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Design, development, and analysis of a twin-fluid fire suppression atomizer and characterization of electrostatically charged droplet sprays

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DESIGN, DEVELOPMENT, AND ANALYSIS OF A TWIN-FLUID FIRE SUPPRESSION ATOMIZER AND CHARACTERIZATION OF ELECTROSTATICALLY CHARGED DROPLET SPRAYS

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College
In partial fulfillment of the Requirements for the degree of Master of Science in Mechanical Engineering

in

The Department of Mechanical Engineering

by

Chad E. Moore
B.S. University of Southern Mississippi, 1997
December 2003
DEDICATION

To Bethany and Maggie
ACKNOWLEDGEMENTS

The work presented herein was successfully accomplished through the help of many people. I owe the greatest debt of gratitude and admiration to my committee members, Dr. Dimitris Nikitopoulos, Dr. Sumanta Acharya, and Dr. Srinath Ekkad. In particular I thank Dr. Nikitopoulos for the use of his laboratories and equipment throughout this work. Also, to Dr. Nikitopoulos I thank you for your time, effort, and patience you provided throughout this work.

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ABSTRACT

A twin-fluid water mist fire suppression atomizer is designed, developed, and analyzed. Of primary interest is the development of a twin-fluid atomizer that produces a large droplet diameter and velocity distribution and also produces a mist with sufficient cone angle to be effective in fire suppression applications. Spray characterization experiments are conducted utilizing Phase Doppler Particle Analysis (PDPA). The effect of atomizer nozzle geometry on internal two-phase flow and resulting spray pattern is investigated.

National Fire Protection Association (NFPA) Standard 750 characterization experiments are conducted to verify that the sprays produced by the developed atomizer are classified as a water mist as defined by the Standard. Water mist sprays are produced using three different atomizing gases: Carbon Dioxide, Helium, and Nitrogen. PDPA measurements obtained utilizing all three gases are compared and analyzed.

Full-scale fire suppression experiments are conducted using the developed twin-fluid atomizers. Identical experiments are conducted with a commercially available water mist atomizer to provide a basis for comparison. Fire tests are conducted on Class B fires consisting of pool, spray, jet, and simulated machinery space fires. The locations of the fires relative to the atomizer are varied to study the effects of atomizer position on fire suppression performance. The results reported herein indicate the atomizer’s ability to rapidly extinguish Class B fires. Also, the mechanisms of extinguishment for each fire scenario are described.

Particle Image Velocimetry (PIV) measurements are conducted on charged droplet sprays. A Spray Triode® electrostatic atomizer is utilized to study the effects of charged droplet sprays with varying electrical boundary conditions near the exit of the
atomizer. The boundary conditions near the atomizer are varied by placing grounded and ungrounded obstructions in the spray flow field. The experimental results indicate the charged droplet’s ability to wrap around objects and sustain counter gravity flow.
CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The use of finely divided water, or water mist as a possible fire suppressant was first studied by scientists at Underwriters’ Laboratories, Inc. (UL) in the mid 1950’s. Although the UL scientists understood the effectiveness and potential of water mist then, insufficient testing and design standards prevented water mist from developing into the conventional protection system, as did the fixed-sprinkler system. Virtually all research and design came to a halt with the introduction of chlorine- and bromine-based gaseous fire suppressants or halons in the 1950’s which offered superior extinguishing properties over a large number of applications.

Since the discovery in the 1980’s of the depletion of the upper atmospheric ozone layer and the belief that halons were a major contributor to the damage a renewed interest in water mist technologies has emerged. Interest in water mist was also inspired by the International Maritime Organization’s (IMO’s) regulation, Safety of Life at Sea, which requires all passenger vessels built prior to April 1980 to have automatic sprinkler protection or an equivalent. When designing retrofit systems for these vessels water mist was attractive to engineers because of the smaller system requirements. Water mist systems usually require much less water that does conventional sprinkler systems therefore, the piping and water capacity would be much smaller.

In 1993 the National Fire Protection Association (NFPA) formed a technical committee to establish standards for water mist technology and provide for reliable design and installation of water mist systems. The result was in 1986 the NFPA acted on NFPA 750, Standard for the Installation of Water Mist Fire Suppression Systems. This standard defines a water mist as, “A water spray for which the Dv0.9, as measured at the coarsest part of the spray in a plane 3.3 ft (1 m) from the nozzle, at its minimum design operating pressure, is less than 1000 microns (µm).”
Dv_{0.9}, is the volume median diameter; that is 90 percent of the total volume of liquid is in drops of smaller diameter and 10 percent is in drops of larger diameter. The subscript, V, denotes median volume diameter.

Conventional sprinkler sprays contain a large percentage of droplets which are large enough to penetrate to the seat of the fire and also serves to wet the fuel surface. Because of the large droplets and the resulting high momentum the primary mode of extinguishment for conventional sprinkler systems is surface cooling. Halons typically work by filling the room with the gaseous agent and then being entrained into the fire where it chemically inhibits the combustion process. The mechanisms of extinction of flames in a fire are several and often more than one is needed to successfully extinguish a fire. The four main theories of these mechanisms are the following:

1. Cooling of the flames to a temperature, below the flash point, where the chemical reactions cannot be maintained.
2. Reduction of oxygen concentration to a level where reactions cannot be maintained.
3. Flow velocity is increased to a point where the residence time of fuel and oxygen in combustible mixture is less than needed by the chemical reaction (blow-out).
4. Radiant heat attenuation

The effects of each of the mechanisms vary depending on the type of fire and enclosure. Since the evaporation of the water takes place only at the surface of the liquid, the greater the surface area of a given volume of liquid, the greater its cooling capacity will be. Thus water mist can achieve a higher cooling effect from the latent heat of vaporization than a conventional sprinkler that produces large diameter droplets.

Water mist systems are considered to have the following advantages over gaseous fire suppressants and conventional sprinklers:
(1) They use water very efficiently therefore, a smaller volume of water is required to extinguish fires. Typical water mist systems use less than one tenth the water of conventional sprinkler systems. The small volume of water required to extinguish fires reduces collateral damage to the space it is protecting. The smaller volume of water needed to extinguish the fire translates into a smaller system (e.g., smaller space required for the system such as piping and water storage)

(2) Research and testing has shown that rapid extinguishment can be achieved using water mist.

(3) They are water-based systems. Water is inexpensive, environmentally benign, and readily available.

(4) They have proven to be effective in suppressing Class A, B, and C fires.

(5) Under certain conditions they can behave as total flooding gases.

There are three basic types of water mist nozzles currently being used: high and intermediate pressure single-fluid nozzles, low pressure single-fluid nozzles, and twin-fluid nozzles. The high and intermediate pressure nozzles typically atomize the water by forcing the water through small orifices at high velocities. High and intermediate nozzles generally produce mean droplet diameters in the range of 30 to 100 µm. Low pressure nozzles typically atomize the water by impinging a water jet onto a plate or bluff body. Low pressure nozzles generally produce on the order of 200 to 300 µm. Twin-fluid nozzles atomize the water by introducing a gas into the flowing liquid either by mixing the gas internally within the nozzle or by using the air to break up the liquid external to the nozzle. Twin-fluid nozzles typically produce droplets with mean diameters of 100 to 200 µm (Grosshandler, 1994). Twin-fluid atomizers require a separate gas supply in addition to the water supply in most applications.

NFPA 750 classifies all water mist systems regardless of the type of atomization nozzle into three categories: high pressure systems, intermediate pressure systems, and low pressure systems. NFPA 750 defines a high pressure system as one where the distribution system piping
is exposed to pressures of 500 psi (34.5 bars) or greater. An intermediate pressure system is defined as a system where the distribution system piping is exposed to pressures greater than 175 psi (12.1 bars) but less than 500 psi (34.5 bars). A low pressure system is defined as a system where the distribution piping is exposed to pressures of 175 psi (12.1 bars) or less.

Research and testing continues to find more applications in which water mist can be used. The following is a list of current applications in which water mist has proven to be an effective fire suppression system:

(1) Pool type fires
(2) Machinery spaces (gas turbine enclosures and engine rooms)
(3) Onboard ships, offshore platforms (occupied areas)
(4) Electrical equipment spaces (data processing and telecommunication equipment)
(5) Onboard aircraft (occupied fuselage area)
(6) Cooking areas (restaurant cooking hoods)

Water mist may be a more effective fire suppressant than gaseous suppressant agents in applications with deep-seated fires and fires near high temperature equipment. In deep-seated fire applications the water mist may be more effective because of the higher cooling capacity and penetration of liquid water. The cooling effect of the mist may be advantageous in applications with high temperature equipment where there is a potential for re-ignition (Alpert, 1993).

This study began by researching the methods in which water sprays are produced. Twin-fluid atomization was chosen to be the method employed to produce the water mist for this study. Twin-fluid atomizers have been proven to be effective in fire suppression applications. It is the objective of this study to design and construct a twin-fluid atomizer to be suitable for installation for applications protecting Class B fires.
### 1.2 Atomization and Sprays

Lefebvre (1989) described the basic processes in atomization along with the atomizers and spray characteristics typically encountered in current spray applications. He also described the different types of atomizers currently in use. Of particular interest to this research, was the characterization of sprays and the parameters required to describe them. Also of interest were the basics of twin-fluid atomizers and their applications.

The author described the characterization of sprays and the convenience of working with mean or average droplet diameters instead of the complete drop size distribution when describing sprays. An equation was given describing mean droplet diameters.

\[
D_{ab} = \left( \frac{\sum N_i D_i^a}{\sum N_i D_i^b} \right)^{1/(a-b)}
\]

where \( i \) denotes the size range considered, \( N_i \), is the number of drops in size range \( i \), and \( D_i \) is the middle diameter of size range \( i \). Thus, for example \( D_{10} \) is the linear average value of all the drops in the spray; \( D_{30} \) is the diameter of a drop whose volume, if multiplied by the number of drops, equals the total volume of the sample; and \( D_{32} \), Sauter Mean Diameter (SMD), is the diameter of the drop whose ratio of volume to surface area is the same as that of the entire spray. Table 1-1 was taken from Table 3.1 of Lefebvre’s book and it lists common mean diameters used in spray applications.

The author described three types of twin-fluid atomizers: air-assist, airblast, and effervescent atomizers. In all three types a gas is introduced into the liquid to augment the
atomization process. In the air-assist atomizer, a high-velocity gas stream impinges on a relatively low-velocity liquid stream, either internally or externally to the atomizer’s nozzle. In internal-mixing type, the spray cone angle is a minimum for maximum airflow, and the spray widens as the airflow is reduced. This type of atomizer is very suitable for applications where highly viscous liquids are used and when good atomization is required at very low liquid flow rates. External-mixing types can be designed to give a constant spray angle at all liquid flow rates. An advantage of this type atomizer is it eliminates the danger of liquid backing up into the liquid line. However, their utilization of air is less efficient, and consequently their power requirements are higher. The major disadvantage to air-assist atomizers is the need for an external supply of high-pressure air. Most air-assist atomizers are capable of providing good atomization over most of the operating range.

Airblast atomizers function exactly the same as the air-assist atomizer; both employ the kinetic energy of a flowing airstream to shatter the liquid jet or liquid sheet into ligaments and
then drops. The primary difference between airblast and air-assist types lies in the quantity of air employed and its atomizing velocity. The air velocity through an airblast atomizer is limited to a maximum value corresponding to the pressure differential across the atomizer nozzle. Airblast atomizers are typically used in combustion applications where the combustion systems operate at high pressures.

The third type of atomizer described was the effervescent atomizer. Effervescent atomization was described as the injecting of gas into the bulk liquid at some point upstream of the injector orifice and the gas is not intended to impart kinetic energy to the liquid stream. The pressure differential between the atomizing gas and the liquid is small, only what is needed to induce the gas into the flowing liquid. A two-phase flow results from the point of injection to the nozzle exit. It was theorized that the liquid flowing through the nozzle’s orifice is squeezed by the gas bubbles into thin shreds and ligaments. This is a critical characteristic of the effervescent atomizer because the drop sizes produced by the atomizer are proportional to the square root of the initial thickness or diameter of the ligaments from which they are formed. Lefebvre identified some advantages offered by effervescent atomization. The advantages are summarized below:

1. Good atomization can be achieved at low injection pressures and low gas flowrates.
2. The system can be designed with large holes and passages thus reducing the risk of plugging the system.
3. The basic simplicity of the device lends itself to good reliability, easy maintenance, and low cost.

