections facilitate rapid installation and removal from the test compartment without opening the enclosures. Alumina sheet insulation along the interior walls of the enclosures provides additional thermal insulation. Each camera/laser pair is mounted on a rail. The separation distance between the camera and laser is fully adjustable (Figures 2 and 3).

The front windows of the camera enclosures are also outfitted with a metal awning through which a nitrogen purge is connected *and* directed at the glass window to minimize light-obscuring condensation and water droplet accumulation. Supplemental condensation protection is provided by a window defogger, made from a semi-resistive, silver paint through which 12 volts DC is passed. Light entering the camera enclosures is filtered through a narrow band pass filter, which passes 808 nm light and blocks visible and other infrared light.

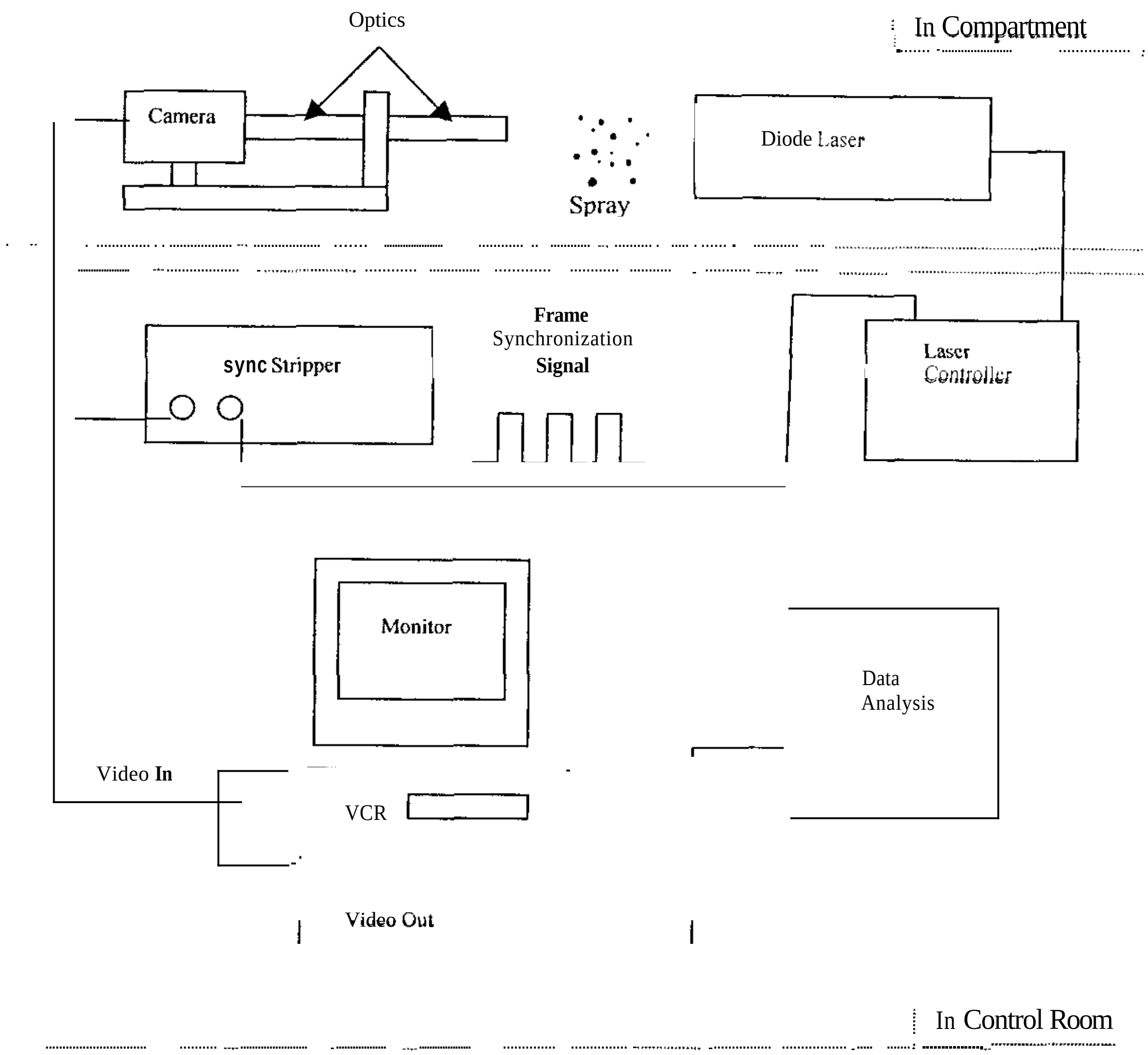

Figure 1. Analog system schematic adapted from Oxford Lasers, Ltd. [7].

SYSTEM CAPABILITIES AND PERFORMANCE VERIFICATION

DROP SIZE AND DISTRIBUTION

Many factors are used to determine an accurate drop size distribution, including the field of view (FOV), micron per pixel calibration factors, and software applied correction factors. The field of view is a factor of the particular **lens** configuration and magnification setting of the camera optics. Each lens configuration and magnification setting has associated with it a range of drop sizes that can be determined. The manufacturer's recommended