A UNIQUE TWIN-FLUID WATER MIST NOZZLE CREATES AN EXCEPTIONALLY HIGH VELOCITY, FINE SPRAY

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ABSTRACT

A twin-fluid water mist nozzle has been developed which produces droplets with a Sauter Mean Diameter, D(3,2) less than 5 microns and droplet velocities on the order of 400 m/s at the nozzle exit. A converging-diverging nozzle is used to accelerate a nitrogen-water mixture to suuersonic velocities. Because of the complexity of flow phenomena withn the nozzle, a computational fluid dynamics approach was taken in designing the nozzie. Various parts of the nozzle were analvzed, and parametrically varied to determine the best designs to test, and optimal conditions at which to run them. Calculations showed that adding a water mass flow equal to the gas mass flow reduced the exit mach number by over 40% compared to a nozzle with no water injection. Injecting water into the diverging section of the nozzle created a large, undesirable shock, and was avoided. Water was injected earlier in the nozzle contour.

Four prototype water mist nozzle configurations were fabricated and tested. Droplet size distribution and velocities at two distances from the discharge were measured using a Phase Doppler Particle Analyzer. Droplet velocities of 100 m/s were measured 8" from the nozzle exit, and 36 m/s were measured 36" from the nozzle exit. Extensive drop size measurements were also taken with a Malvern drop sizing instrument. Computational fluid dynamics predictions of dropiet size and velocity compared well with measured size and velocity.

Pan fire extinguishing tests will be performed to gauge the twin-fluid water mist nozzle's effectiveness. The nozzle shows good promise to fill a need for halon alternatives.

INTRODUCTION

With the phase-out of halon fire suppression agents, many alternatives have been proposed and studied. Water mist svstems have generated great interest because water poses no environmental problems and water's heat of vaporization is almost twenty times that of Halon 1301, orfering the potential to quickly quench a fire. Previous water nozzles have produced water droplets with diameters around 40-100 microns and velocities less than 30 m/s. While this meets the definition of a water mist nozzle, smaller drop sizes and higher velocities may be beneficial. Smaller drop sizes will increase the quench rate, reduce the mass of water required, and may better serve total flooding applications with obstructions. Droplets with high velocities will reach the fire quickly, and will have enough momentum to reach a fire and penetrate it.

This development effort is primarily directed to fire protection in Naval aircraft. The unique performance of the nozzle will make it effective in other applications also. The design goals centered around measurable nozzle exit properties. Very high velocity, small droplets were desired with the lowest gas-liquid mass flow ratio possible.

WATER MIST NOZZLE DESIGN

The water mist nozzle was primarily developed using CFD analysis. CFD was the most appropriate approach because the design involves complex two-phase flow, turbulence, gas compressibility, atomization, and secondary droplet break-up. Design variables which were optimized included gas inlet pressure, nozzle geometry (length, converging contour, diverging contour), water injection scheme, and gas-liquid ratio. In the course of the CFD analvsis, several significant conclusions were drawn.

1. Accelerating water to high velocity imposes a significant momentum penalty on the gas flow. An increase in the water mass flow, for the same gas flow, will reduce the velocity of the gas.

2. Droplets in supersonic flows do not follow the streamlines well unless their diameter is less than 5 microns.

3. Nozzles with a gas-liquid ratio of 3 down to 1 perform well, with high exit velocities. As the ratio drops below 1, the exit velocities deteriorate markedly. At a ratio of 0.3, parts of the nozzle have become subsonic.

4. Secondary droplet break-up has a significant influence on nozzle performance. High velocities in the nozzle can continue to break up the water as it is carried toward the exit.

NOZZLE DROP SIZES

Brass prototypes were fabricated for evaluation. The primary evaluation criteria for the nozzle performance were droplet diameters and velocities. A Phase Doppler Particle Analyzer, PDPA, (based on laser velocimetry) was used to measure droplet velocity and size. The drop sizes were less than 15 microns, the bottom range of accurate measurement for the PDPA, so sizes were also measured with a Malvern instrument (based on laser diffraction). The Malvern can measure drop sizes accurately down to 5 microns with the configuration used.

Both instruments generate several different drop size values for the sprav. Sauter Mean Diameter, D (3,2), is the diameter of a drop having the same volume-surface area ratio as all droplets measured. Volume fraction diameters are the diameter of drop encompassing less than the given volume of droplets. For example, D(v,90) is the diameter of droplet for which 90% of the sprav volume has smaller drop sizes. A log-normal distribution was fit to the diameter data and a geometric mean and standard deviation, $\bar{X}$ and N, were caiculated. These two values were corrected for the high sprav densitv (extinction). Other diameters such as number fraction [i.e. D(n,90)] and mean number [D(1,0)], were not useful because the values were below the accuracv limits of the instruments.

Four different injection schemes were tested over slightly different ranges of gas-liquid ratio (GLR), but generallv falling between 0.1 and 5.0. All nozzles performed well. Figure 1 shows typical photos of the water plume exiting the nozzle. The mist is quite fine, well mixed with the nitrogen, and flowing at high veiocitv. Both veiocitv and droplet size measurements were similar for all four injection schemes. Differences observed will not be discussed in great depth.