Also, given was a summary of the published equations for estimating the drop sizes produced from air-assist atomizers. The following equation describing the Sauter Mean Diameter (SMD) for an air-assist atomizer was developed by Sakai et al. (1978).
SMD = \left(14 \cdot 10^{-6} \cdot d_o^{0.75}\right) \cdot \left(\frac{m_L}{m_A}\right)^{0.75}

where, \(d_o\) = nozzle orifice diameter, \(m_L\) = mass flowrate of the liquid, and \(m_A\) = mass flowrate of the gas.

Whitlow and Lefebvre (1993) defined an “internal mixing” twin-fluid atomizer as one that exposes the liquid to an atomizing gas before leaving the nozzle body. They defined an effervescent atomizer as one that introduces the atomizing gas directly into the flowing liquid at some point upstream of the nozzle discharge orifice in such a way as to create a bubbly two-phase flow. When the bubbly flow mixture exits the discharge orifice, the rapidly expanding bubbles shatter the surrounding liquid into droplets. The authors used a plain-orifice twin-fluid effervescent atomizer to study the effects of gas/liquid ratios (GLRs) on the internal flow and spray pattern produced by the atomizer. Where GLR is defined as the following:

\[
GLR = \frac{\dot{m}_{\text{gas}}}{\dot{m}_{\text{liquid}}}
\]

where; \(\dot{m}_{\text{gas}}\) = mass flowrate of atomizing gas

\(\dot{m}_{\text{liquid}}\) = mass flowrate of liquid

Drop size measurements of the sprays were made using a Malvern particle size analyzer. The atomizers were operated at pressures from 10 to 100 psig. GLRs ranged from 0 to 0.6. Water was used as the atomizing liquid and air as the atomizing gas. Results indicated that as the GLRs were increased across the operating range, three regimes of atomizer operation were identified from visual observation. The three regimes resulted from the changes in the internal two-phase flow. The three regimes were designated as follows: bubbly, transition, and annular.
The bubbly flow regime was found to exist at the lower GLRs. As the GLR was increased across the bubbly flow regime, a point was reached at which the atomizer operation and spray start to exhibit instabilities. This marked the onset of the transition regime. The annular flow regime was found to occur at high GLRs, where the instabilities observed in the transition regime were no longer present. The authors determined that although good atomization could be achieved while operating in the annular flow regime, the best utilization of the available atomizing air was obtained while operating in the bubbly flow regime.

Roesler and Lefebvre (1987) studied the atomizing performance of an aerated-liquid atomizer operating under conditions of bubbly flow. The atomizer tested consisted of a plain-orifice atomizer with provision for injecting air or gas through a porous tube into a flowing liquid stream. Water injection pressures were varied from 25 to 100 psid and GLRs from 0.001 to 0.05. A light diffraction technique based on Faunhoffer diffraction theory was used to measure drop size and droplet distributions. Experiments were conducted at various GLRs and injection pressures. Their results indicated that high quality atomization could be obtained at small injection pressure differentials on the order of 25 psid. At these small pressure differentials mean drop sizes of 80 µm were obtained at GLRs of 0.01. At higher operating pressures, around 100 psid SMD’s below 40 µm were obtained over wide ranges of GLRs. The researchers also investigated the effects of orifice diameter on the atomization quality. Their findings indicated that good atomization could be achieved independent of the diameter of the discharge orifice. Moreover, the atomization quality was largely dependent on the injection pressures. A decrease in injection pressure always served to increase the mean droplet size.

The authors concluded that atomization quality was largely independent of the size of the nozzle discharge orifice. However, the bubbly flow mechanism of atomization was limited to
low GLRs, where the actual values depended on the injection pressure. High injection pressures permitted high values of GLRs.

Chin and Lefebvre (1993) studied the flow patterns in internal-mixing, twin-fluid atomizers. The effects of varying the GLRs and atomizer’s mixing chamber pressure were studied. GLRs were varied from 0.0006 to 0.60. The chamber pressure was varied from 55 psig to 123 psig. The authors concluded that increases in GLR always lead the flow pattern in the mixing chamber away from the bubbly flow towards annular flow at high GLRs. They also reported that an increase in chamber pressure always extended the range of GLRs over which bubbly flow could be maintained.

Lefebvre (1996) studied the spray cone angles produced by plain-orifice air-assist atomizers. He used a radial patternator to measure the radial distribution of liquid within the spray. Measurements of effective spray cone angle were carried out over ranges of operating pressures and GLRs of 40 to 100 psig and 0.012 to 0.020 respectively. The results obtained showed that spray cone angle is largely independent of atomizer operating conditions over the ranges tested. Large increases in operating pressure and/or GLR produced only small increases in spray angle.

Lefebvre also reported that in general, the spray cone angles of air-assist atomizers, as indicated by the outer boundaries of the spray, are about twice as large as those produced by conventional plain-orifice pressure atomizers. He also noted that with multiple-orifice and conial-sheet atomizers, the internal flow passages can be designed to give virtually any desired spray cone angle.

Wang, Chin, and Lefebvre (1989) examined the atomizing performance of an aerated-liquid nozzle with special influence of gas-injector geometry on spray characteristics. A Malvern spray analyzer was used to measure mean drop size and drop –size distributions.
Measurements were carried out for water being sprayed into air at normal atmospheric pressure and temperature. Nitrogen was used as the atomizing gas. Two different gas injectors were employed one with a single hole of 0.025 in. and the other had 20 holes, each of 0.012 in. The two configurations were chosen to provide a wide variation in gas-injector geometry. Nitrogen injection pressures were varied from 5 to 100 psid and GLRs were varied from 0.002 to 0.023. Experiments were conducted at the various injection pressures and GLRs. Mean drop sizes were measured using a Malvern particle analyzer. SMDs measured ranged from 20 to 250 µm for all injection pressures and orifice diameters. The case where the injection pressure was 100 psid and the orifice diameter was 0.063 in. produced the most monodisperse spray. From analysis of the experimental data acquired on aerated-liquid atomization the following conclusions were drawn:

1. Over the orifice range of diameters from 0.03 to 0.09 in., injector orifice size had little effect on atomization quality. Results indicated that the smallest injector orifice provided the finest atomization at the lowest injection pressures, while the largest diameter orifice exhibited superior atomization at higher injection pressures. The general conclusion was that atomization performance was relatively insensitive to the injector orifice diameter.

2. Gas injector geometry had little influence on the mean drop size of the spray. However, multi-hole gas injection produces a slightly more monodisperse spray than single-hole gas injection, for the same total effective hole area.

Schmidt and Sojka (1999) studied the performance of an air-assist pressure-swirl atomizer and investigated its limitations. The design of the atomizer was based on a pressure-swirl nozzle, but differed from conventional single-fluid pressure-swirl designs in that the liquid film in the exit orifice was stabilized by axially injecting air through the upstream plane of the swirl chamber.
Drop size measurements were obtained using a Malvern particle size analyzer. Experiments were conducted using three different nozzle configurations and four different liquids. Water, two different mixtures of water/glycerin, and ethanol were used as the atomizing liquids. The atomizer employed consisted of the nozzle body, an aerator tube, a liquid distribution and guide unit, a swirl chamber insert, and the exit orifice. The sizes of the exit orifices used were 0.381 mm, and 0.305 mm. The atomizer was operated at supply pressures of 240, 380, and 510 kPa. Mass flowrates of 0.5, 1.0, and 1.5 g/s were used along with GLRs ranging from 0 to 0.025.

The drop size data indicated that an increase in liquid supply pressure, liquid mass flowrate, or atomizing GLR leads to a decrease in SMD. The data also showed that the spray quality was independent of swirl chamber geometry at constant liquid supply pressure and GLR for low viscosity liquids. Atomizer exit orifice diameter had little effect on SMD when operating at constant supply pressure for the same low viscosity liquids. However, the effects of liquid mass flowrate and exit orifice diameter were coupled with an increase in exit orifice diameter, leading to an increase in SMD when liquid mass flowrate was constant. The data also indicated that mean drop size increased with an increase in either liquid viscosity or surface tension.

1.3 Water Mist Fire Suppression

Grosshandler, Lowe, Notarianni, and Rinkinen (1994) compared a fine water spray to a gaseous agent in extinguishing fires in data processing equipment, an environment typically protected by halon 1301. A scaled-down 0.04 m³ computer cabinet was constructed to house the mock electronics package. The fuel was a 3 mm thick plate of poly(methyl methacrylate) placed vertically central to a number of aluminum plates “circuit boards”. The top of the computer cabinet was constructed of a thin porous plate which could be adjusted to allow for varying degrees of obstruction. The mock computer cabinet was enclosed in a 3.2 m³ chamber to emulate
the physical system of interest. They examined the influence on extinguishing efficiency by varying the nozzle geometry, nozzle location relative to the fire, the water application rate, and the amount of shielding or obstruction surrounding the fire. Cooling fans were installed on the bottom of the fire apparatus to force air both upwards and downwards. The following parameters were identified as being the most strongly dependant on the ability of the discharge nozzle to effectively suppress an obstructed fire:

1. fraction of open area between the nozzle and the fire
2. lateral distance between fire and the highest droplet concentration
3. the spray momentum

It was found that that downward air movement created by the cooling fans did not significantly effect the time to extinction but, upward flow significantly lengthened the time to extinction. They found that 40% obstruction was sufficient to decrease the spray momentum and total water flux to a level that greatly reduces the chances for successful fire suppression.

Liu and Kim (1999) studied the effectiveness of water mist in restaurant cooking areas. In particular, they studied the effects of water mist and cooking oils. They performed a series of full-scale tests with a deep fat fryer placed under an overhead hood. The liquid cooking oil in the fryer was heated until it ignited. The fire was allowed to freely burn for 2 minutes prior to activating the water mist system. A series of thermocouples were installed in and around the fire zone to measure the fire, cooking oil, and fryer metal temperatures. Temperature measurements showed that temperatures far from the cooking oil dropped rapidly with the activation of the water mist. The fryer surface and oil temperature decreased but not as rapidly. They report that initially most of the water droplets hitting the fryer were consumed by the fire plume and quickly evaporated into steam before they could reach the liquid oil surface. After the fire was suppressed water droplets were able to impact the oil surface significantly reducing the oil
temperature. Cooling of the fire plume and the wetting/cooling of the oil were reported as the predominant extinguishing mechanisms of water mist on cooking oil fires.

Mawhinney (1993) used a twin-fluid nozzle to produce a water mist and studied its effectiveness on liquid pool fires. The experimental setup was arranged such that the spray could be applied from above or below the pool fire. Spraying downward directly onto the flame was the most effective. Spraying upward served only to exacerbate the burning. Any obstructions placed in the path of the spray reduced its ability to extinguish the fire. The obstructions reduced the spray’s momentum and the amount of suspended water in the air.

Cousin (1992) used 200 liters of aviation fuel as a fire source contained in a tray (3m x 2.5m) placed in the fuselage “passenger cabin” of a Boeing 707. Conditions within the cabin were monitored to determine the survivability within for a sufficient time for passengers to evacuate. The nozzles inside the cabin were set up such that they could be activated in zones. This way only the nozzles nearest the fire became activated. In all experiments the temperature within the cabin were lowered. It was considered that a principle benefit of the water mist was the effect it had on retarding the rate of fire growth of the cabin contents. The water mist was found to reduce the concentration of toxic gases and particles present during the initial stages of the fire. The main effects on improved tenability were due to retardation of fire growth with some evidence for washing out of acid gases.

