APPLICATION OF FINE WATER MISTS TO FIRE SUPPRESSION

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INTRODUCTION

There is growing interest in alternatives to Halon compounds for use in fire suppression systems. In particular, recent experiments have indicated that the application of very fine droplet water mists can be effective in extinguishing fires. Water mists are non-toxic, and should minimize residual damage and post-fire cleanup requirements. In order to optimize this approach to fire suppression it is necessary to understand the mechanism by which fine water mists evaporate, and how the droplet size impacts the evaporation rate.

This paper discusses the processes of heat and mass transfer in the droplet and describes the parameters that impact evaporation. The actual mechanism by which fires are extinguished remains a matter for further detailed study, but it is speculated that both the heat absorbed in the evaporation process and the increasing partial pressure of water vapor in the environment surrounding the fire conmbute to the process.

Information is also presented on the design and testing of a novel spray nozzle for the production of fine water droplets. The configuration of the nozzle can be modified to produce droplets of the optimum size for fire suppression. A prototype module of the nozzle has been built and characterized to measure the size distribution of droplets generated.

DROPLET EVAPORATION

Droplet evaporation is characterized by two simultaneous processes: the transfer of heat to the droplet surface, and the transfer of liquid mass from the droplet surface. These processes are interactive, since heat must be constantly transferred to supply the latent heat of vaporization to the droplet in order to maintain the evaporation process, or the droplet will cool to the wet bulb temperature of the surrounding gas at which point the evaporation stops. Small droplets injected into a gas have little momentum, and quickly come to rest relative to the gas. Heat transfer then occurs as conduction, while mass transfer is controlled by diffusion of water vapor from the surface of the droplet. The evaporation rate can be expressed as:

$$dW/dt = 2 \pi D_v D (P_{wb} - P_w)$$

where D_v is the diffusivity of the water vapor in air from the surface of the droplet, D is the droplet diameter, P_{wb} is the water vapor pressure at the temperature of the saturated droplet and P_w is the partial pressure of water vapor in the surrounding air.

The water vapor diffusivity is function of the temperature and pressure of the air, where the diffusivity increases approximately as the temperature raised to the 1.8 power. The vapor pressure difference term is also important at elevated temperatures since the saturation vapor pressure increases dramatically as the droplet temperature approaches the boiling point. Of course, heat transfer to the droplet must be at rates high enough to maintain elevated temperatures while the evaporation process "sinks" significant quantities of heat from the droplet surface, or evaporation slows and eventually stops.

It is significant to note that the evaporation rate is proportional to the diameter of the droplet. This would lead to the conclusion that larger droplets are desirable if maximum possible evaporation rates are needed. However, the equation presented is for a single droplet, and does not take into account the number of droplets that comprise a fixed volumetric injection. A quite different result is seen when the number of droplets is factored into the calculation. The droplet evaporation equation can be revised to reflect an injected mass of water m that is contained in droplets of diameter D. The modified equation is:

$$dW'/dt = 12 D_v m (P_{wb} - P_w) / D^2$$

Now the increase in evaporation rate with decreasing droplet diameter for a fixed mass of water is easily seen. Figure 1 presents the effect of droplet diameter on the rate of heat transfer in a hot gas stream. The volume of water injected in the flow is constant, so that the number of droplets in the hot gas is increased as the diameter decreases. The increase in the ability of the spray to remove heat from the gas stream is seen to be dramatic at diameters less than 100 microns.