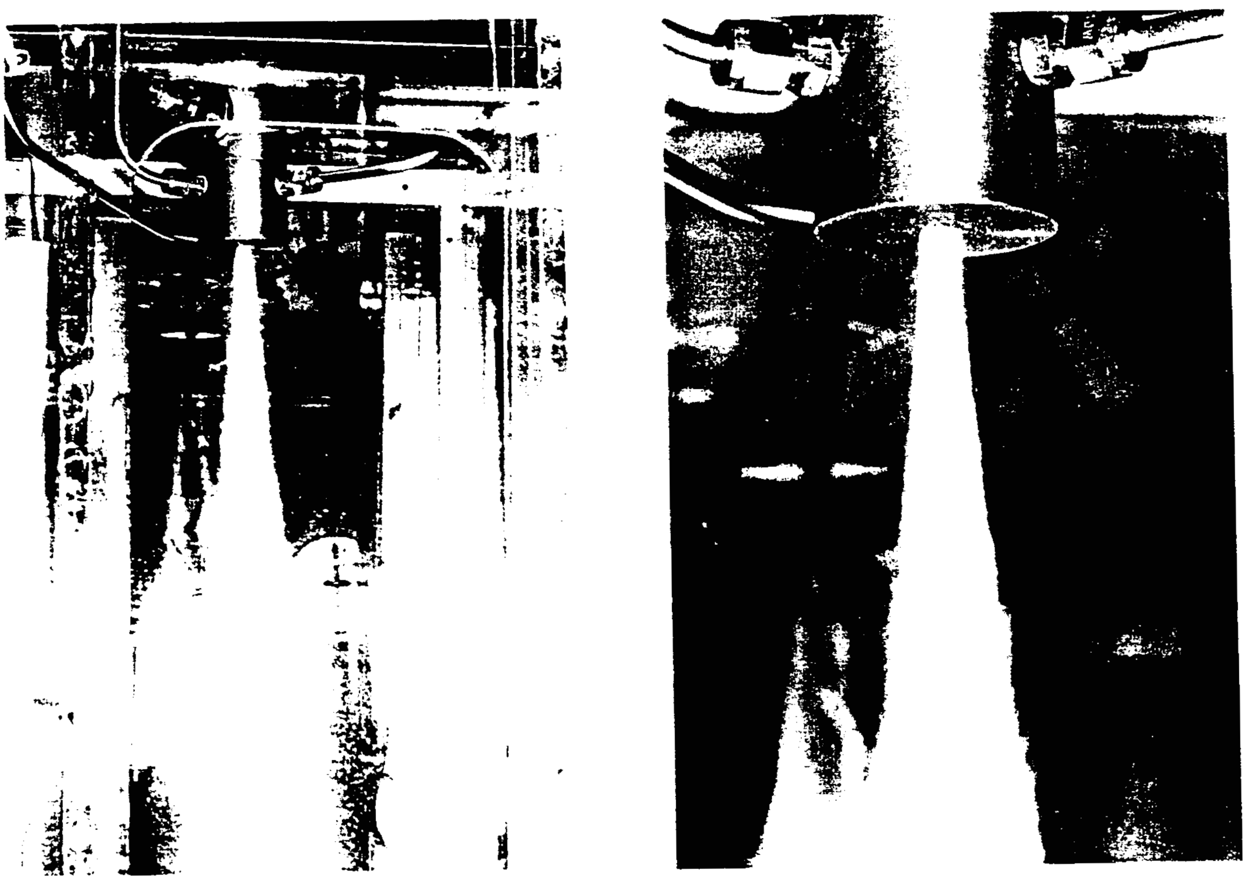

Figure 1 Photographs Show the Nature of the Water Mist

For GLR of 0.7 to 5.0, the gas phase conditions were constant. The water **flow** rate was vaned by changing the water pressure. For GLR of 0.1 to 0.7, the water pressure could not be increased, so the gas mass flow was reduced by dropping the inlet pressure. The nozzle was no longer operating under design conditions. Dropping the gas pressure no longer allowed an ideally expanded nozzle exit flow. The resulting oblique shocks quickly reduced the gas velocity downstream of the nozzle. Figure 2 contrasts the calculated gas velocities downstream of an ideally expanded nozzle versus an over-expanded nozzle. Both cases have no water injection. The data begins at the nozzle exit where both cases have similar gas velocities. The over-expanded case (reduced inlet pressure) shows the rapid decrease in velocity downstream of the nozzle exit. The slower gas velocity, compared to the ideally expanded case, will result in lower droplet velocities. CFD shows that running the reduced inlet pressure is not ideal if high droplet velocities are desired.