upper size limit is 1/3 FOV; the approximate limit of quantification is 1/100 FOV. **A** drop with a diameter less than 1/100 of the FOV can still be detected, but its small pixel area inhibits accurate size determination. The approximate limit of detection is 1/200 FOV. Table 1 includes a partial listing of field of view parameters and drop size capabilities for given lens configurations for the analog camera. Micron per pixel calibration factors were verified by obtaining images of 108 and 15 μm diameter NIST-traceable microspheres. Number-mean diameters for the size standards were typically within **2%** of the nominal value. Table 2 contains data from the digital camera size verification tests.

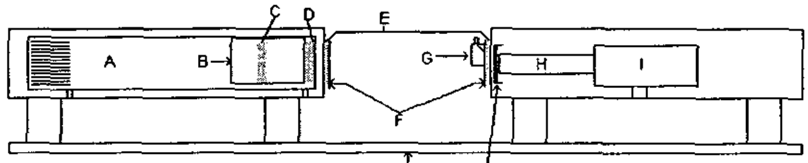

Figure 2. Schematic of camera and laser enclosures mounted on a rail.

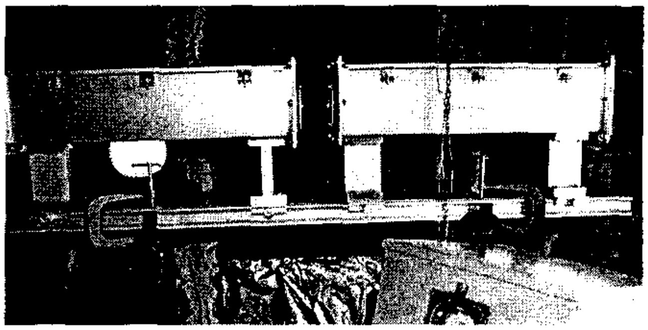

Figure 3. Camera and laser enclosures in 28 m^3 compartment.

TABLE 1. PARTIAL LISTING OF FIELD OF VIEW PARAMETERS FOR ANALOG CAMERA.

Magnification Setting	Lens Option 1				Lens Option 3			
	Field of View (μm)	1/200 FOV (μm)	1/100 FOV (μm)	1/3 FOV (μm)	Field of View (μm)	1/200 FOV (μm)	1/100 FOV (μm)	1/3 FOV (μm)
0.58	4303	21	43	1434	17214	86	172	5738
1	2496	12	25	832	9984	50	100	3328
2	1248	6.2	12	416	4992	25	50	1664
3	832	4.2	8.3	271	3328	17	33	1109
4	624	3.1	6.2	208	2496	12	25	832
7	357	1.8	3.6	119	1426	7.1	14	415

1/200 FOV - Limit of Detection, 1/100 FOV ~ Limit of Quantification, 1/3 FOV - Upper size limit

TABLE 2. DIGITAL CAMERA DROP SIZE VERIFICATION TESTING.