The reason for the enhanced heat transfer is reflected in the relative time required to evaporate these small droplets. In Figure 2, the relative evaporation time is plotted as a function of droplet diameter, a 50 micron droplet is used as the baseline. Evaporation time is proportional to

Figure 1. Evaporative Heat Transfer

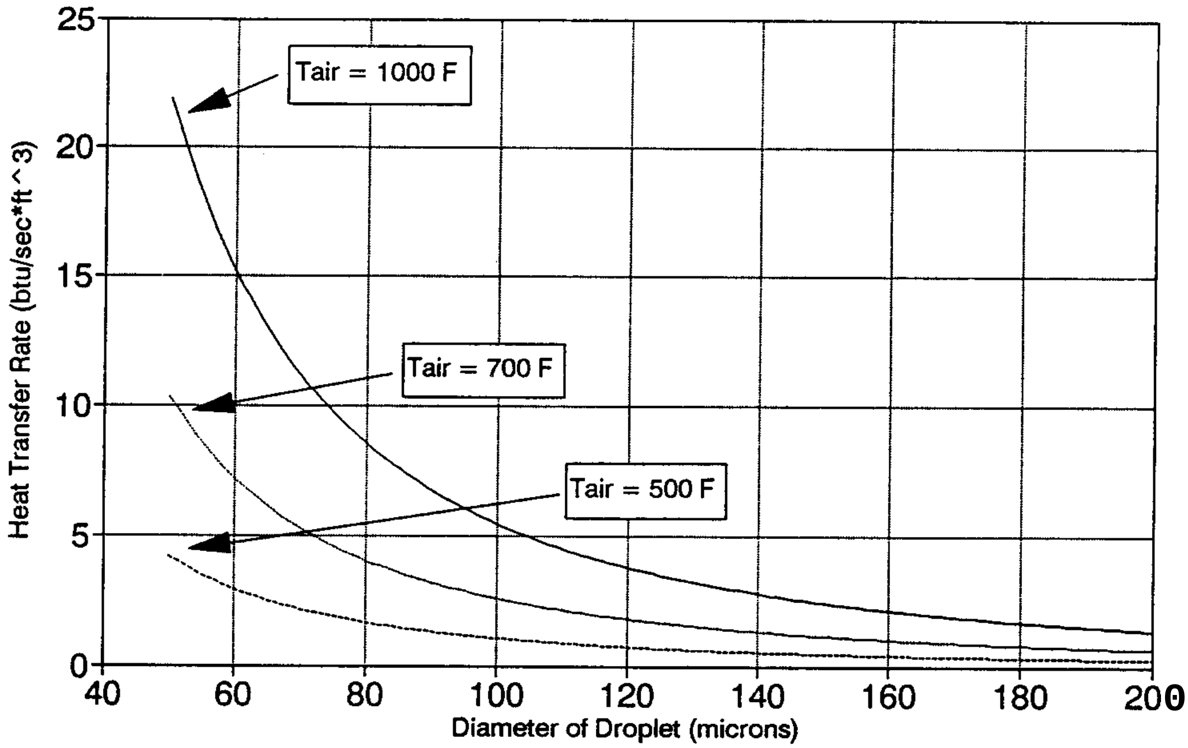
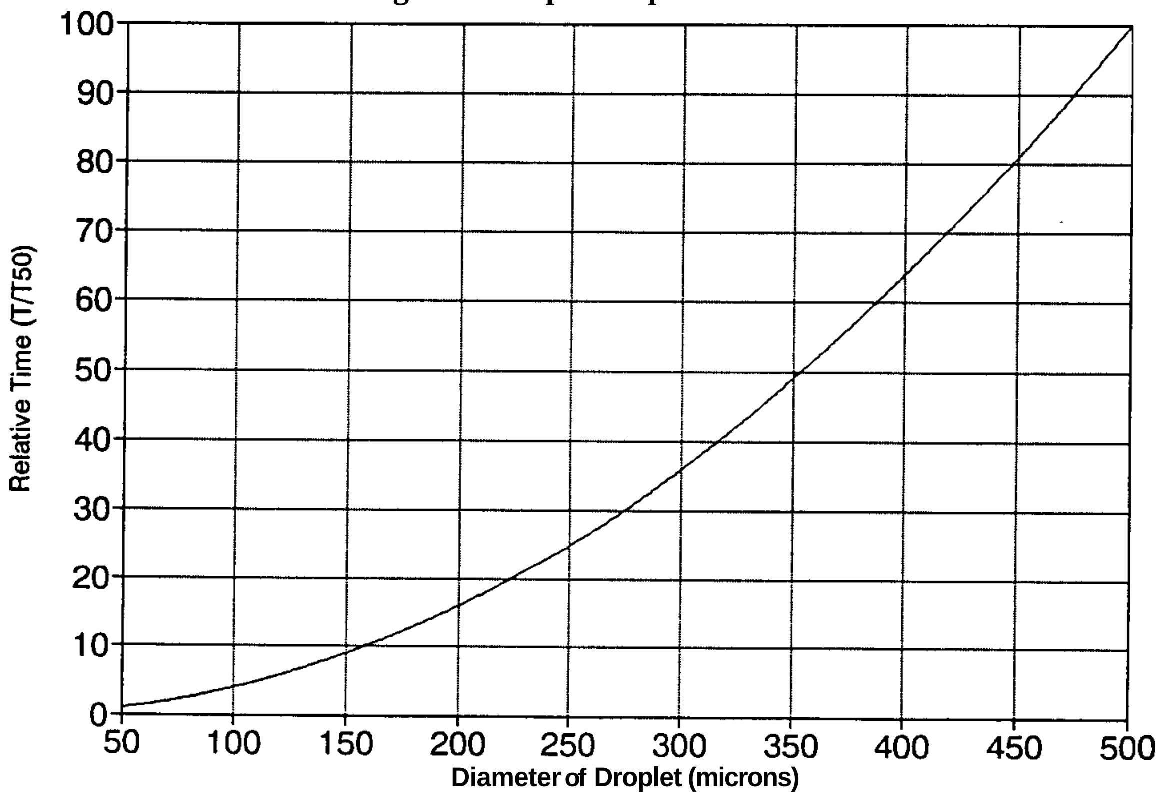