Gameiro (1993) used twin-fluid nozzles to study the effects of water mist in a full-scale turbine enclosure. The fire scenario was a combination of a number of fuel pools and a sprayed jet of fuel leaks and pressurized pipe ruptures in the gas turbine enclosure. Fires were extinguished in under 15 seconds using 2-10 liters of water. For this application it was recommended that a self-contained modular system be used with a 200 liter water reservoir and two 67.5 liter high-pressure air cylinders.
Wighus (1994) performed experiments in a 2.5 x 2.5 x 5 m enclosure with various water mist nozzles. The fire source was propane forming an equivalent pool fire with dimensions 0.3 x 1.3 m. This scenario produced a 1 MW fire. Ventilation was provided through an inlet opening at floor level, and an outlet opening at the ceiling. The nozzles produced sprays with a full cone, with a mean nominal water droplet diameter ranging from 500 to 1600 µm. A concept for analyzing the effect of various water sprays on fires was developed. The analysis was based on measuring the heat fluxes from the fire to the different parts of the fire enclosure and its surroundings. A ratio of the heat loss to the room and environment, excluding the loss to the water, characterizes the effectiveness of a water spray. The Spray Heat Absorption Ratio (SHAR) was derived and defined as the following:

$$\text{SHAR} = 1 - \frac{Q_{\text{wall}} + Q_{\text{ceil}} + Q_{\text{floor}} + Q_{\text{vent}}}{Q}$$

or SHAR can be expressed as:

$$\text{SHAR} = \frac{Q_{\text{water}}}{Q}.$$  

where; $Q_{\text{wall}}$ = heat transferred to the walls of the facility  
$Q_{\text{ceil}}$ = heat transferred to ceiling of the facility  
$Q_{\text{floor}}$ = heat transferred to the floor of the facility  
$Q_{\text{vent}}$ = heat transferred to the ventilation air  
$Q_{\text{water}}$ = heat transferred to water spray  
$Q$ = total heat transferred from fire
The absorption of heat from a fire by water was found to be a function of water discharge rate and mean water droplet diameter. An observation made when varying the parameters was that a spray which did not instantly absorb more than 60% of the heat released by the fire, failed to extinguish the fire. Another observation was that if extinguishment was not obtained instantaneously, the SHAR characteristic for extinguishment was above 0.7. The results indicated that the necessary water application rate to achieve extinguishment was reduced consistently at a droplet size below 1000 µm. To extinguish a fire of 1 MW a water application rate of approximately 0.03 gpm/ft² was needed, when the mean droplet diameter was approximately 600 µm. The water application rate required for extinguishment with a spray producing droplets with a mean diameter above 1000 µm is more than 2.5 times larger, approximately 0.08 gpm/ft². The enclosure temperature was reduced when the spray was activated typically 100 °C, from the mean temperature of 200-300 °C. Also, heat flux densities to the walls and ceilings and the soot concentration were reduced with the activation of the water spray. The main factors found to affect the interaction of water mist and the fire plume were the fire size, the discharge rate of water, and the mean water droplet diameter. The reduction of gas temperature and heat flux to the enclosure is larger with small droplet than with large ones.

Liu, et al (1998) studied the effect of air convection on the performance of water mist fire suppression systems. Experimental results were obtained from a full-scale test series of water mist systems using various ventilation conditions. Full-scale tests were performed under fire scenarios with different fire sizes, types, and locations in an empty enclosure and in a mock machinery space. The tests were conducted in an enclosure 9.7 m x 4.9 m x 2.9 m, with a corner 2.9 m x 2.2 m removed. The enclosure contained a 2.0 m x 0.9 m door. Ventilation conditions varied from natural ventilation by opening the door to the enclosure to forced ventilation by using an exhaust fan with a flow rate of 0.737 m³/s. Single-fluid and twin-fluid nozzles were
used in the experiments. The single-fluid nozzle operated at 6 lpm and produced droplet diameters ranging from 200-400 µm. The twin-fluid nozzle operated at 5 lpm and produced droplet diameters ranging from 200-400 µm. The effect of air convection on fire suppression was measured by an analysis of extinguishment times and the distribution of room temperatures and gas concentrations in the compartment. Fire scenarios for the single-fluid nozzles consisted of square-pan fires, round-pan fires, a wood crib fire, and a spray fire. Fire scenarios for the twin-fluid nozzles consisted of a diesel engine mock-up, large shielded pool fire (round pan), and shielded spray fire. Heptane was used as the fuel for the pool and spray fires.

The results of the single-fluid nozzle experiments showed that the effect of natural air convection on fire suppression was mainly limited to the area close to the door. The results for the twin-fluid nozzle experiments showed that for both the shielded heptane pool and spray fires were extinguished at almost the same time, when there was no air convection in the compartment. Under natural ventilation conditions the time extinction increased from 113s to 145s but the extinguishment time for the shielded pool fire was significantly extended from 114s to 420s. In all the twin-fluid tests the fires were extinguished under natural convection conditions however, the extinguishment times were longer and varied with the type of fire. When there was forced-air convection in the enclosure, the extinguishment time for the spray fire was 510s and for the round-pan fires, the twin-fluid nozzles were not successful in extinguishing.

The strong dynamic mixing created by the water mist spray is able to restrict the penetration of air convection into the depths of the compartment as the air in-flow through the door is quickly mixed with the gases in the room near the doorway and loses its energy for subsequent convection. The effect of natural convection on the performance of the water mist is dependent on the fire location in the enclosure and the characteristics of the water mist system. The single-fluid water mist system produced a strong dynamic mixing by its high water spray
momentum, only fire suppression near the door was influenced by the open door. The suppression of fires located elsewhere in the enclosure were not effected by the open door. For the twin-fluid water mist system which produced a lower momentum water spray, the air from outside the enclosure was able to penetrate more deeply into the compartment and influenced the fire suppression, resulting in longer extinguishment times. The forced ventilation experiments results showed that the loss of a large quantity of water vapor from the fan reduced the ability of the water mist to extinguish the fires.

Kokkala (1998) performed a series of extinguishing tests on pool fires for ten liquid fuels with flash points in the range of -6 °C to +234 °C applying seven different sprinklers or nozzles. Pool size was varied from 0.4 m\(^2\) to 12 m\(^2\), and the nozzle height from 3 m to 8 m. The tests were carried out indoors in an 18 m high laboratory hall with a floor area of approximately 380 m\(^2\). The maximum ventilation rate was about 30 m\(^3\)/s. Circular pools were used to contain the fuels. Control criteria were developed to measure the success of the fire suppression without the fire having to be completely extinguished. The fire was deemed to be under control when both 1) - the temperature 1 m above the center of the pool surface decreased below 100 °C and 2) - the flame length in any direction decreased permanently below 1 m. The flame lengths were determined from video recordings. A dimensionless temperature was defined as a convenient measure of the suppression effect of the water spray and is defined by the following:

\[
R_T = \frac{(T_s - T_{FL})}{(T_B - T_{FL})}.
\]

where; \(T_s\) = fuel surface temperature

\(T_{FL}\) = fuel flash point temperature

\(T_B\) = fuel free burning temperature
In most cases the reported mechanism of extinguishment was deemed to be cooling of the fuel below the fire point. The effect of pool size on the extinguishment characteristics of the fire was that a larger fire does not only increase the times to extinction but in a larger pool the fire may remain permanently uncontrolled. They theorized that this effect is probably due to heat transfer to the fuel: the longer heat is absorbed by the fuel the more heat capacity is stored to keep vaporization going. Reliable extinguishment was achieved on liquids with flash points greater than approximately 60 °C. Lower flash point liquids could only be extinguished by blowing off the flame from the vicinity of the fuel surface. The effect of nozzle type and nozzle position was studied. A plot of the nondimensional temperature $R_T$ at 1 min as a function of nominal water application rate showed that the higher momentum sprays were more effective in controlling the fires than the lower ones. Increasing the nozzle height above the fire makes it more difficult for the spray to penetrate the plume. It was observed when the largest drops from nozzle positions high above the fire contacted the surface of the pool, fuel sputtered to the flame above. Temperature measurements showed that the bulk of the fuel was below the flash point. When the spray was turned off the flames vanished from the surface. Results from varying the water application rate showed that the fuel temperature varies considerably over the surface, and it depended strongly on the local water application rate. Local hot spots on the surface of the fuel can perpetuate the combustion process. Times to extinction varied from 1:29 to 5:50 for LIAV 230 fires and nozzles located 5 m above the fire.

Smith and Lazzara (1998) studied the effects of water mist fire suppression of fires in underground fuel storage areas. A large-scale fire suppression facility (FSF) was constructed to simulate an underground diesel fuel storage area. The main entry of the FSF was 153 ft long and the crosscut was 40 ft long. Each entry was 18 ft wide by 7 ft high. Self-closing doors were located in the main entry 30 ft from the crosscut. The FSF had a water delivery system with a
storage capacity of 2000 gallons and the capability of delivering 100 gpm at 175 psi. The fires were contained in either a 3 ft x 3 ft x 0.5 ft or 5 ft x 7 ft x 0.5 ft metal trays producing fire sizes of approximately 0.5 or 2.0 MW, respectively. Five gallons of low sulfur diesel fuel were used in each experiment. The fires were placed at various places within the FSF. Thermocouples were placed directly above the fires and were considered extinguished when all the thermocouples measured temperatures below 30 °C. Nozzles where used that produced Dv, droplet diameters ranging from 200 to 800 µm. The results indicated that the extinguishing effectiveness of the water mist decreased with increasing droplet diameter, independent of fire location. At droplet diameters above 500 µm, a reduction in the effectiveness of the mist was observed resulting in longer times to extinguishment. The water system pressure and flow rates were varied using the same nozzle, fire size, and fire location to determine if water pressure or flow rate had an effect on extinguishment. In tests with droplet diameters less than 500 µm, no effect was observed. In tests with droplet diameters greater than 500 µm, the mist was more effective at higher water pressures. The results of the flow rate experiments showed a small increase in time to extinguish the fires as flow rate increased. In experiments with droplet diameters less than 300 µm, the two type nozzles performed similarly. The fire location was varied to study the effects of extinguishment. Tests were droplets were produced having diameters less than 400 µm, no effect was observed. Larger droplets, on the order of 800 µm, were less effective in extinguishing wall and corner fires. The fire size was also varied to determine its effect on extinguishing. In tests with droplet diameters less than 500 µm, no effect was observed. In tests with larger droplets sizes, the smaller fires were more difficult to extinguish. The optimum droplet diameter was determined to between 200 and 400 µm, independent of pressure, flow rate, nozzle type, fire location, and fire size.
Braidech and Neale (1955) studied the effects of what they termed “finely divided water” on pool fires and crib fires using gasoline, kerosene, ethyl alcohol and wood. The tests were performed in a 3 ft. x 3 ft. cross section by 5 ft. high enclosure. The top of the enclosure could be removed or adjusted to vary the degree of ventilation. Pressure type atomizing nozzles were used to produce the spray. Experiments were performed using sprays with droplet SMD’s ranging from 133 to 2785 µm. The nozzles were arranged such that they could be sprayed either vertically downward perpendicular to the fuel or horizontal parallel to the fuel.

They found that the predominant mechanism of extinguishment was dilution of the oxygen supply in the burning zone. Steam was produced as a result of the evaporating water droplets displacing the oxygen in the burning zone. Also, the cooling effect of the water spray was found to be an important mechanism of extinguishment. Their work showed the advantage that small droplets have in fire extinguishment since the rate of evaporation and the cooling effects of the water are directly proportional to the droplet surface area.

Using nozzles with known droplet distributions, experiments on each of the fires indicated there was an optimum average volume diameter ($D_{0.5}$) of approximately 300 mm below which extinguishment was achieved and above which there was an increase in the quantity of water needed to extinguish the fires. A lower limit to the droplet diameters of 150 µm was determined because the droplets must arrive at the heated area with sufficient momentum to penetrate the hot air currents and turbulent gases moving upwards and away from the fire to be effective in fire extinguishment. Droplets of 150 µm or less did not have sufficient momentum. Droplets that were too large did not evaporate completely when passing through the burning zone but contacted the unburned fuel, thus cooling the fuel and aiding in extinguishment.

Mawhinney, Dlugogorski, and Kim (1997) proposed a system to classify water mists to facilitate the discussion of water mist systems. They presented evidence of invigoration of
combustion caused by the introduction of water mist. Also, they discussed the primary mechanisms of extinguishment for water mist systems.

They proposed a classification system for water mists that distinguishes “coarser” and “finer” water mists. The cumulative percent volume was used to develop the criteria. Three classifications were proposed: “Class 1” mists were defined as those sprays where $D_{v0.1} < 100 \mu m$ and $D_{v0.9} < 200 \mu m$, “Class 2” mists $D_{v0.1} < 200 \mu m$ and $D_{v0.9} < 400 \mu m$, and “Class 3” mists $D_{v0.1} > 200 \mu m$ and $D_{v0.9} > 400 \mu m$. These classifications were established to be useful in the discussion of water mists and not meant to be rigorous or “scientific” but only to provide a distinction between mists of different droplet diameter. Class 1 and Class 2 mists were considered to be truly mists in this paper.