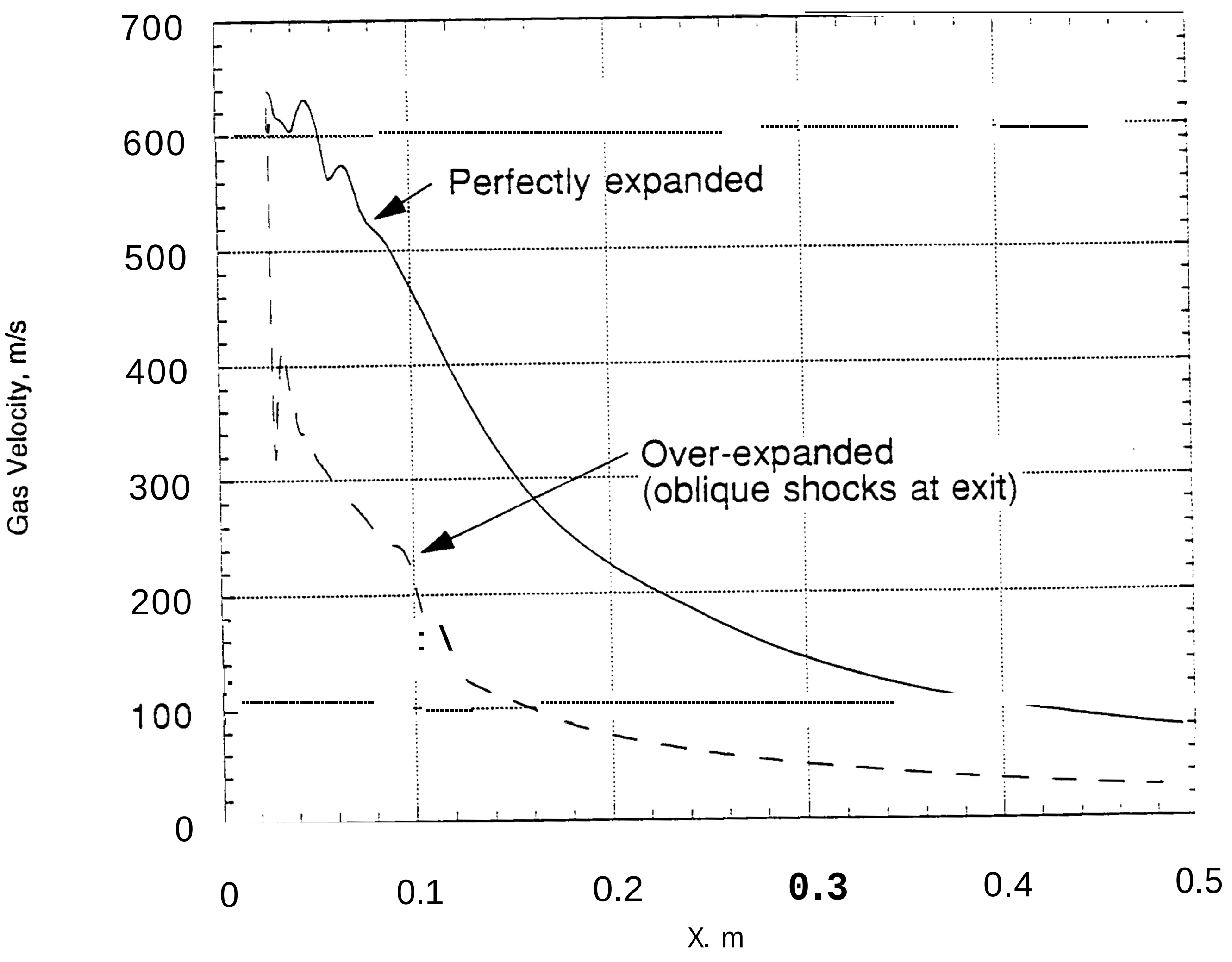

Figure 2. An Ideally Expanded Nozzle Maintains Higher Velocities Downstream of the Nozzle Exit

Drop sizes generated by the water mist nozzle were exceptionally small. For GLR of 0.8 to 5.0, drop sizes were essentially constant. As GLR decreased below 0.8, larger drop sizes were measured. Drop size data presented was measured 12" from the nozzle exit with the Malvern instrument. Table 1 summarizes drop size results for one nozzle. All droplet diameters are in microns.

GLR	1.67	3.53	0.71	0.32
$M_{nitrogen}$ (kg/s)	0.054	0.054	0.054	0.031
M_{water} (kg/min)	2.1	4.2	4.9	5.78
D (3,2)	3.4	3.4	3.8	13.9
D (v,10)	2.1	2.1	2.1	2.2
D (v,50)	3.7	3.7	4.2	28.6
D (v,90)	7.4	***3.6***	12.7	138
$\bar{X}$	3.9	3.3	3.6	49
N	1.74	2.10	2.42	2.58

These drop sizes are generally below the ideal range for either the Malvern or PDPA instruments. Comparisons below 5 µm should only be qualitative in nature. The larger drops seen at low GLR could be due to either 'the effect of the low GLR or the fact that the gas phase flow was off-design. CFD predicted lower gas velocities in areas with low GLR. The lower gas velocity and the lower gas density would both tend to increase drop sizes. The nozzle design could be further optimized to yield smaller drop sizes with lower GLR.