Figure 2. Droplet Evaporation Time



the square of the diameter, so that a droplet four times the baseline diameter takes 16 times as long to evaporate, and one ten times that diameter takes 100 times as long! It is important to note that upon injection into the hot gas stream, the many small droplets are evaporating simultaneously; this is the reason for the high heat transfer rates presented earlier.

One additional effect of the evaporation rate is worth noting. In a spray nozzle, the droplets produced are not absolutely uniform in size, but in fact cover a spectrum. Typically, a normal distribution of sizes is produced, and the spray of the nozzle is characterized by measuring the Sauter mean diameter (SMD) of the spray. The SMD is simply the diameter of a droplet whose volume to surface area ratio is equal to the total volume of the droplet population divided by the total surface area of that population.

COMPUTER MODELING

A computer model for the evaporation of a spray in a heated duct was used to predict the evaporation of a droplet population as a function of residence time in the duct. The results of the modeling are presented in Figure 3. The largest volume fraction of the water droplets were 60 microns in diameter at injection. The range of diameters was from 20 to 120 microns. The smallest droplets, at 20 microns, are seen to evaporate in the first 50 milliseconds after injection. At 270 milliseconds, the 40 microns droplets are gone. Although initially present in a significantly smaller proportion than the 40 micron droplets, the 120 micron droplets take a full 1.6 seconds to evaporate in this calculation.

The conclusion to be drawn from this cursory analysis is that the application of fine mist sprays can significantly increase the rate of heat transfer from a fire, so that it can be extinguished in a timely manner with relatively small amounts of water. The optimization of the heat transfer to minimize both the time and water quantity applied to the blaze is process that will require experimentation to account for the dynamic nature of the heat transfer and gas mixing in a flame.