The authors described three primary mechanisms of extinguishment but also discussed two other mechanisms that may have a secondary role in extinguishment. Fire testing performed at the National Research Council Canada (NRCC) revealed some fires were predominantly extinguished by heat extraction or cooling. Heat is absorbed in three ways when water is applied to a fire: from hot gases and flames, from the fuel, and from the objects and surfaces near the fire. They reported that the primary advantage of Class 1 and 2 over Class 3 mists was to increase the rate at which the water extracts heat from the hot gases and flames, using a smaller volume of water. The gas-phase cooling mechanism depends on the density of small droplets supplied with sufficient energy to cause turbulent interaction with the droplets and flame. Heat extraction from the fuel and surrounding surfaces is achieved predominantly by wetting. Class 3 mists are more effective in this mode of cooling. The larger droplets directly impinge on the fuel and surrounding surfaces thus cooling them. The NRCC tests also showed that oxygen displacement was also a primary mechanism of extinguishment.
Hanauska and Back (1993) evaluated the ability of water mist to behave as a total flooding gas. They tested dual-fluid fixed orifice; dual-fluid sheet/slit orifice; single-fluid, high pressure multiple-orifice nozzles; and single-fluid, high pressure grid/matrix-type nozzles. Experiments were conducted in a 10 x 10 x 8 ft compartment on Class A wood crib fires and Class B spray and pool fires. Both obstructed and unobstructed fire scenarios were studied. The average water discharge rate per compartment floor area ranged from 0.01-0.03 gpm/ft² which corresponds to a volumetric density of 0.0016-0.0045 gpm ft³. The droplet diameter distribution for all nozzles was approximately $D_{V0.5} \approx 75 \, \mu m \pm 25 \, \mu m$.

Experimental results indicated that all of the nozzles were able to extinguish unobstructed fires on the floor of the compartment with water discharge densities on the order of 0.02 gpm/ft². Large fires were reportedly easier to extinguish than small fires due to the displacement of oxygen by the vaporization of the water droplets. The air-atomizing nozzles extinguished the unobstructed fires faster than the single-fluid nozzles. This was attributed to either the higher momentum/increased flame penetration or flame blow out. Air was replaced with nitrogen as the atomizing gas in some tests and was found to increase the fire fighting capabilities of the twin-fluid nozzles. Obstructed fires were more difficult to extinguish with increased horizontal droplet travel distance. Fires with travel distances of approximately one foot were extinguished but were not for greater distances. Although some of the highly obstructed fires were not extinguished their size and intensity were greatly reduced by the water mist.

Hills, Simpson, and Smith (1993) conducted experiments with water mist nozzles and conventional sprinklers in Class C fire applications. The experimental setup consisted of switch gear bays which were comprised of vertically mounted, parallel printed circuit boards (PCBs). High pressure single-fluid nozzles, twin-fluid nozzles, and conventional sprinklers were used to generate the water mist and sprays. The nozzles were arranged on top of the switch gear.
Nichrome ribbon was weaved into a reed relay board stripped of all its components. The wire was connected to a 20 A variable transformer. The ribbon was ignited with approximately 30 V AC thus beginning the fire. Experiments were performed on both live and unpowered switch gear.

Experimental results showed that the single-fluid, high pressure nozzles were most efficient in extinguishing the fires in the unpowered case. The high velocity spray produced by the high pressure nozzles repeatedly extinguished fires within 2 seconds using less than 0.26 gallons of water. The maximum temperature inside the switch gear was measured to be 930 °F. High water flow rate, conventional sprinklers used more water and gave longer extinguishment times than the high pressure sprays. Air atomizing nozzles performed well for small scale fires however, greater fire intensities resulted in longer extinguishing times and used more water than the high pressure single-fluid nozzles.

Fire suppression tests were conducted on live switch gear. The authors report that the results did not differ from the unpowered switchgear. The fires were extinguished in under 2 seconds using the top-mounted, single-fluid nozzles. Experiments conducted on live switchgear showed that water mist did not damage the electrical equipment contained in the bay.

Alpert (1993) published a paper describing the advantages of water mist over gaseous agents and conventional sprinkler systems. The primary advantage of a water mist system over a gaseous agent, in particular Halon 1301 is the benign environmental effects of water. Water does not present any danger to personnel that may possibly inhale it as opposed to the halon agents along with the new halon replacement chemicals. The new gaseous agents suggested for replacement of Halon 1301 are much more expensive and are not as readily available as water. Water has proven to be as effective or perhaps more effective in the suppression of deep-seated fires and fires near high temperature equipment surfaces compared to gaseous flooding systems.
Some of the new replacement gases have been identified as being corrosive to the protected area once discharged. Water mist may offer the advantage of reduced corrosion rates due to the small quantities of water required.

The primary advantage of water mist of conventional sprinkler systems is the reduced water flow rates. Thus, the resulting collateral damage is less with water mist systems. Water mist can be used near high temperature surfaces because the potential of damage from rapid cooling of the equipment from large droplets and high volumes of water is reduced. Flammable liquid fires, which cannot readily be controlled with conventional sprinkler systems, can be extinguished using water mist.

Chaiken and Smith (1997) studied the effects of water mist in extinguishing diesel fuel fires in underground mine diesel refueling areas. The authors theorized that two different transport mechanisms by which water droplets enter the fire plume result in fire extinguishment. The first mechanism is the direct injection of water droplets into the fire plume from overhead nozzles. It is believed that this mechanism involves larger droplets and results in time to extinguishments on the order of several minutes. Second, is an indirect injection of water droplets resulting from small droplets that get entrained in the sideways airflow that feeds oxygen to the fire. This small droplet entrainment is thought to cause rapid quenching of the fire and results in extinguishments on the order of seconds.

A parametric model of the indirect water injection mechanism was developed and critical spray conditions for achieving rapid quenching of pool fires were presented. Considering the mass flow rate of water $m_w$ required to reduce the fire plume temperature below the ignition temperature, the fuel burning rate $B$, the time, $t_h$, required for air to travel the radius of the pool fire, the Stokes terminal velocity, $v_d$, and the time, $t_v$, required for a water droplet to fall a
vertical distance, L, the fire plume height, an expression was developed that described the relationship of the entrained water to fire extinguishments.

\[ \frac{t_v}{t_h} = K \frac{B}{r_d^2} \]

Where K is a constant given in cgs units as 0.016 sec-cm and \( r_d \) is the droplet diameter. The extinguishment requirement is that \( t_v \geq t_h \) and leads to a critical droplet diameter criteria as follows:

\[ r_d^2 \leq 0.016B \]

Values of B range from 0.001 to 0.01 cm/sec, and using the above expression suggests that the critical droplet diameters range from 80 to 250 µm.

Next the required water mass flow rate criteria were developed. Considering the total mass of water, \( M_w \), required in the volume containing the fire and the Stokes droplet settling time, \( t_v \), the total mass flow rate required for extinction was reported to be:

\[ \dot{m}_w = 2.2 \times 10^8 r_d^2 \]

Where the units of \( m_w \) are g/sec, \( A_x \) is the cross-sectional area of the enclosure, and \( r_d \) is the critical droplet radius. The water mist nozzles must produce a spray with the critical mass flow rate containing radii \( \leq r_d \).

The authors then conducted experiments to test their parametric model. The Fire Suppression Facility used for the experiments was constructed to simulate an underground diesel fuel storage area. Pool fire tests were contained in two trays one 3 ft x 3 ft and one 5 ft x 7 ft, which normally contained 3 to 5 gallons of diesel fuel. Four locations of the pool fire were
chosen for the experiments: (1) centered under a spray nozzle; (2) off-center between neighboring nozzles; (3) against a single wall; (4) in a corner (against two walls). Temperature inside the facility was measured by numerous thermocouples placed throughout the facility. The nozzles used for the experiments were commercially available spiral or impingement type and were ceiling mounted and operated to manufacturer’s specifications. The number of nozzles varied from 2 to 12 depending on the water demand needed to cover entire floor area. Water flow rate from the nozzles ranged from 4.9 gpm to 50.5 gpm.

The effectiveness of the water mist was determined by studying the temperature versus time behavior of the thermocouples inside the facility. If the measured temperatures decreased quickly to less than 100°C within one minute than the extinguishment of the fire was considered rapidly quenched. Anything not exhibiting this behavior was reported as ‘no’ extinguishment.

Results from all the pool fire tests were plotted on a single plot of total water flow rate versus droplet size. A curve was fitted with the following equation representing the critical mass flow rate as a function of droplet diameter

\[ m_w = 1.5 \times 10^7 r_d^2 \]

The observed constant coefficient was found to be an order of magnitude smaller than that calculated from the parametric model. From the experimental data a critical mean droplet diameter of 250 µm was reported which was approximately 30% less than their model predicted.

The authors concluded that the order of magnitude agreement between the parametric model and the experimental results was encouraging but further testing of the model was needed. They intended on using this model as a starting point for the design of pool fire tests as well as the approach to analysis of the extinguishments results.
1.4 Present Investigation

The research presented herein was separated into two parts. Part I of the research focused on the design, development and analysis of a twin-fluid water mist fire suppression atomizer. Part II consisted of the study of charged droplet spray patterns in the presence of varying electrical boundary conditions.

Part I of the research began with the design and development of the twin-fluid water mist atomizer and its fire suppression effectiveness. Past efforts and commercially available water mist atomizers used high pressure water to produce the water mist. This research implemented a twin-fluid atomizer, atomizing gas and water, to produce the mist. It is suggested that the twin fluid atomizer operates at lower pressures and has comparable fire suppression characteristics to its high pressure single fluid counterparts. This investigation has been divided into four phases, Phases I-IV which are described below.

Phase I of the investigation focused on design and development of a twin-fluid water mist atomizer. The investigation began by using an atomizer developed by a Louisiana State University (LSU) senior project design team. The atomizer used compressed air at 55 psig and a volumetric flowrate of 33 SCFM that was injected into flowing water at 50 psig and a volumetric flowrate of 0.05 GPM. The atomizer was designed to be used in spray combustion applications. Mean droplet diameters on the order of 80 \( \mu \text{m} \) were produced. These operating conditions and droplet distributions were much smaller than the water mist fire suppression requirements. Spray characterization experiments with this atomizer were conducted and a basis for design was developed. Unstable flow, low liquid flow rates, small droplet distribution, and small spray cone angle were problems that were identified of the senior project team’s atomizer.

These problems were addressed and after trial and error experimenting with various atomizer designs an atomizer that met the design objectives of the research was developed.
Phase II of the research used Phase-Doppler Anemometry (PDA) measurements to characterize the sprays produced by the twin-fluid water mist atomizers. Measurements were made for both single-hole orifice atomizers and multi-hole orifice atomizers. Atomizing gas flowrates varied from 25 SCFH to 310 SCFH. Water flowrates varied from 0.5 to 3.2 GPM. Different nozzles were studied to optimize the fire suppression characteristics of the spray produced. Flow conditions were varied for each nozzle to maximize the liquid flow rate and minimize the gas flow rate while maintaining a steady well-atomized spray.

Phase III of the research focused on satisfying National Fire Protection Association (NFPA) Standard 750. NFPA 750 outlines the procedure for characterization of water mist fire suppression atomizers. PDA measurements were carried out on sprays that used water and three different atomizing gases. The atomizing gases chosen were Carbon Dioxide (CO₂), Nitrogen (N₂), and Helium (He). These gases were chosen because of their widely differing densities and to study the effects of atomizing gas density on the resulting spray and droplet distribution. During this phase volumetric liquid and gas flow rates were fixed and measurements were taken using all three atomizing gases.

In Phase IV, full-scale fire suppression performance testing of the water mist atomizers was conducted. Fire testing was conducted in LSU’s fire testing facility. Atomizers developed in Phases I-III were mounted within the facility and full-scale fire tests were conducted to study the atomizers’ fire suppression effectiveness. Pool fires, spray fires, and simulated machinery space fires were conducted. The position of the fires were varied within the facility to study the effects of nozzle position relative to the fire position. Temperature profiles within the facility, fluid flow rates, and times to extinction have been reported for these experiments.

Part II of the investigation studied the flow field from an electrostatic atomizer with various electrical boundary conditions. A SPRAY TRIODE® electrostatic atomizer, provided by
Charged Injection Corporation, was used to produce the charged droplet spray. An experimental testing facility was constructed such that the electrical boundary conditions could be controlled and varied. Particle Image Velocimetry (PIV) measurements were conducted to measure and characterize the flow field produced by the SPRAY TRIODE®. Electrical boundary conditions were varied near the atomizer to study the charged droplet flow field when the electrical conditions were changed. Velocity vector field results have been reported for unobstructed, grounded obstructed, and ungrounded obstructed flow fields.
CHAPTER 2. EXPERIMENTAL FACILITIES

2.1 Phase I Experimental Facility

A schematic diagram of the experimental facility for Phase I of this study is shown in Figure 2-1. Domestic water was supplied from a water storage tank through a liquid rotameter where the water flow rate was read. An inline pressure gage was placed downstream of the rotameter such that the pressure just upstream of the atomizer could be measured. From the pressure gage the water was piped to the atomizer water inlet connections. The atomizing gas, CO2, was supplied from a compressed gas cylinder. The CO2 was piped through a gas rotameter then through a pressure gage terminating at the gas inlet of the atomizing gas injector. The atomizer was installed inside the spray facility oriented vertically downward. CO2 was injected into the water through an annular gas sparger injector. The water-CO2 mixture was then discharged through the nozzle exit orifice. The water and gas flow rates were controlled by adjusting the needle valves supplied with the rotameters. Spray from the nozzle was collected in a catch basin below. The water was collected in a catch pan then manually discarded.