CFD showed that secondary droplet breakup was a significant phenomena in the water mist nozzle. As the gas moves through the nozzle, it accelerates to high velocities. The relative velocity between droplet and gas typically increases because the gas accelerates faster than drag forces accelerate the droplet. The slip velocity can exceed 100 m/s. When the relative velocity reaches a high enough value (based on Reynolds and Weber numbers) the droplet breaks up into smaller droplets. After break-up, the relative velocity can increase again and repeat the cycle.

Figure 3 shows the droplet size history as a function of the absolute droplet velocity for one case. Various sizes of drops are generated by the initial atomization process. Droplet traces are shown for droplets with initial sizes of 10, 20, 30, and 50 microns. The droplet increases in velocity until it begins to break up. The figure shows larger drops break up more quickly (at lower velocity) than small drops. Their change in diameter is also more significant the first several times break-up occurs. All the droplets in this case repeat the break-up and acceleration cycle many times before reaching their final diameter. For the water mist nozzle, the predicted droplet diameters were 1 - 10 microns. The code does not predict the statistical diameters such as D(3,2) or D(v,50). However, the predicted diameters are in the same range as the measured values.

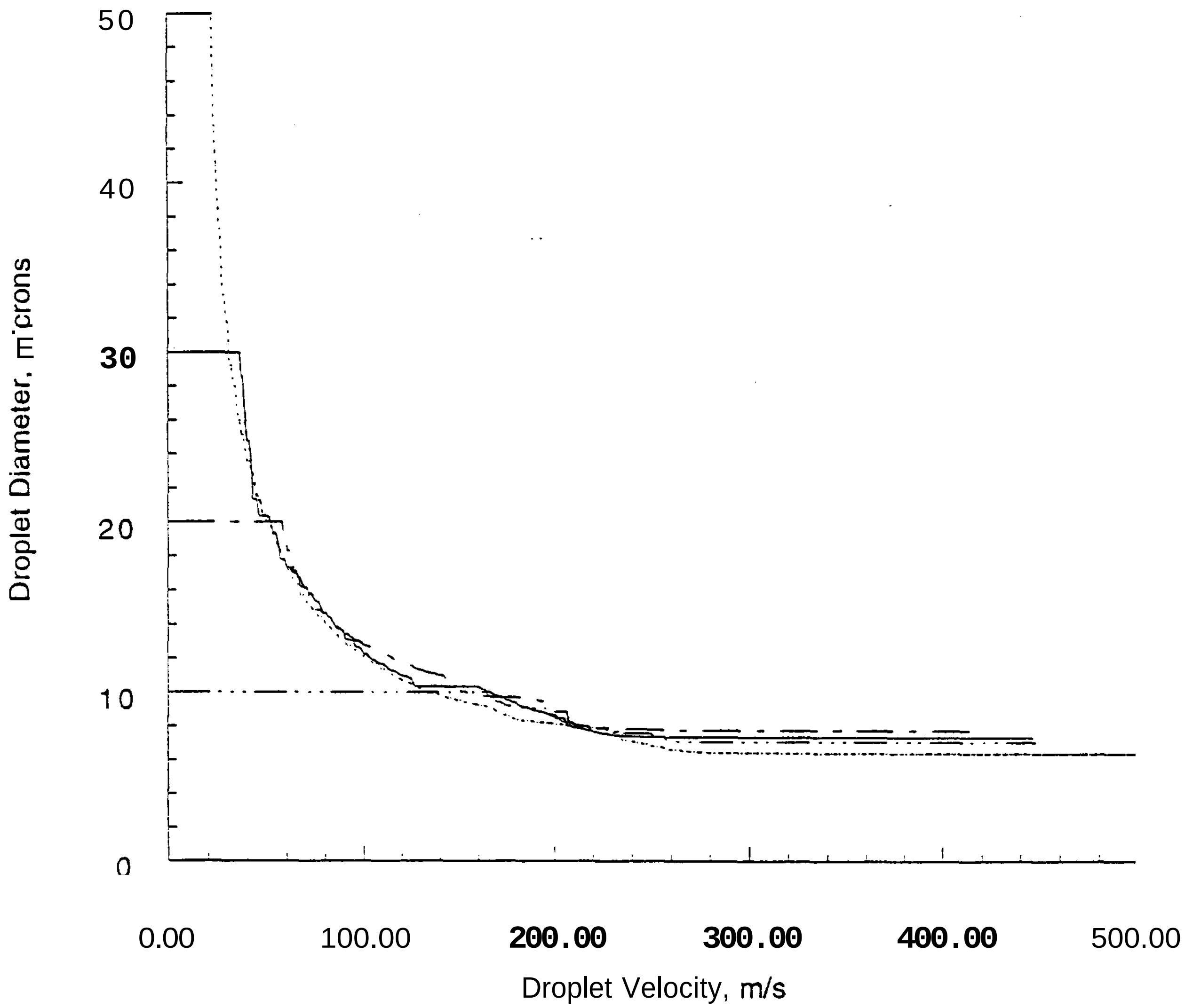

Figure 3. Droplets Break Up to Smaller Diameters as They Accelerate

For the purposes of a water mist nozzle in a fire extinguishing application, the water droplets are extremely fine. As a result, evaporation rates will be very high.