LINEAR VGA NOZZLE CONCEPT

For the past two years ADA Technologies, Inc. (ADA) has been developing the linear Variable Gas Atomization (VGA) nozzle for application to humidification of flue gas streams. The development work has been funded by the US Department of Energy under the Small Business Innovations Research (SBIR) Program. The linear VGA nozzle is a dual-fluid water spray device that operates at air pressures less than 40 psig and air-to-liquid mass flow ratios (ALRs)

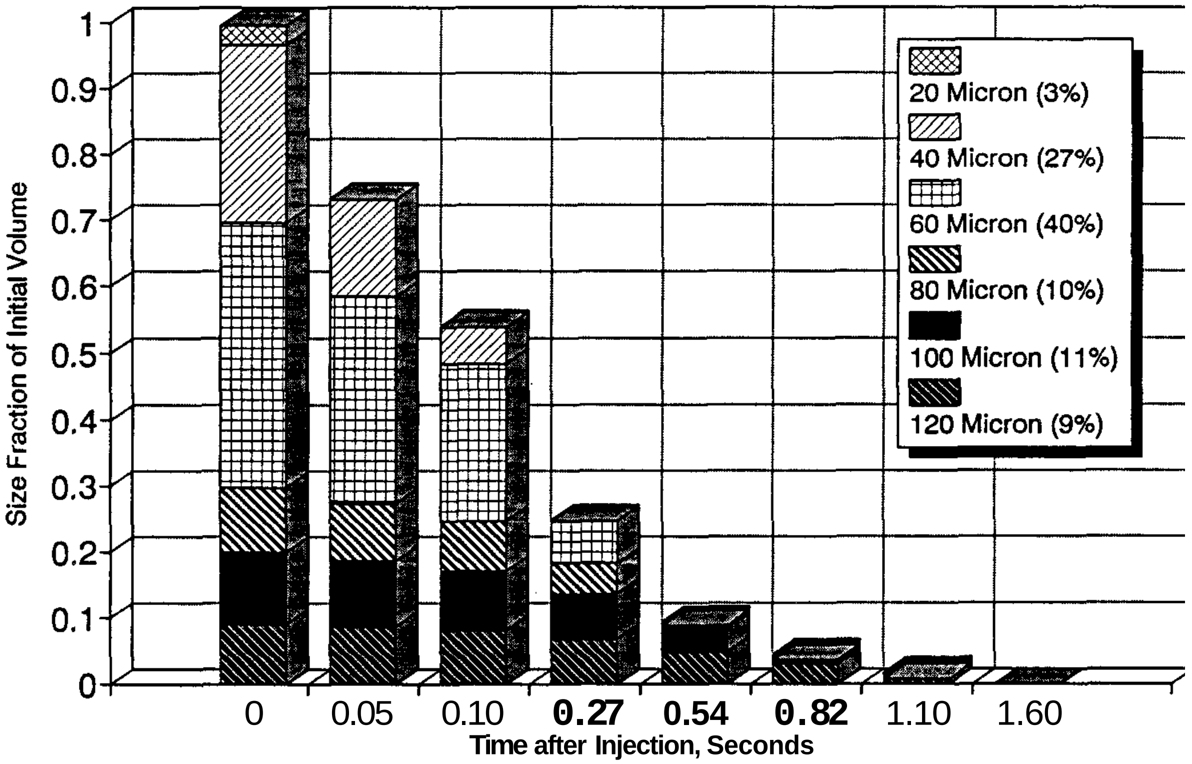


Figure 3. Droplet Evaporation in Hot *Air*

below 0.5. The patented design uses the difference in pressure between the water and air components to control the thickness of the linear slit from which the liquid sheet is discharged. This sheet thickness is important because it directly impacts the size of droplets produced in the nozzle.

A schematic cross-section of the concept for the linear **VGA** n o d e is shown in Figure **4.** Water is pumped to the center of the nozzle, where it is contained by two cantilevered divider walls, which touch at their tips. The walls separate the water flow passage from the **air** flow passage. **During** operation of the nozzle, the air pressure is slightly less than the water pressure; this difference causes the divider walls to deflect slightly at the tips. **A** very thin but uniform water sheet is discharged from the tips of the divider walls, where it is immediately contacted on both top and bottom by the air flow. Because the air is much less dense than the water, its flow velocity is much greater. The difference in velocity creates a shearing action that breaks the water sheet into droplets, which **are** then discharged through the throat of the nozzle into the surrounding gas stream. The droplets generated in this manner **are** on the order of the dimension of the thickness of the water sheet; this is why the thickness of the liquid sheet is critical to the performance of the nozzle.