The water tank used was a U.S. DOT Title 49, Code of Federal Regulations, Parts 171 to 190 pressure vessel. The water tank was pressurized using the building compressed air. An inline pressure regulator was mounted at the connection to the building air system. The pressure regulator was set at the required pressure to sufficiently pressurize the water tank. Mounted on top of the tank was a refrigerant recovery valve that was used to pressurize the water and to siphon water from the tank. From the tank, the water was piped through 3/8” polybutylene tubing to a Dwyer Model 620 water rotameter. Once through the rotameter the water was piped with 3/8”
Figure 2-1 Phase I Piping Schematic Diagram
polybutylene tubing through an inline pressure indicator and then to the atomizer. The pressure indicator was a Moody Price 2.5” face, diaphragm type, 0-200 psi range instrument.

The CO₂ storage cylinder was a U.S. DOT Title 49, Code of Federal Regulations, Parts 171 to 190 pressure vessel. The CO₂ cylinder was filled with liquid CO₂. A 90° angle gate valve was placed on top of the cylinder and was used to conduct the CO₂ vapor from the cylinder. A standard industrial gas regulator was connected to the angle valve and was used to both monitor the pressure inside the cylinder and to set the CO₂ supply line pressure. CO₂ was piped via ¼” polybutylene tubing from the cylinder to a Dwyer Model 820 gas rotameter. From the gas rotameter CO₂ was piped with ¼” polybutylene tubing through an inline pressure indicator. The gas pressure indicator was placed just downstream of the rotameter such that pressure measurements could be recorded and used for rotameter scale reading corrections. A Moody Price 2.5” face, diaphragm type, 0-250 psi range was used as the pressure indicator. After traveling through the pressure indicator the gas was piped to the atomizer.

2.2 Phase II and Phase III Experimental Facility

A schematic diagram of the Phase II and Phase III experimental facility is shown in Figure 2-2. The experimental facility used for Phases II and III was similar to that utilized in Phase I except this facility was modified to accommodate multi-hole orifice nozzles. The larger cone angles produced by the multi-hole nozzles required a larger catch basin and the distance from the atomizer to the catch basin was increased. Since NFPA 750 atomizer characterization specifications had to be followed, a minimum
Figure 2-2 Phase II and III Piping Schematic Diagram
distance of 3'-6” from the atomizer to the catch basin had to be maintained. This also allowed clearance for the transmitting optics and the catch basin.

Water was supplied from a 50 GAL, 150 psig ASME pressure vessel. The water tank was pressurized with nitrogen, N₂, supplied from a compressed gas cylinder. Fixed on the N₂ gas cylinder angle valve was a standard industrial inert gas regulator. The pressure regulator was set to the desired pressure to provide the design water pressure. A siphon tube was placed within the water tank such that water could be taken from the bottom of the tank. From the water tank to the water inlet on the atomizer, the water piping system was the same as described above for Phase I experiments. The atomizer used for Phases II and III is shown in Figure 4-4.

The atomizing gases were supplied from standard U.S. DOT Title 49, Code of Federal Regulations, Parts 171 to 190 pressure vessels. From the atomizing gas pressure vessels to the gas inlet on the atomizer, the atomizing gas piping system was the same as described above for the Phase I experiments. The atomizing gases were injected into the flowing water through the conical gas injector shown in Figure 4-3.

The spray was collected in 3’-6” x 3’-6” x 3’-6” catch basin. The catch basin was constructed from galvanized sheetmetal. Water collected in the catch basin was drained into a bucket and manually discarded.

2.3 Phase IV Experimental Facility

The testing facilities utilized for Phase IV of this study consisted of a fire testing chamber, experimental fires, and an automated fluid delivery system. Each of the components are described below.
2.3.1 Fire Testing Facility

Figure 2-3 shows the outline drawing of the fire testing facility. The facility was constructed of a stainless steel exterior, lined with refractory brick. Figure 5-5 shows the experimental facility. It was rectangular in shape having dimensions of 4’-9 1/2” x 7’-9” x 9’-1”. There was a perforated metal platform 1’-6” above the facility floor. It was on this platform that the pool fires were placed and the pipe supports used in the spray fires were supported. In the top of the facility was a 10” diameter flue that extended through the roof of the building to provide the chamber’s exhaust ventilation. A 2’-6” x 6’-6” door was installed on one side to allow access into the chamber. Two small openings were provided in the side of the facility, one 12” x 12” for visual observation and the other 6” x 6” for fire ignition. Figure 2-3 shows the position of each opening. Water piping was installed inside the chamber to deliver water to the atomizers. A pre-fabricated piping system was installed to accommodate multiple type atomizers, i.e., twin-fluid and single-fluid atomizers. Figure 2-3 also depicts the position of the atomizers, water piping, and gas piping within the facility. The water mist fire suppression atomizers were mounted and installed vertically downward.

2.3.2 Experimental Fires

The ethyl alcohol pool fires consisted of burning 3 quarts of alcohol in a 24 x 36 x 3” open container of welded sheet metal and angle iron. Figure 2-4 shows the pool fire container and the locations of the pool fires within the facility. The open container was constructed of 1/8” thick sheet metal as the bottom of the container and 3 x 3 x 1/8 angle iron as the sides. The container was located on the platform within the chamber. The
Figure 2-3 Fire Testing Facility

container was placed at three different locations within the chamber, in the center, against one wall, and in one corner, to study the effectiveness of the atomizers when the relative position of the nozzle and fire was varied. Figure 2-4 indicates the position of the pool fire container for all three pool fire sceneries.

Ethyl alcohol and propane spray fires consisted of spraying the fuels through a 1 gpm Lawrence fuel injector located within the fire testing facility. The fuel injector was
supported from the facility’s platform. The fuel injector was located in the center of the chamber 1’-8” south of the atomizer, See Figure 2-5 for details. 0.164 GPM of ethyl alcohol was sprayed from the fuel injector. Experiments were conducted with propane spray fires with the fuel injector located at the same locations within the chamber as with ethyl alcohol. A propane flowrate of 75 SCFH was used for all propane spray fires.
A 8” dia. x 1’-0” long stainless steel cylinder was placed within the chamber during several of the fire tests to simulate a machinery fire. The cylinder was placed within the pool fire container and the spray fires were projected onto the cylinder to simulate a piece of equipment on fire. Figure 2-6 depicts the simulated machinery fire test setup. The simulated machinery fires were conducted to study the effectiveness of the atomizers when a hot metal object was placed inside the fire. It was theorized that the

![Diagram of spray fire fuel injector details]

Figure 2-5 Spray Fire Fuel Injector Details

hot metal object might diminish the atomizer fire suppression effectiveness due to the added mass that must be cooled near the seat of the fire.

Prior to the ethyl alcohol pool fire suppression test using the Cone-4B1 atomizer and the Grinnell AM10 atomizer, dry fire tests were conducted with the fuel only. Three quarts of ethyl alcohol were ignited and allowed to burn with no water application. The temperature profile within the chamber was measured and recorded. Also, the time to
extinguishment was measured. The dry tests were conducted to establish a basis in which the water tests could be compared.

2.3.3 Fluid Delivery System

Figure 2-7 shows the Piping and Instrument Diagram for the automated fluid delivery system. The fluids were stored and pressurized using pressure vessels: water, atomizing gas, and nitrogen. Also included in the delivery system was piping, pipe fittings, pressure regulators, pressure sensors, temperature sensors, flow control valves, solenoid ON/OFF valves, check valves, pressure relief valves and a control and data acquisition system. The fluid delivery system was completely automated supplying the fire suppression nozzles with water and atomizing gas and logging key fluid flow data.

Water was stored in a 120 gallon ASME Section VIII coded pressure vessel. Pressurization for the water tank was provided by nitrogen that was stored in a compressed gas cylinder. The water tank pressure was set using a standard inert gas
pressure regulator. From the tank water was piped through the delivery system where a ON/OFF solenoid valve was placed. A flow orifice was located downstream of the solenoid valve to measure water flow rate. Pressure up and downstream of the orifice was measured using inline pressure transducers. The upstream and downstream pressure measurements were made by the control software as inputs in the water flow rate calculations. Next a pneumatically controlled flow control valve was installed downstream of the orifice. After existing the control valve the water was piped via 1” flexible rubber hose to the fire testing chamber. Within the fire testing chamber was a copper piping circuit that allowed for various configurations of atomizers (See Figure 2-3). Finally, the water was supplied to the atomizing nozzles and discharged into the fire testing chamber.

Atomizing gas (CO$_2$, and N$_2$) was stored in standard compressed gas cylinders. The gas pressure was set using standard industrial gas pressure regulators. The gas was piped from the pressure regulator with 5/8” stainless steel tubing to a nominal 1” stainless steel pipe. A 1” ON/OFF solenoid valve was installed just downstream of the 3/8” x 1” increaser to initiate or cease gas flow. Five pipe diameters downstream of the solenoid valve was an inline thermocouple used to measure the gas temperature. Installed downstream of the thermocouple was a flow orifice. Gas pressure up and downstream of the orifice was measured using inline pressure transducers. Next in the gas piping was a pneumatically controlled flow control valve. After existing the control valve the atomizing gas was piped via flexible ¾” rubber hose to the fire testing chamber. Finally, the atomizing gas was supplied to the atomizing nozzles, mixed internally with water and discharged into the fire testing chamber.
2.3.4 Temperature Measurement System

Eight (8) type K thermocouples were installed inside the fire testing chamber at the locations shown in Figure 2-8. Thermocouples TC7 and TC8 were moved within the facility depending on where the fire was located, See Figure 2-8 for locations. The thermocouple analog signals were wired back to the automated delivery system where their readings were logged.

2.3.5 Water Spray Distribution Tray

A water spray distribution pan was constructed to measure the volume flowrate of water delivered to the regions near atomizer. Figure 2-9 depicts the water distribution tray. The tray was constructed from 1/8” thick clear plastic sheeting. Twenty four (24) 4x2x4” bins were formed to give the distribution tray overall dimensions of 4x48x4”. Each water bin was sealed from adjacent bins watertight.
Figure 2-7 Phase IV Piping and Instrument Diagram
Figure 2-8 Thermocouple Locations Within Fire Testing Facility

<table>
<thead>
<tr>
<th>THERMOCOUPLE</th>
<th>X(IN.)</th>
<th>Y(IN.)</th>
<th>Z(IN.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td>28.75</td>
<td>60</td>
<td>56</td>
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<tr>
<td>TC2</td>
<td>28.75</td>
<td>60</td>
<td>12</td>
</tr>
<tr>
<td>TC3</td>
<td>12</td>
<td>60</td>
<td>46.5</td>
</tr>
<tr>
<td>TC4</td>
<td>28.75</td>
<td>60</td>
<td>81</td>
</tr>
<tr>
<td>TC5</td>
<td>45.5</td>
<td>60</td>
<td>46.5</td>
</tr>
<tr>
<td>TC6 (CENTRAL/WALL)</td>
<td>18.75</td>
<td>72</td>
<td>46.5</td>
</tr>
<tr>
<td>TC6 (CORNER)</td>
<td>39.5</td>
<td>72</td>
<td>12</td>
</tr>
<tr>
<td>TC7 (CENTRAL/WALL)</td>
<td>18.75</td>
<td>3</td>
<td>46.5</td>
</tr>
<tr>
<td>TC7 (WALL)</td>
<td>39.5</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>TC8</td>
<td>40</td>
<td>72</td>
<td>29.25</td>
</tr>
</tbody>
</table>

Figure 2-9 Water Spray Distribution Tray
CHAPTER 3. INSTRUMENTATION AND DATA ACQUISITION

3.1 Phase Doppler System

A schematic of the instrumentation used for the atomizer spray characterization measurements is shown in Figure 3-1. Phase-Doppler Anemometry (PDA), a light-scattering technique was used to measure the spray droplet diameters and velocity. The two-component Phase-Doppler system used for the measurements was based on a standard four-beam configuration. The intersection of the four beams defined the probe volume. As a droplet with an x and y velocity component, $U_i$ passes through the probe volume it causes the scattered light flux to oscillate with a Doppler frequency and the velocity of the droplet can be calculated:

$$U_i = \frac{f_d \cdot \lambda}{2 \cdot \sin \left( \frac{\theta}{2} \right)}$$

Where $f_d$ is the Doppler frequency, $\lambda$ is the incident laser light wavelength and $\theta$ is the beam intersection angle defined as:

$$\theta = \arctan \left( \frac{bs}{2f_t} \right)$$

Where $bs$ is the transmitting beam separation in millimeters and $f_t$ is the focal length of the transmitting optics in millimeters. Phase-Doppler theory predicts the size of a spherical droplet can be determined from the phase-difference of the scattered light as received from two different angles using a corresponding number of photo-detectors. The droplet size is proportional to the phase difference as follows:

$$D = \frac{\phi \cdot \lambda}{\pi \cdot n_1 \cdot \xi}$$
Where $\phi$ is the measured phase difference between two photo-detectors, $\lambda$ is the incident light wavelength, $n_1$ is the index of refraction of the droplets, and $\xi$ is a proportionality constant depending on $\lambda$, $\theta$, the scattering angle $\beta$, the elevation angle, $\psi$ of the photo-detector (Stanley 2000).