NOZZLE DROP VELOCITY

Droplet velocities were measured on the spray plume centerline with the PDPA, with most data taken 8" from the nozzle exit. The 8" distance was chosen instead of the nozzle exit because the spray at the nozzle exit is very dense and has a very high velocity. Both those factors made measurements at the nozzle exit difficult. An overview of the droplet velocities measured is presented in Figure 4. The different nozzle configurations represent different water injection schemes. For a range of GLR between 0.7 and 1.7, the velocity is fairly constant. As GLR is increased above that range, the droplet velocities increase. When GLR was reduced below 0.7, velocities began to drop off markedly. This is due to the combined effect of the GLR change and the introduction of oblique shocks at the nozzle exit when the gas inlet pressure was reduced. Again, additional design optimization would improve the low GLR performance.

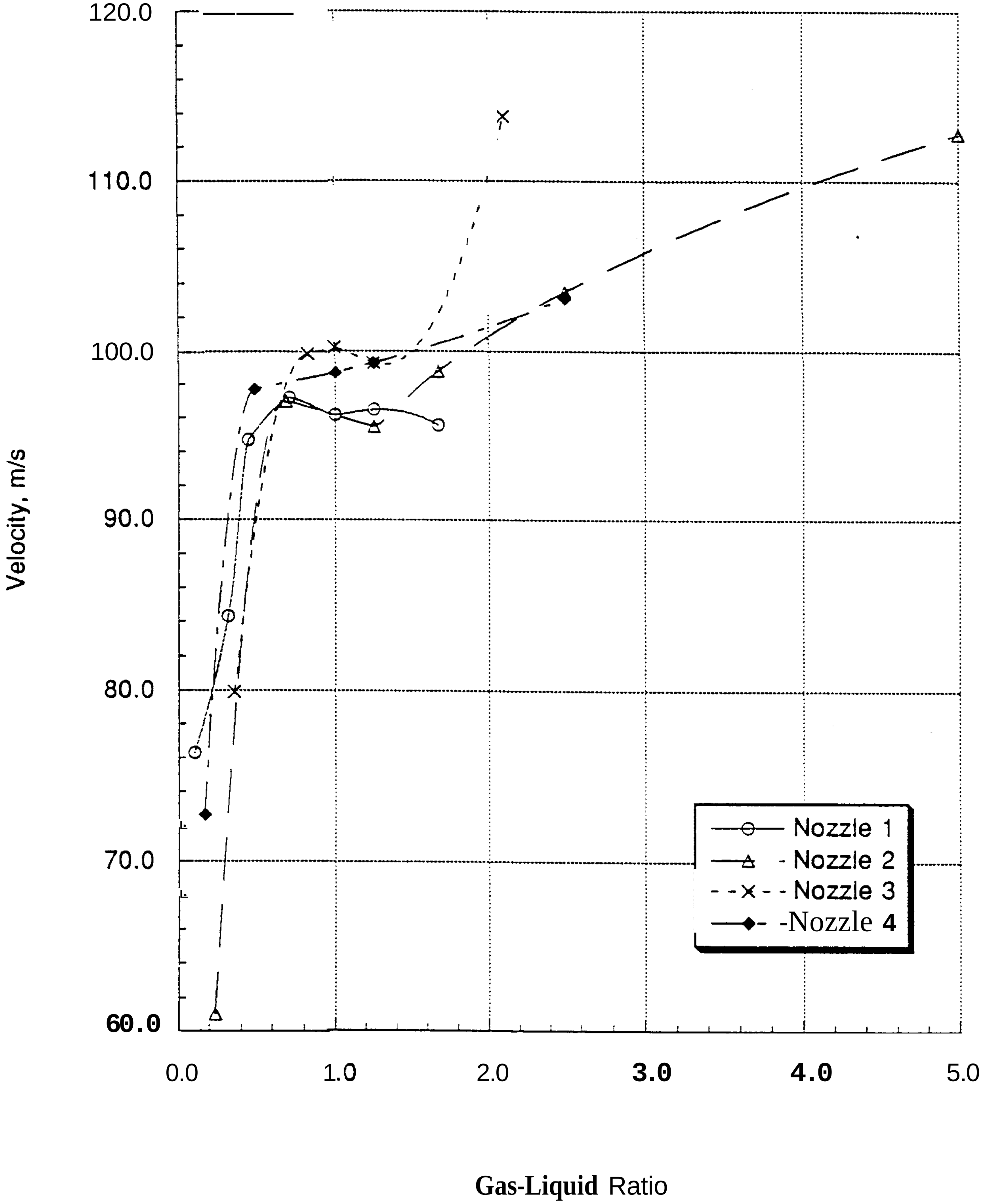

Figure 4. Droplet Velocities are a Function of Gas-Liquid Ratio

For a typical GLR=1.0 condition, the PDPA velocity distribution histogram is shown in Figure 5. The figure shows that droplet velocities vary a nominal amount above and below the mean veloaty. The RMS velocity is 13%of the mean. The PDPA was also used to correlate droplet velocities with diameters at this condition. **A** scatter plot generated by the PDPA is a compilation of the velocity and diameter of all the drops measured. Figure 6 shows the plotted data points with a line denoting a mean relationship between drop size and velocity. The plot shows that the droplet velocity is independent of droplet size. **All** sizes of droplets vary over the same velocity range.