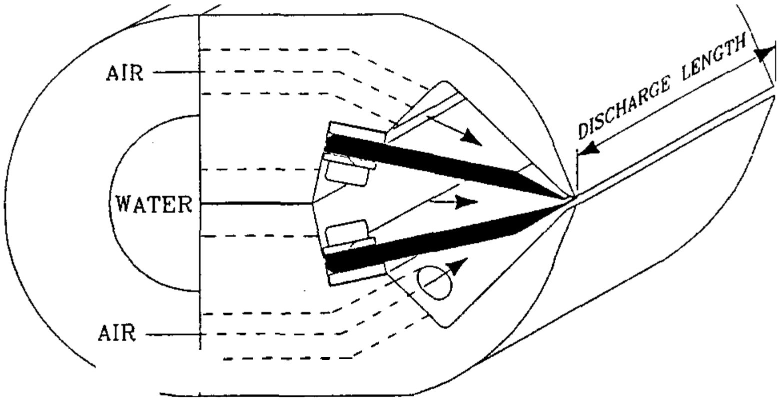


Figure 4. Schematic of the Linear VGA Nozzle

The key difference between the linear VGA nozzle and current commercial devices lies in geometry of the discharge orifice. Conventional nozzles use an axisymmetric design for the exit, when the diameter of the water injection orifice controls the size of the droplets produced; when a larger flow is needed, the orifice diameter is increased. There is an unwanted side effect to the increase, however, since the larger diameter orifice produces larger diameter droplets. In contrast, the linear VGA nozzle is scaled up by simply increasing the length of active nozzle. The thickness of the liquid sheet remains constant, so that an increase in flow causes no increase in the size of the droplets produced in the nozzle.

The development project has included subscale design evaluation and optimization tests, where a number of design dimensions and features were explored, and a prototype development phase, where fabrication, installation and operating issues were addressed. Configurational parameters that were investigated included the thickness of the divider wall sections, the seals at the ends of the linear segment, materials of construction, and the design of the discharge throat in the nozzle. Operational parameters that wen studied centered on the air and water flowrates that could be maintained in the nozzle without compromise of the size distribution produced.

Two characteristics of the spray were used to evaluate the relative performance of candidate nozzle configurations. These were the Sauter Mean Diameter of the droplets and the mass fraction of droplets greater than 100 microns in diameter.

NOZZLE PERFORMANCE EVALUATION

Subscale nozzle configurations in both stainless steel and aluminum were evaluated by measurement of the spray droplet size and velocity dismbution with a Phase Doppler Particle Analyzer (PDPA). This instrument employed a laser technique to determine the velocity and diameter of individual spray droplets as they travelled through a sample volume. The PDPA was computer controlled and could handle up to 50,000 droplets per second. The sample volume was quite small, and in order to obtain data representative of the entire spray, measurements were made over a grid of sample points on a cross section of the spray pattern. Individual measurements were then weighted by the volumetric flux through the sample volume in order to obtain characteristic values for a fixed set of operating conditions.

Because of the relatively large flow capacity of the prototype linear VGA nozzle, a High Flow Test Bed (HFTB) was designed, outfitted and set up at the Arapahoe Steam Electric Generating Station of Public Service of Colorado. The completed HFTB has an air flow capacity of over 200 ACFM, much higher than available in most laboratory environments. The HFTB is shown schematically in Figure 5.