The light scattering system consisted of a Spectra-Physics 2000 Series argon-ion laser, fiber optic transmitting cable, transmitting and receiving optical components including three receiving detectors. The optical equipment and signal processing unit were manufactured by Dantec.

![Figure 3-1. Phase Doppler Instrumentation and Data Acquisition Schematic](image-url)
The spray characterization experiments used a two-component PDA system that used green light (514.5 nm) for U velocity measurements and blue light (488 nm) for V velocity measurements. The signal processor was equipped with a coincidence filter such that signals are only validated if they are validated on both U and V velocity channels. The U photomultipliers were equipped with band-pass filters so that they received only scattered light in their respective colors. A 1000 mm focal length lens was used for the beam transmitting optics. Table 3-1 contains a summary of the experimental optical parameters, probe volume sizes used in this study, and the velocity and diameter resolution achieved with each setup.

Table 3-1. PHASE-DOPPLER Optical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Droplet Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering Angle (°)</td>
<td>30</td>
</tr>
<tr>
<td>probe Volume:</td>
<td></td>
</tr>
<tr>
<td>x-Dimension (mm)</td>
<td>0.1453</td>
</tr>
<tr>
<td>y-Dimension (mm)</td>
<td>0.1450</td>
</tr>
<tr>
<td>z-Dimension (mm)</td>
<td>2.2530</td>
</tr>
<tr>
<td>number of fringes</td>
<td>36</td>
</tr>
<tr>
<td>Fringe Spacing (µm)</td>
<td>3.9956</td>
</tr>
<tr>
<td>velocity resolution (m/s)</td>
<td>0.561</td>
</tr>
<tr>
<td>diameter resolution (µm)</td>
<td>0.479</td>
</tr>
</tbody>
</table>
3.2 Fluid Delivery and Temperature Measurement System

Data acquisition and fluid flow control for the full-scale fire tests utilized National Instruments (NI) data acquisition hardware and LabVIEW software. Figure 2-7 shows which fluid and flow parameters were measured. Fluid flow was controlled centrally from a Human Machine Interface (HMI) console. The HMI console consisted of a flow control computer, monitor, and data acquisition cards. Data measured from the inline piping components were input into two SCC-FT01 feed through/breadboard modules. Installed within the feed through modules were NI SCC-DO01 digital processing cards and SCC-C120 2 and 8 channel input cards. 0-20mA signals were transmitted from the inline flow measuring devices and the thermocouples to the SCC-C120 input cards. From the SCC-C120 cards the signals were transmitted to the flow control computer were the data was manipulated and stored. Digital signals from the flow control computer were sent to the SCC-DO01 card and from there the signals were transmitted to the inline piping components to control the fluid flow. Installed in the flow control computer were two NI PCI-6024E cards. These cards allowed for a total of 24 inputs.

Flow control was accomplished utilizing the LabVIEW software. A control scheme was designed and programmed within the LabVIEW software that automated the fluid delivery system once initiating the command to commence flow. The fluid delivery system sequence of operation, for the twin-fluid atomizers, was as follows:

1. Determine both gas and water control valve stroke position for desired fluid flow rate prior to fire testing. This was done due to the duration of some of the fire tests, the pneumatically actuated valves would not have time to come to the set point before fire extinguishment. Once the valve stroke position was determined, the position was maintained such that
when the fluid flows were initiated the desired flow rates could be sustained. The control valves were controlled with a digital signal from the HMI to the valve actuators.

2. The experimental fire was ignited within the fire testing facility.

3. After a pre-burn time of typically one to two minutes, the atomizing gas was activated (the gas ON/OFF solenoid valve was opened). At this point all inputs into the HMI began logging data.

4. Once the atomizing gas was activated, the control system executed a five second delay before activating the water (the water ON/OFF solenoid valve was opened).

5. All fluid flow inputs to the data acquisition system were logged throughout the duration of the experiment. Inputs included: water and gas up and downstream pressure, orifice differential pressure, atomizing gas temperature, and eight temperature inputs from inside the fire testing facility.

6. The fluid delivery system continued to supply water and atomizing gas to the nozzles until the operator at the HMI console manually shut the system down. The system was shut down upon extinguishment of the fire (both solenoid valves were closed).

The sequence of operation for the fluid delivery system during fire testing using the Grinnell AM10 nozzle was the same as described above for the twin-fluid atomizers with the exception no atomizing gas was used. Thus, after the fire pre-burn the water was initiated and the system operated as described above.

The sampling rate and control system response rate was 1 Hz for all experiments. Figure 2-8 shows the locations of the thermocouple positions within the fire testing facility. The thermocouples were connected to the data acquisition system. Since some of the thermocouples were in the path of the water spray, they were shielded with
stainless steel sheet metal placed above them between the thermocouple sensor and the atomizers. The temperature was measured near the free surface of the ethyl alcohol during the pool fires. Temperature measurements were made within the fuel spray for the spray fires.
CHAPTER 4 PHASE I RESULTS; DESIGN OF TWIN-FLUID ATOMIZERS

4.1 Twin-Fluid Atomizer Design and Development

Phase I of this study began with the design and development of a twin-fluid atomizer for applications in water mist fire suppression systems. The design of the twin-fluid atomizer began with a design that was developed by a senior project design team at LSU. The atomizer was a twin-fluid, internal mixing unit constructed of commercially available plumbing hardware. Air was injected into water through an annular sparger injection tube and the air/liquid mixture was discharged through a single-hole orifice. Figure 4-1 shows the internal geometry of the atomizer.

Components of the atomizer included a sintered metal gas injector or sparger, mixing chamber, and exit nozzle. The sparger was constructed of a ¼” stainless steel, SS, tube with a SS sintered section. The mixing chamber and outer water pipe was constructed of ½” clear acrylic piping. The exit nozzle was made from a 3/4” brass FNPT pipe cap with a single 0.035” diameter hole drilled in the center with a 0.065” countersink. Details of the nozzle are shown in Figure 4-1.

The current research began by determining design objectives for the twin-fluid atomizer. Outlined in the design objectives was the atomizer’s ability to produce a large droplet distribution, maximize the liquid flow rate while minimizing the gas flow rate, and produce a sufficient cone angle to be effective in fire suppression applications.

A large droplet distribution aids in all modes of fire suppression due to the size and momentum of the droplets. The larger, high momentum droplets aid in fuel cooling because the liquid droplets penetrate the fire plume and penetrate to the seat of the fire. Smaller droplets cool the space surrounding the fire by absorbing heat from the fire and
surrounding enclosure. The small droplets are vaporized as they fall towards the fire and surrounding hot surfaces. Vaporization of the droplets causes rapid expansion of the liquid resulting in displacement of oxygen and consequently starving the fire of oxygen. Minimizing the quantity of atomizing gas was considered an objective in order to reduce the amount of atomizing gas required for storage and delivered to the atomizer. Storage of the atomizing gas increases the size of the space required to install twin-fluid fire suppression systems, thus by minimizing the quantity required we minimize the space
required. Also, minimizing the gas required reduces the size of the piping and tubing required for piping and connected to each atomizer. A large spray cone angle was considered an objective to provide a large area of coverage per atomizer. Large spray cone angles coupled with good droplet distributions result in fewer atomizers per unit area required for fire suppression.

Experiments began by studying the spray characteristics produced by the LSU senior design atomizer and several problems were discovered. First, the flow inside the mixing chamber was very unstable. 33 SCFH of air and 0.05 GPM of water were the design flow conditions discharged from the atomizer. Since the atomizer was constructed out of clear acrylic pipe, the unstable flow within the mixing chamber could be visually observed. This unstable flow within the atomizer produced an unstable spray. Further evidence of unstable flow was a pulsating, periodic sound radiating from the atomizer. The spray produced under these flow conditions was sporadic and oscillated between good and poor atomization. The spray oscillated at the same frequency as the two-phase flow pulsations within the atomizer. From Nikitopoulos’ (1998) two-phase flow maps it was determined that the atomizer was operating in the transition flow regime between bubbly flow and annular flow. Lefevbre (1997) documented the unsteady flows from twin-fluid atomizers when operating in this transitional flow regime. The second problem discovered was the nozzle did not produce sufficient liquid flowrates required for fire suppression applications. Third, from PDA measurements conducted in the senior project design, the droplet distribution and velocities produced did not meet the project design objectives. Fourth, the cone angle the nozzle produced was not sufficient for fire suppression applications.
From the audible and visual unsteadiness observed within the atomizer it was theorized that the air and water were not getting well mixed before exiting the nozzle. Therefore, CO$_2$ was chosen to replace air as the atomizing gas for two reasons. First, CO$_2$ is much more soluble in water than is air, therefore the higher solubility was thought to promote better mixing between the two fluids thus a more stable two-phase flow within the atomizer. Second, since the development of this atomizer is to be used in fire suppression applications, CO$_2$ could possibly aid in the spray’s fire suppression capabilities.

Experiments were performed using CO$_2$ as the atomizing gas with the original atomizer and similar flow and spray characteristics were produced as previously observed with air. Experiments were conducted over a wide range of CO$_2$/water GLR’s and no conditions were found that produced stable flow. After analyzing the internal flow it was determined that the mixing of the two fluid phases was not the problem. It was then theorized that the gas injection area into the flowing water was too large and was causing the unstable flow. The atomizing gas was injected into the water through the entire length of the sintered metal sparger. This large injection distance resulted in a non-uniform pressure field along the length of the injector. The non-uniform pressure caused a gas injection rate that varied along the length of the sparger resulting in non-uniform flow and setting up pulsations within the atomizer. Since the two-phase flow was already known to operate in an unstable flow regime the gas sparger pressure field problem only exacerbated the unsteadiness. Chin and Lefebvre (1993) reported using a conical gas injector in an internal mixing twin-fluid atomizer and successfully producing a stable, well atomized spray. Chin and Lefebvre’s atomizer shown in Figure 4-2 featured a liquid
acceleration region, an air injection region, mixing chamber, two-phase mixture acceleration region, and nozzle exit. Based on this paper, a new cone shaped injector was designed and constructed. We incorporated all of the regions described by Chin and Lefebvre into the redesign of our atomizer and gas injector. The conical gas injector is shown in Figure 4-3.

![Figure 4-2 Chin and Lefebvre’s (1993) Internal-Mixing Atomizer Configuration](image)

Figure 4-2 Chin and Lefebvre’s (1993) Internal-Mixing Atomizer Configuration

The injector was constructed from round yellow brass stock. The tubular portion (Part 1 Figure 4-3) was bored with a 0.170 in. diameter drill then the outside diameter was turned down to its design thickness of 0.25 in. A conical end was machined on one end at 70° from the horizontal with the same thickness as the cylindrical portion. The cap (Part 2 Figure 4-3) was machined from the same yellow brass stock and a cavity was milled inside the cap. Eight equidistant 0.0158 in. diameter holes were radially drilled around the circumference of the cap. The cap was then soldered onto the tubular portion. The tube and cap were then soldered into a straight 3/4” NPT x 1/4” compression adapter to complete the gas injector assembly.
The new gas injector was installed in the existing mixing chamber/nozzle (shown in Figure 4-1) and experiments were performed. Using the new gas injector, the atomizer produced a considerably more stable flow and spray. However, the internal flow and resulting spray did not display the stability outlined in the design objectives. The two-phase flow most probably moved from the transition regime between the bubbly and annular flow regimes to near the border of the annular flow regime.

Since a considerable improvement in the stability of the spray had been achieved but still an unacceptable amount remained, we decided to increase the fluid pressures and flowrates to try and identify stable flow conditions at higher pressures. Therefore, it was decided to redesign the atomizer and mixing chamber to enable going to higher pressures. The operating pressures of the atomizer at this point were at the maximum for the acrylic components comprising the outer atomizer and mixing chamber. A brass mixing chamber was constructed with the same dimensions as the acrylic. The CO₂ and water
pressures were increased from 55 and 50 psig to 85 and 80 psig respectively and the CO2 and water flowrates were increased from 33 SCFH and 0.05 GPM to 68 SCFH and 0.3 GPM respectively.