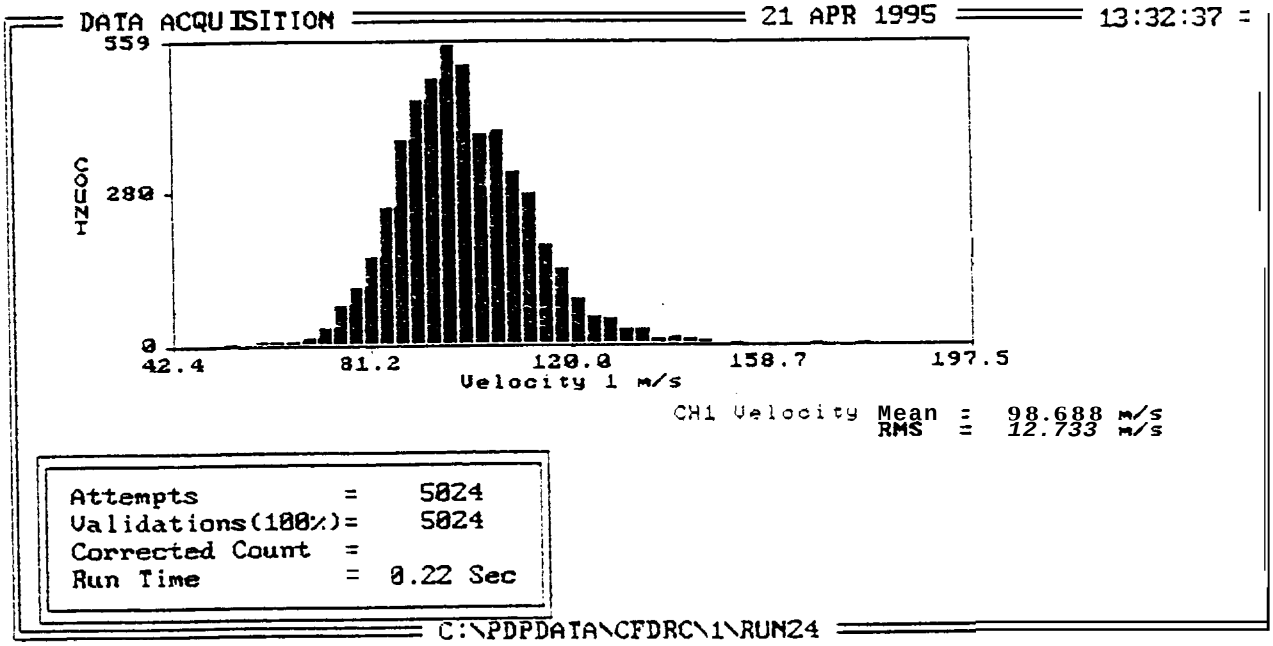

Figure 5. Typical PDPA Droplet Velocity Distribution

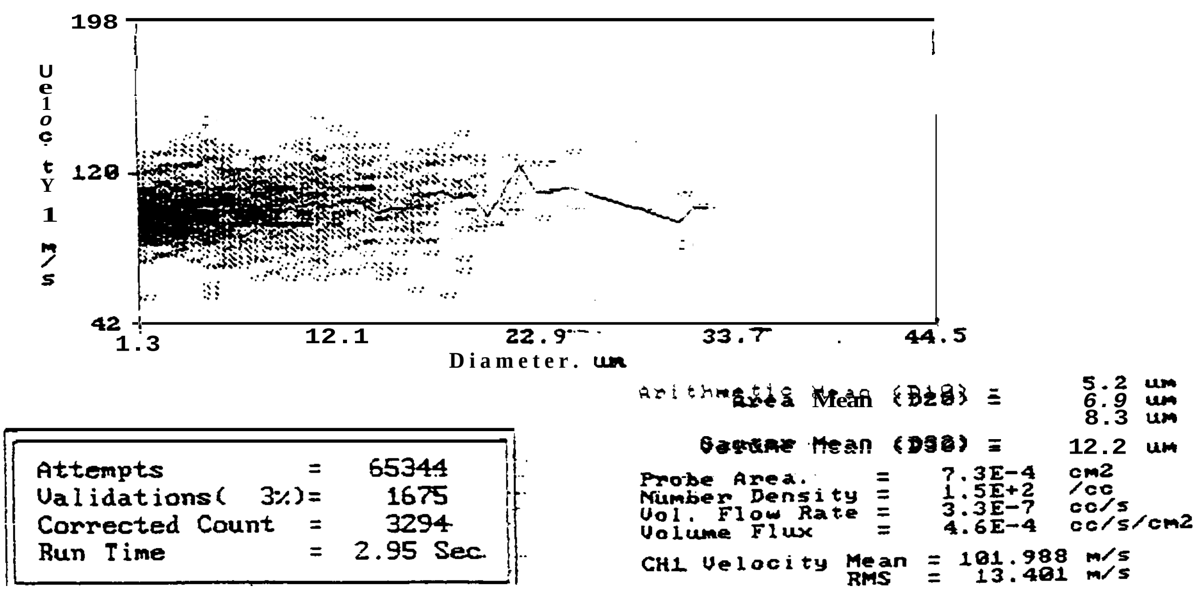

Figure 6. PDPA Indicates Droplet Velocities are Independent of Their Diameter

The nozzle design was also evaluated 36" downstream of the exit. At this distance downstream, the droplets will have reached a quasi-steady state with the gas flow. The continuing effects of turbulence, however, preclude all the droplets from achieving a uniform velocity. The mean velocity 36" downstream was measured as 36.0 m/s. Figure 7 shows that the droplet velocities do vary over a wide range. The RMS velocity is 32% of the mean.

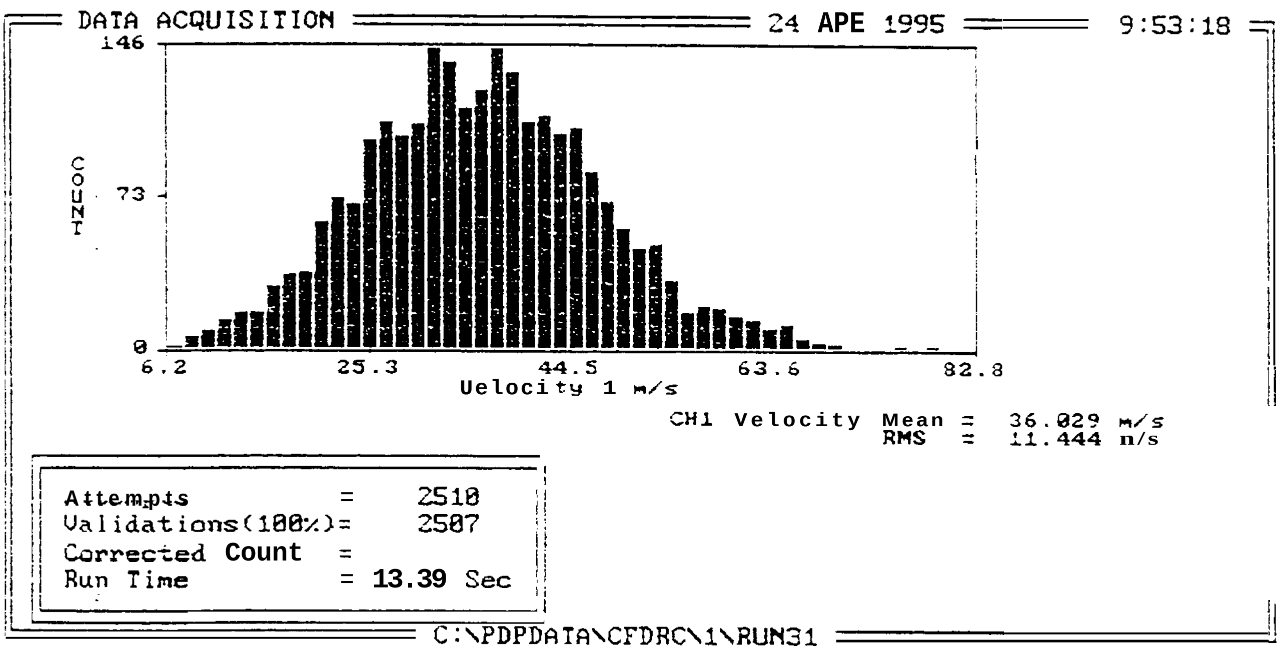

Figure 7. Droplet Velocities are Still High 36" from the Nozzle Exit

The measured droplet velocities compare well with the velocities predicted downstream of the nozzle exit. Figure 8 shows the CFD predicted droplet velocities for the range of diameters generated. The smaller 1-2 micron droplets exit the nozzle at their maximum velocity and decelerate continuously. The larger droplets exit the nozzle before reaching the gas velocity. Downstream of the exit, the gas velocity is still higher than the droplet velocity so the larger droplets are still accelerated for a short distance. The 7.3 microns droplets reach a peak velocity of 474 m/s at a distance of 0.023 m from the nozzle exit. The 9.7 micron droplets reach a peak velocity of 371 m/s at a distance of 0.073 m from the nozzle exit.

The measured velocity at 36" matches the CFD predicted velocity for 1-2 micron droplets exactly. At 8" the measured velocity was 17% lower than the predicted velocity for 1-2 micron droplets. Since velocities could not be measured at the nozzle exit, the exit velocity must be inferred from the above comparisons. The water mist nozzle appears to generate droplets with an initial velocity near 400 m/s at the exit.