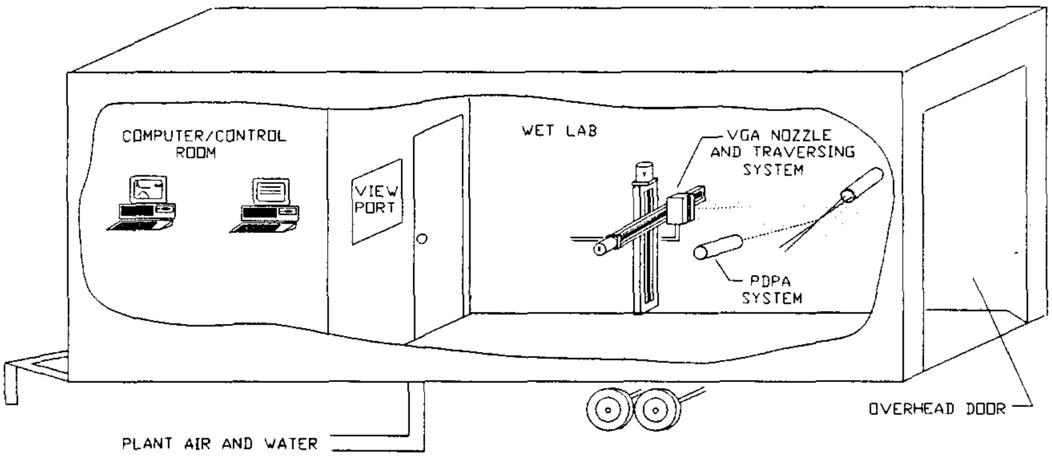


Figure 5. High Flow Test Bed Layout

The HFTB is equipped with instrumentation to control the flow of water and air to the nozzle under test, to measure the droplet size and velocity distribution in the spray, and to monitor the flow conditions in the nozzle. Nozzle tests in the HFTB are controlled completely from the forward room through two personal computers and several switches. One computer controls the operation and data acquisition for the PDPA. The second monitors the instrumentation installed in the nozzle, including water and air flow rates, pressures of both fluids, and the temperature of the air. The data acquisition system in the second PC also controls the rate of air flow to the nozzle through a digital air regulator. Data from all instruments is converted into engineering units, averaged, and recorded every minute during a test. A switch box in the forward room controls the stepper motors that position the nozzle in the X and Y planes relative to the PDPA sample volume.

Early in the development effort, it was recognized that an automated control scheme for the air and water supply would be critical to any commercial installation. To investigate the requirements and operation of such a control circuit, plans were made to build and test a first-generation flow control system for the HFTB test fixture.

N o d e tests in the HFTB can be conducted by a single person because of the automation incorporated in the new test fixture. In a typical test, the conditions of water flow rate and ALR are held constant, and a series of PDPA runs are made on a mamx of locations across the face of the nozzle spray pattern. PDPA samples are taken in half-inch increments until more than 30 seconds are needed to acquire a 10,000 droplet sample; at the center of the spray this size sample is acquired in well under one second. A typical mamx to characterize a single spray condition encompasses 75 to 90 measurements, and is completed in about 90 minutes with the automated setup of the HFTB. ADA has also developed a computer program to access and reduce the information from the individual PDPA files for each measurement location. This allows the large data files produced by the PDPA to be analyzed and summarized on a single page table in a few minutes.

LINEAR VGA NOZZLE DEVELOPMENT AND TEST

The hear VGA n o d e was initially designed and fabricated as a three inch long development test article. Several design configurations were tested, and the results were employed to develop a prototype full-scale module for use in humidification applications. The full-scale module was fabricated from stainless steel, and was designed so that the unit could be easily disassembled in order to check the integrity of interior surfaces in the module periodically during testing.

The prototype module was operated in the HFTB, with the PDPA used to collect data on the spray droplets in the pattern. A summary of the test results is presented in Table 1. It is significant to note that the nozzle is capable of producing droplets of less than 50 microns Sauter mean diameter at air pressures of 40 psig or less; current commercial nozzles that produce similar droplet sizes require air pressures of 60 to 150 psig. The prototype design is simple, rugged, and can be made from a range of materials, to suit the operating environment and application for which the particular nozzle is intended.