A series of experiments were conducted with the redesigned mixing chamber with the intention of find an operating range in which stable flows could be maintained. However, after experimenting over a wide range of GLR’s, stable operating conditions could not be established. The increased pressures and flowrates improved the atomization of the spray but did little for the stability. From visual observation it could be seen that at the higher pressures the atomization was more efficient and the cone angle of the spray was increased. However, the pulsating internal flow and spray remained. Therefore, the focus of the research returned to the acrylic atomizer and formulating what was causing the unstable pulsating flow inside the atomizer.

The brass mixing chamber constructed for the higher pressure experiments was abandoned and was replaced with the original acrylic chamber. During the process of rebuilding the atomizer the acrylic chamber was installed into the atomizer body such that the chamber extended further into the atomizer body. Inserting the chamber further into the body resulted in reducing “Dimension B” Figure 4-3. Experiments were conducted with the slightly new configuration and the experiments revealed a more stable flow. More experiments were conducted and the mixing chamber was inserted further into the atomizer body and even more stable flow resulted. After operating the atomizer over a wide range of GLR’s and observing stable, well-atomized sprays it was determined the closer the injector was placed to the step change in internal diameter (I.D.), the more stable the flow and spray became.
With this evidence of stabilized flow, a new atomizer and mixing chamber was designed such that the distance from the CO\textsubscript{2} injection point to the nozzle exit orifice could be varied. Figure 4-4 shows the atomizer that was designed and constructed with the ability to vary the mixing volume, i.e., the distance from CO\textsubscript{2} injection to the exit orifice.

This atomizer was machined from round yellow brass stock. It featured an adjustment nut (Part 1) that was held in place by snap rings and sealed to the atomizer body (Part 2) by two o-rings. The nut was threaded onto the body and had the ability to be moved up and down relative to the CO\textsubscript{2} injector while the atomizer was operating. This ability to move in operation, allowed for optimization of the position of the exit orifice relative to the CO\textsubscript{2} injection point. The varying of relative position of the gas injector and exit orifice changed the internal two-phase mixing volume of the atomizer. It was determined that varying this volume changed the stability of the internal flow and thus the resulting spray pattern. Figure 4-5 shows the assembly of the twin-fluid atomizer with the adjustable two-phase mixing volume.

The initial mixing chamber component (Part 3) was designed to have the same internal geometry as the acrylic chamber. Several mixing chamber geometries shown in Figure 4-6 were designed and machined to study the effects of mixing chamber geometry on the spray produced. Experiments were conducted with each of the mixing chamber geometries. The same conical gas injector (Part 4) designed and constructed for the previous atomizer was used for this design.

Since the problem of flow and spray instability had been resolved, the low liquid flowrate and cone angle problems were next addressed. A multi-hole nozzle (Part 5)
Figure 4-4 Twin-Fluid Atomizer with Multi-Hole Exit Orifice and Adjustable Two-Phase Mixing Volume

was conceptualized to increase both liquid flow rates and cone angle. Figure 4-7 shows the multi-hole nozzles that were designed and constructed. The nozzles were designed for specific liquid flowrates. From the literature, it was determined that most commercially available water mist atomizers operated at approximately 3 GPM. Therefore, we chose 3 GPM as our multi-hole nozzle design water flowrate.

The multi-hole nozzles were designed and constructed to both increase the fluid flowrates and increase the effective spray cone angle. The nozzles were designed with conical tapers in which the exit orifices were drilled at eight equidistant locations around the circumference. The conical shape allowed the water to discharge at an angle from the vertical thus increasing the effective cone angle. These nozzles featured eight exit orifices with a water spray jet discharged from each. Eight exit orifices were chosen to provide sufficient coverage around the circumference of the nozzle such that there would
be no voids in the spray at distances downstream of the nozzle. Phase Doppler measurements were conducted along with visual inspection of the sprays produced by each nozzle to determine the resulting spray characteristics.

Figure 4-5 Assembly Drawing of the Twin-Fluid Atomizer with Multi-Hole Exit Orifice and Adjustable Two-Phase Mixing Volume

4.2 Effects of Mixing Chamber Geometry

The first chamber tested was Mixing Chamber A shown in Figure 4-6(a). This geometry was matched to the geometry of the clear acrylic mixing chamber previously tested. This geometry featured a sharp edge inside the chamber where the inside diameter was reduced from 0.62 to 0.495 in. Experiments were conducted with this
mixing chamber and all four nozzles shown in Figure 4-7. Liquid and gas flowrates were varied from 1.0 to 3.0 gpm and 80 to 200 SCFH respectively. The adjustment nut on the atomizer was varied throughout the experiments and it was found that the best results were observed when the gas injector was placed 0.125 in above the sharp change in internal diameter. The sharp change in internal diameter causes a large local pressure drop and the two-phase flow was accelerated in this region. Under these flow conditions the two-phase flows were in the annular flow regime. Operating in this regime promoted

Figure 4-6 Twin-Fluid Atomizer Mixing Chambers
flow and spray stability. Good atomization and stable flow was observed throughout the ranges described above. However several liquid/gas combinations were identified to produce more favorable sprays that demonstrated good atomization and maximized cone angles.

Experiments were conducted with Mixing Chamber B, shown in Figure 4-6(b) installed in the atomizer. Chamber B differs from A by the distance from the end of the

![Figure 4-7 Multi-Hole Nozzles](image-url)
chamber to the sharp step change in internal diameter. This distance was reduced in Chamber B than in A. The distance was decreased to study if decreasing the mixing volume further effect the atomization. It was discovered that the change in geometry had a pronounced effect on the atomization. All four multi-hole nozzles shown in Figure 4-7 were tested with Chamber B. The decreased mixing volume resulted in instability in the spray and internal flow. The instability was attributed to a resonance time, natural frequency, required to maintain stable flow within the atomizer. This resonance time was dependent on the distance from the point of gas injection to the nozzle exit orifices. Additional planned experiments with this mixing chamber were abandoned due to the problems incurred.

Finally, Mixing Chamber C shown in Figure 4-6 was tested. Mixing Chamber C differed from the other two chambers by the internal tapered geometry. Chamber C was tapered from an internal diameter of 0.62 in. to 0.495 in. The tapered geometry was chosen to see what effect a gradual decrease in internal diameter would have on the internal flow and spray. A series of experiments were conducted with Chamber C and all the multi-hole nozzles shown in Figure 4-7. The experiments were conducted over the same fluid flow ranges described for Mixing Chamber A. Qualitative results from the experiments indicated that the tapered internal geometry did not perform as well as Mixing Chamber A. The spray was considerably unstable and not well atomized. Also, audible instability could be heard coming from the atomizing indicated that the internal two-phase flow was in a transitional regime. This instability in this case was attributed to the gradual decrease in I.D. rather than a step change. The gradual change did not accelerate the two-phase mixture to the point where annular flow could be maintained.
Therefore, from the qualitative experiments conducted with the different mixing chambers it was decided to continue the study using only Mixing Chamber A. The spray produced from Chamber A was the most stable and well atomized of the three geometries tested. These findings were consistent with Chin and Lefbvre (1993) results were they reported increased stability in internal-mixing atomizers with decreased internal diameters. The best results were observed when the atomizers were operating in the stable annular flow regime. When the atomizer operates in this regime the atomizer operates as a classical plain-jet airblast atomizer, comprising a central core of high-velocity air surrounded by a thin annular film of water. The two phases are completely separated, with the air flowing at very high velocity and the liquid flowing at much lower velocity due to the frictional losses along the chamber walls. The high relative velocity between the air and the liquid ensures good atomization.

4.3 Effects of Multi-Hole Nozzle Geometry

All the multi-hole nozzles shown in Figure 4-7 were used in conjunction with the all three mixing chambers as described previously. Experiments were conducted with all four nozzles and from visual observation CONE-4B1 was determined to perform best. During these visual qualitative experiments several flow conditions for each atomizer/nozzle combination was identified where stable flow was observed. The stable flow conditions found were the conditions at which the Phase II PDA measurements were conducted.
5.1 Phase I Experimental Flow Conditions

The experiments conducted in Phase I of this study for the most part were qualitative. Various combinations of liquid and gas flow conditions were used to determine the optimal flow conditions for the twin-fluid atomizers. Phase I primarily focused on the development of the atomizer and identifying the flow conditions that produced the water mist outlined in our design objectives. Audible and visual observation was used as the primary means of developing the stable, well-atomized spray desired. Experiments in this phase of the study were focused on the atomization process and the flow patterns within the twin-fluid atomizer. The primary purpose of this phase of the study was to design, develop, and construct a twin-fluid atomizer with those characteristics outlined in the literature that were known to be effective in fire suppression applications.

5.2 Phase II Experimental Flow Conditions

Phase II of this study consisted of conducting PDA measurements on the sprays produced by the various atomizer/nozzle combinations found in Phase I. Various flow conditions were tested and analyzed in an attempt to design an atomizer to meet the previously stated design objectives. CO₂ atomizing gas and water flow rates were determined based on visual and audible observations of the sprays. The sprays were optimized based on flow and atomization stability. Testing conditions were also determined based on the resulting spray cone angles observed. Once these flow conditions were identified the measurements were conducted. The flow conditions for this phase of the study are denoted as Cases 001 through 013 in Table 5-1. GLR’s ranged from 0.008 to 0.052. The purpose of this phase of the study was to characterize the spray produced by each atomizer and nozzle combination. Figure 5-1 shows the points at which the PDA measurements were taken. A centerline scan was performed from 15 in. below the nozzle to 20 in. below the nozzle. Both 0° and 90° radial scans were
performed to determine the radial droplet diameter and velocity profiles along with the spray symmetry. Radial scans were made from the nozzle centerline out to 15 in. from the centerline. In the centerline and 0° scans SMD’s, U-velocity, and V-velocity components were measured. In the 90° scans SMD’s, U-velocity, and W-velocity components were measured.

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5.3 Phase III Experimental Flow Conditions

Similar to the Phase II measurements, the Phase III PDA measurements were conducted to characterize the sprays produced by the water mist fire suppression nozzle. Phase III differed from Phase II by the atomizing gas was varied. CO₂, N₂, and He were
used as the atomizing gases to study the effects of the atomizing gas on the resulting spray. Also, NFPA 750 was satisfied by characterizing the sprays at 3.3 ft (1 m) below the nozzle. Phase III used information learned from Phases I and II and incorporated that knowledge when determining the fluid flowrates. In both previous phases the majority of the water flowrates were not adequate for fire suppression applications. Therefore higher flowrates were chosen with help from the literature on water mist fire suppression. 2.4, 2.8, and 3.2 GPM were chosen for this phase of the study and to be further studied in the fire tests for Phase IV. The flow conditions for Phase III are denoted as Cases 014 through 022 in Table 5-1. GLRs for this phase ranged from 0.002 to 0.024.

Phase-Doppler measurements were obtained along the radius of the spray, 3.3 ft below the nozzle exit. SMD’s, U-velocity, and V-velocity components were measured.
from \( r = 18.25 \text{ in.} \) to \( r = 27.75 \text{ in.} \). Figure 5-2 shows the points at which the measurements were obtained.

![Figure 5-2 Phase III PDA Measurement Locations](image)

**Figure 5-2 Phase III PDA Measurement Locations**

### 5.4 Phase IV Experimental Flow Conditions

Phase IV of this study consisted of conducting full-scale fire suppression tests of the water mist atomizers on ethyl alcohol pool fires, ethyl alcohol spray fires, propane spray fires, simulated machinery fires, and combinations of the pool, spray, and machinery fires. Table 8-1 contains the fire suppression test matrix. Table 8-1 indicates the Case No., atomizer used, type of fire, and location of fire. The purpose of this phase of the study was to characterize the effectiveness of the water mist fire suppression atomizer when placed in Class B fires. Also, the fire suppression results were used to
compare the effectiveness of the LSU developed atomizer, Cone-4B1, with that of commercially available ones. Flow conditions for this Phase were the same as described for Phase III, Cases 014 through 022, with the exception that the cases that utilized He as the atomizing gas were excluded. It was determined from the Phase III results that the sprays produced by the CO₂ and N₂ atomizing gases were most suitable for fire suppression applications.
CHAPTER 6 PHASE II EXPERIMENTAL RESULTS

6.1 Experimental Conditions

Measurements were conducted to characterize the sprays produced by twin-fluid water mist fire suppression atomizers developed in Phase I. The experiments were conducted for one (1) single-hole exit orifice atomizer and four (4) multi-hole exit orifice atomizers. In each case the water flowrate was maximized while the atomizing gas flowrate was minimized. Optimizing the water and gas flow rates was achieved by first maximizing the gas flowrate at the supply pressure then slowly increasing the water flow until the maximum flowrate at the set supply pressure was achieved. Once the water flowrate was maximized the gas flowrate was reduced until a stable, well-atomized spray was observed. The gas flowrate was minimized to try and reduce the quantity of atomizing gas required to produce a well-atomized spray. The experimental flow conditions for each case tested in this phase is summarized in Table 5-1.