Certified Diameter	Measured	Certified Diameter	Measured
108 ± 4 μm	**110.4± 4.5 μm**	**14.9± 0.6 μm**	**14.5 ± 1.0μm**

The software has the capability to apply several different correction factors and rejection parameters, such as focus rejection, depth of field correction, border contact rejection, and edge contact correction. Focus rejection discards any drops not within a user defined acceptance distance. The acceptance distance setting can be used to limit the depth of the observed volume over which the system counts drops. Generally, the acceptance distance is less than the field of view. Depth of field correction accounts for the fact that a small drop, relative to the FOV, has a higher probability than a large drop, relative to the FOV, of being out of focus at the extremes of the acceptance distance, and therefore not counted. The correction applies a multiplier, as a function of the lens option, drop size, and acceptance distance, to the number of drops seen of that size. Border contact rejection is applied to drops that are only partially within the field of view. Edge contact correction accounts for the higher probability of larger drops being only partially within the field of view. The correction applies a multiplier, as a function of the lens option and the drop size, to the number of drops seen of that size. The system accurately determines the size of drops on the order of 15 to 100 μm. However, verification of the accuracy of the corrections above when applied to a range of drop sizes in a 3-dimensional spray event is still in progress.

Analog System		Digital System	
Calculated	**Measured**	Calculated	Measured
5.6 m/s	5.5 ± 0.3 m/s	2.4 m/s	2.4 ± 0.1 m/s
4.1 m/s	3.7 ± 0.5 m/s	5.9 m/s	5.5 ± 0.2 m/s

uated as testing progresses. To map the spray event within the compartment, sampling locations have been chosen at the following locations: near the nozzle, one meter below the nozzle, and near the fire. Data from tests, with and without a fire, using these sampling locations will enable the determination of nozzle spray properties and the fate of the water mist/spray drops as they travel from the nozzle, through the hot layer and to the fire.

LIMITATIONS

NUMBER DENSITY

The drop visualization system determines drop size distribution and velocity directly. At most, the probe volume is illuminated for 10% of the time; however, in practice it **is** illuminated for <1% of the time. As a result, most drops that pass through the probe volume do so when the area is not illuminated. The number density must be estimated by sampling for known time intervals that ensure statistical accuracy.

VELOCITY

The velocity reported for each drop is the component of the velocity vector in the focal plane. The velocity of a drop traveling at an angle with respect to the focal plane will differ from the vector representation of the drop velocity in the focal plane. Optimizing the orientation of the system with respect to the anticipated spray trajectory increases the accuracy of velocity determinations. Software rejection parameters, which minimize velocity error, will be evaluated.

STANDARD SPRAY

Attempts have been made to generate a standard three-dimensional spray with a known drop size distribution and velocity distribution such that the performance of the system can be verified in one step. This effort continues.

CAMERA WINDOWS

Despite the presence of a both a nitrogen stream directed at the camera enclosure windows and a window defogger, accumulation of water in the form of condensation and droplets can attenuate the laser intensity reaching the camera. This gradually decreases the contrast of the image and can ultimately block it. Development of more effective purge and defogger systems will continue during performance verification.

SYSTEM SETTINGS

Laser pulse separation, camera optics, and magnification, cannot be changed during a data collection. The laser pulse separation is a numerical value that can only be entered into the software before data collection, upon which all subsequent velocity calculations are based. Changing the camera optics and magnification settings requires opening the enclosure. The laser duration can be adjusted remotely during collection, but the chances of affecting the drop image contrast adversely, as well as blurring a rapidly moving drop, are key concerns.

FUTURE PLANS

Performance verification is underway to evaluate software corrections applied to drop size distribution and velocity determination during three-dimensional spray events. Monitoring of enclosure performance when placed near the hot layer and fire will be carried out to establish the range of operating conditions. In the very near future, the system will be employed to measure routinely the spray performance in terms of size distribution, velocity, and number density and determine the fate of water mists and sprays during fire suppression testing in planned water spray and water mist test series at NRL-CBD.

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