Table 1. Prototype Linear VGA Nozzle Spray Characterization Results [a]

Water Flow (gpm)	Air Pressure (psig)	SMD (microns)	Fraction > 120 Microns (%)
4	28	42.1	2.9
5	40	40.7	5.7
5	40	39.7	6.3
5	40	40.4	5.4

[a] All data taken at an air to liquid ratio of 0.4 lb/lb.

The prototype development effort included the design and assembly of an automated flow control system for both the air and water supplied to the nozzle. A programmable microcontroller was used to implement a control scheme where feedback of both water and air flows are used to maintain a user-specified air-to-liquid ratio in the nozzle. The control system was installed and refined during tests in the HFTB.

Arrangements were next made to test the nozzle in-situ, installed in the exhaust gas duct of an operating power plant downstream of the air preheater equipment and upstream of the particulate control equipment. Two tests were run, one for twelve hours and a second for twelve days. Immediately following the twelve hour test, the power plant entered a scheduled shutdown, permitting the prototype nozzle to be inspected at its installed location inside the duct. Careful review showed that there was no evidence of any droplet impact on the walls or ceiling of the ductwork, even though the nozzle was positioned only 18 inches from the side wall and 24 inches from the ceiling. The duct was approximately 18 feet wide by 10 feet high.

The encouraging results of this short-term test led to the planning and completion of a longer term test for a total of 12 days. The nozzle was heavily instrumented for the longer term test, and was found to operate successfully in the flue gas environment where the temperature ranged from 235 to 305 °F. The nozzle completed the test with only minimal deposition of fly ash on the housing, and the flow control system successfully monitored and modulated air and water flows to the nozzle for the duration of the test. The water tap used to supply the nozzle was from a fire hydrant on an unused water line, so that the rust and grit content of the water was quite high, thus causing clogging of the water filters with an accompanying decrease in water flow to the nozzle.

Plans are now under development to test the prototype design on a larger scale, where six to ten nozzles would be installed in a power plant to reduce the temperature of the flue gas at the entrance to the electrostatic precipitator, in order to improve the particle collection efficiency.

APPLICATION OF THE LINEAR VGA NOZZLE TO FIRE SUPPRESSION

Several features of the linear VGA nozzle make it an exciting candidate for application to fire suppression. These include:

- Production of small droplets at low air pressures and low air to liquid ratios. The prototype produced 40 micron droplets at 40 psig air pressure, and an ALR of 0.4.
- Dense spray generation. A nine inch long module is capable of supplying five gpm, and the design is such that a header can have multiple modules installed along its length.
- Potential to adapt the concept to low-cost materials for mass production. The module halves could be cast in bronze, with a simple machining step to finish the divider walls for proper operation.
- Fine water mists are non-toxic so that they can be applied in areas that remain occupied.

In order to evaluate the potential of the linear VGA nozzle for fire suppression, a simple test was run. A 20 inch diameter pan was filled with diesel fuel to a depth of about one-quarter inch, and the fuel was ignited. A single three inch long linear nozzle (one of the development test articles) was mounted about eight feet above the pan. The fuel fire was allowed to reach a fully-developed condition, at which time the flow of air and water to the nozzle was initiated. The nozzle was able to extinguish the fire in less than ten seconds. Several other tests were run with the nozzle at increasing distances from the fuel pan. At twelve feet the nozzle was not able to extinguish the fire, but there was some question as to the coverage provided by the nozzle spray pattern. It was believed that the spray was only contacting the fire at the edges of the pattern.

These "quick and dirty" test results were encouraging; the next step is to take a more rigorous approach to the design and test of a version of the linear VGA nozzle specifically for fire suppression. Parameters of interest in an investigation would include the optimum droplet size, spray density, spray pattern divergence, and the effectiveness of water spray mist fire suppression on a range of combustible materials. The use of fine water sprays in the suppression of fires is an alternative to halons that merits further investigation.