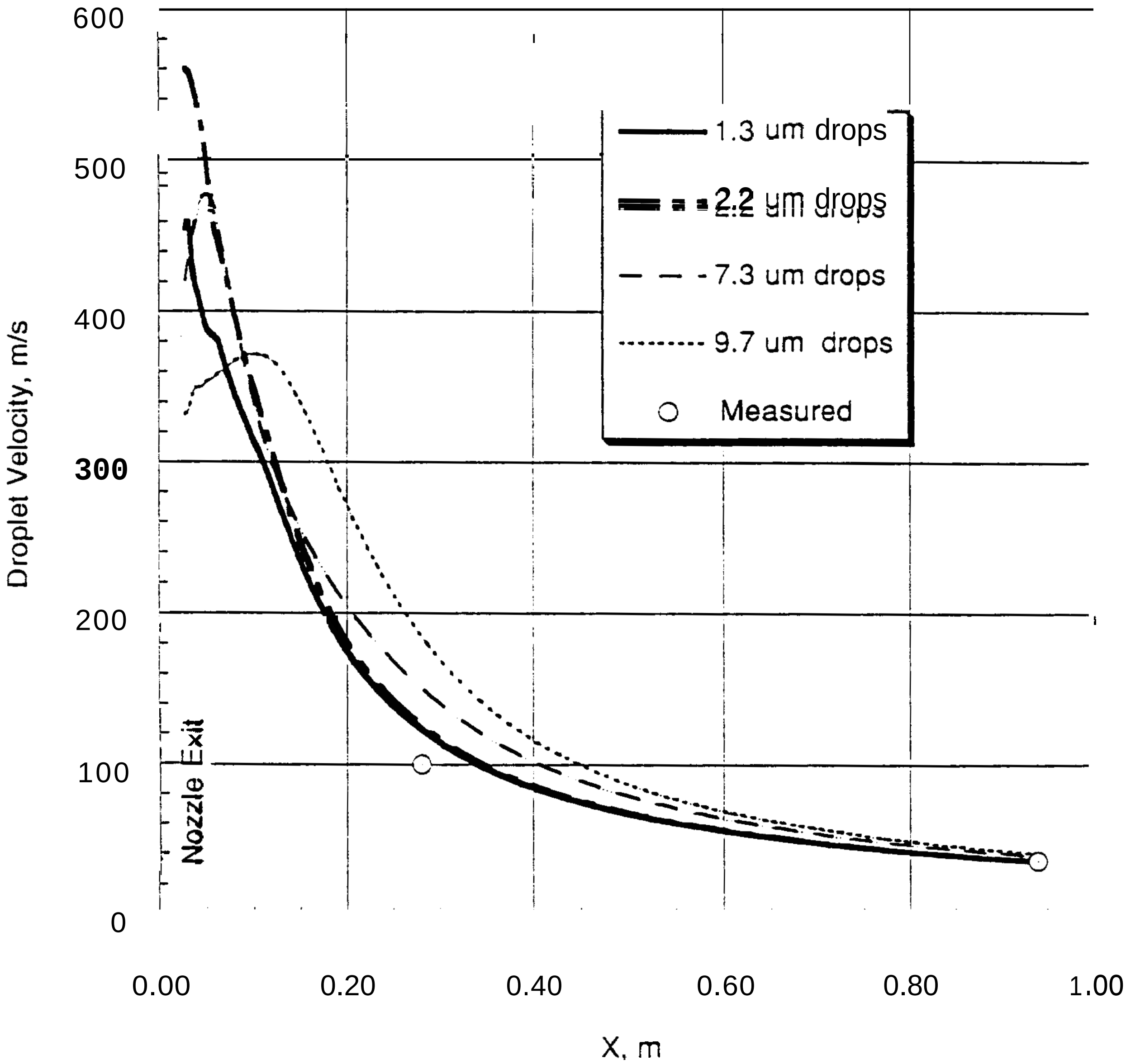

Figure 8. CFD Predicted Velocities Compared Well with Measurements

Another important design parameter for a rapid response fire extinguishing system is the transport time. In the event of an application, rapid deployment is crucial. The CFD model was used to determine the time required for droplets to travel 36" downstream of the exit plane in an established plume. Typical transport times through the nozzle itself, from the moment of injection to crossing the exit plane were 1-2 ms. The total time from injection to reaching 36" downstream of the exit was 12-13 ms. These times would be slightly higher for the initial plume development, but would still be quite short. Coupled with a fast-acting sensing and switching system, this water mist nozzle is capable of very rapid water mist application.

CONCLUSIONS AND FUTURE PLANS

The fine water mist nozzle developed by CFDRC has good potential in the fire extinguishing arena. The advantages of using water as an extinguishing agent have been well documented. Water mist is desired in many applications because of the small drop sizes. This design creates exceptionally small droplets, enhancing the benefits of high heat extraction rates. The size of droplets may facilitate applications in obstructed spaces because the drops will follow the gas flow around corners. Water mist nozzles have been criticized in general because the smaller droplets do not have enough momentum to penetrate a fire plume.

The CFDRC water mist nozzle creates a plume of droplets with a high initial velocity, but also maintains good velocities ior some distance.

This nozzle will be developed in a high response sensing and switching system for an aircraft application. Zallen International Associates is assisting CFDRC in the system design. The next step in its evaluation is pan fire extinguishing and then nacelle fires. This work will occur later this year at the sponsoring Navy site.

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