6.2 Single Hole Exit Orifice Spray Characterization Results

Spray characterization measurements using a single component PDA system were conducted on the single-hole exit orifice atomizer with the conical gas injector shown in Figure 4-3. Using Case 001 flow conditions and a nozzle with a 0.05 in. exit orifice, droplet mean diameters and vertical downward velocities have been measured to characterize the spray. The results obtained from these measurements are presented in Figures 6-1 and 6-2. Figure 6-1 shows the mean droplet diameter distribution along the centerline of the nozzle spray. Measurements were taken at three axial locations along the centerline namely x/D = 40, 80, 120, where x was the distance below the nozzle and D was the diameter of exit orifice.
The droplet diameter distributions measured along the centerline of the spray discharged from the single-hole orifice displayed a small dependence on axial location. Each distribution shows a large range of droplets produced and all display peaks in the neighborhood of 56 $\mu$m. The droplet distribution at $x/D = 40$ shows a mean droplet diameter of 58.68 $\mu$m. The distribution is skewed somewhat to the larger droplet diameters. At $x/D = 80$ the mean droplet diameter was measured to be 52.69 $\mu$m with a tighter distribution than that shown at $x/D = 40$. At $x/D = 120$ the mean droplet diameter was measured to be 57.75 $\mu$m and the distribution was even more centered around the mean than at $x/D = 80$. These distributions show the atomizer’s ability to produce droplets that vary considerably in diameter. In all the above measurements the droplet diameters ranged from approximately 20 to 120 $\mu$m.

Figure 6-2 shows the droplets vertically downward mean velocity and the corresponding mean droplet diameter measured at various locations along the spray centerline. The velocity profile shown indicates a steady decrease in droplet mean velocities along the spray centerline. Mean velocities ranged from approximately 53 m/s to 37 m/s. Correspondingly, the droplet diameters did not vary significantly along the centerline.

The droplet diameter distributions measured along the radius of the spray displayed a strong dependence on radial location. Mean droplet diameters ranged from 52.08 $\mu$m at the centerline of the spray to 90.04 $\mu$m at the outer fringes of the spray. Figure 6-3 shows the droplet diameter distribution produced by the atomizer at various locations along the radius of the spray namely $r/x = 0$, 0.15, and 0.3 and at a fixed axial
Figure 6-1 Centerline Droplet Diameter Distributions

CASE 001
r/x=0
Q_H2O=0.3 gpm
Q_CO2=67.9 scfh
D_10=58.68 µm
σ_p=21.36 µm

COUNT (%)
0 2 4 6 8 10 12
D_1 (µm)

COUNT (%)
0 2 4 6 8 10 12
D_2 (µm)

COUNT (%)
0 2 4 6 8 10 12
D_3 (µm)

Figure 6-2 Centerline Mean Droplet and Downward Velocity Profiles

Figure 6-3 Radial Droplet Diameter Distributions

CASE 001
r/x=0
Q_H2O=0.3 gpm
Q_CO2=67.9 scfh
D_10=52.69 µm
σ_p=20.54 µm

COUNT (%)
0 2 4 6 8 10 12
D_1 (µm)

COUNT (%)
0 2 4 6 8 10 12
D_2 (µm)

COUNT (%)
0 2 4 6 8 10 12
D_3 (µm)

Figure 6-4 Radial Mean Droplet and Downward Velocity Profiles

CASE 001
Q_H2O=0.3 gpm
Q_CO2=67.9 scfh
P_H2O=50 psig
P_CO2=55 psig
location below the exit orifice at $x/D = 80$. In this case $r$ was the radial distance from the nozzle centerline and $x$ was the axial location below the nozzle exit. The droplet distribution at $r/x = 0$ shows a mean droplet diameter of 52.08 $\mu$m which is in agreement with the measurements made at $x/D = 80$ in the centerline scan measurements. At $r/x = 0.15$ the droplet distribution is much more spread out over the range of droplet diameters and has a mean droplet diameter of 57.81 $\mu$m. The droplet distribution shifts to larger droplet diameters at $r/x = 0.30$. The mean droplet diameter increased to 90.04 $\mu$m at this radial location. The droplet distribution became tighter than those at the previous locations. This was indicative of the larger droplets being concentrated near the fringes of the spray. It was attributed to the decreased in atomization efficiency with increasing distance from the nozzle centerline.

Figure 6-4 shows the mean vertically downward velocity and the corresponding mean droplet diameters at various radial locations within the spray. All these radial measurements were taken at $x/D = 80$. The velocity profile indicates a rapid decrease in droplet velocity with increasing distance from the spray centerline. Mean droplet velocities vary from 37 m/s at the centerline of the spray to 1 m/s at the fringes of the spray. The droplet diameter profile along the radius of the spray indicates a constant diameter until $r/x = 0.15$. At $r/x = 0.15$ it is shown that the droplet diameters increase much more rapidly with increasing distance from the spray centerline.

This information indicates that the high velocity droplets were concentrated in the core of the spray. It could not be determined if the large droplets that were shown to be concentrated around the outer fringes of the spray were also a result of droplet coalescence. The cone angle of the spray was calculated to be 20.6°. Figure 6-5 shows
the cone angle produced by the atomizer. The cone angle was calculated by assuming the spray was symmetric about the atomizer centerline and the last point in which PDA measurements could be obtained was assumed to be the radial limit of the spray.

6.3 Multi-Hole Nozzle Measurements Utilizing Nozzle Cone-4B

Spray characterization measurements were conducting on a multi-hole exit orifice water mist atomizer using Nozzle Cone-4B shown in Figure 4-7. Using Cases 002, 003, and 004 flow conditions, two-component PDA measurements were made to characterize

![Figure 6-5 Single-Hole Orifice Cone Angle](image-url)
the spray produced by the multi-hole nozzle at various operating conditions. For each operating condition a centerline scan was made beginning at 15 in below and measuring at 1 in increments to 20 in below the exit of the atomizer. Two radial scans were made at 16 in. below the nozzle exit to measure the droplet diameter and velocity profiles within the spray. One scan was made at $0^\circ$ and the second scan at $90^\circ$ to test for spray symmetry. See Figure 5-1 for PDA measurement locations for all Phase II experiments.

Figure 6-6 shows the SMD, U and V velocity components measured for Cases 002, 003, and 004 centerline scan experiments. It can be seen from Figure 6-6 that Case 002 produced the smallest SMD droplets than in the other two cases. Case 002 produced droplets ranging from approximately 105 to 140 $\mu$m. It can also be seen in Figure 6-6 that Case 002 produced the highest droplet mean velocities ranging from 1.45 m/s to 1.1 m/s. The V velocity component was smallest for Case 002. This indicates that the droplets in this case were traveling nearly vertically downward. In the other two cases, 003 and 004, the U velocities were near 0 m/s or were negative in sign. The negative sign indicates the droplets were traveling upward in these regions of the spray. It was observed visually during the experiments that with the multi-hole nozzle there were regions of recirculation within the spray. These regions of recirculation were concentrated in the core of the spray and their intensity varied depending on the axial distance from the nozzle. The V component velocities for Cases 003 and 004 ranged from near 0 m/s to 0.3 m/s indicated more horizontal movement of the droplets compared to Case 002.

Figure 6-7 shows the SMD, U, and V velocity components measured throughout the $0^\circ$ radial scan experiments 16 in. below the nozzle exit for Cases 002, 003, and 004.
Figure 6-6 Nozzle Cone-4B Centerline Profiles of SMD, U, and V Mean Velocities

Figure 6-7 Nozzle Cone-4B Radial Profiles of SMD, U, and V Mean Velocities

Figure 6-8 Nozzle Cone-4B Radial Profiles of SMD, U, and W Mean Velocities
The SMD radial profile for all three cases show in general an increase in SMD with increasing radius from the nozzle centerline. SMD’s ranged from 100 to 270 µm for each of the cases. The U and V velocities for each case show a bell shaped profile. This indicates the high velocity droplets are concentrated near the core of each jet discharged from each exit orifice. This trend was seen in the case of the single-hole orifice above. Maximum U velocities measured near the center of each jet averaged 7.5 m/s. The V velocities measured were all positive at each radial location for all cases. This was evidence there were no regions of recirculation as was measured in the centerline scan. The average SMD at the maximum velocity position was measured to be 130 µm. This indicates that the core of each jet contains high momentum droplets. For Cases 002 and 003 the maximum velocity was measured at 10.5 in from the centerline of the nozzle. The maximum velocity was measured at 9 in from the nozzle centerline for Case 004. At the maximum velocity location for Case 004 a SMD of 135 µm was measured which is smaller than each of the other two cases indicating a well-atomized spray. Also, Case 004 produced smaller droplets, on average, at each radial location.

Next, the spray produced using the Nozzle Cone-4B was tested for symmetry. A radial scan was made at 16 in. below the nozzle 90° from the previous radial scan. Using the same flow conditions, i.e., Cases 002, 003, and 004, PDA measurements were conducted. Figure 6-8 shows the SMD, U, and W velocity components measured. Comparing Figures 6-8 and 6-7 it can be seen that the SMD’s for Case 002 agree for r = 6 in. Both curves exhibit the same trend past r = 6 in. but in the case of the 90° scan the SMD’s show a much greater slope. The maximum SMD measured in the 0° scan was 197 µm at 12 in from the nozzle centerline. In the 90° scan the SMD measured at 12 in.
from the nozzle centerline was 270 \( \mu \)m. Furthermore, the U velocity profiles of the 90° scan do not agree with the 0° scan. The 0° profile is bell shaped with a maximum at 10.5 in from the nozzle centerline. The 90° scan does not exhibit the same shape curve, its curve steadily increases with a maximum velocity of 6.8 m/s measured at 12 in. from the nozzle centerline. It was conjectured that the nozzle/atomizer had a preferred orientation. This preferred orientation was either created by the flow patterns within the atomizer that caused the two-phase flow to be non-uniformly discharged through the nozzles or the construction of the nozzle was not symmetric. If the flow patterns within the nozzle were not symmetric as it entered the exit orifices the resulting spray would not be symmetric. Moreover, if the construction of the nozzle was not uniform, non-symmetric spray patterns would result. Non-uniform construction could have come from the drilling of the exit orifices or the fabrication of the nozzle internal geometry.

Comparing Figure 6-8 and 6-7 in can be seen that the SMD’s exhibit a similar profile and size distribution for the Case 003 flow conditions. Over the range \( r = 6 \) in to \( r = 12 \) in. the SMD’s closely match. The velocity profiles however do not agree. Both profiles demonstrate a similar curve but the magnitude of both velocities do not match. An example is at \( r = 10.5 \) in., in the 0° scan U was measured to be 9.2 m/s and in the 90° scan U was measured to be 3.4 m/s. This proves the momentum the droplets have within the spray varies depending upon which jet they were discharged through.

Comparing the results plotted for Case 004 in Figure 6-7 and 6-8 it can be seen that that the SMD profiles strongly agree in the range from \( r = 6 \) in. to \( r = 12 \) in. Both curves demonstrate similar trends as well as size distribution. However, the U velocities do not agree as was found for the Case 003 measurements. In the 90° case the maximum
U velocity was measured to be 8.1 m/s at r= 12 in. as opposed to the 0° case where the maximum U velocity was measured to be 6.2 m/s at r = 9 in. Again, the asymmetry demonstrated under these flow conditions were believed to be a result of either non-uniform flow within the nozzle/atomizer or asymmetry in the nozzle construction.

The W velocity components measured in the 90° radial scans ranged from -0.25 m/s to 0.25 m/s. This is indicative that the spray does not contain much swirl at these radial locations. The sprays at these radii, in the heart of the jet, are traveling downward and outward away from the nozzle centerline.

Using the data obtained from the PDA measurements an effective cone angle was calculated. Table 6-1 shows the calculated cone angles for Cone-4B.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cone Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>002</td>
<td>80.2</td>
</tr>
<tr>
<td>003</td>
<td>82.4</td>
</tr>
<tr>
<td>004</td>
<td>86.4</td>
</tr>
</tbody>
</table>

6.4 Multi-Hole Nozzle Measurements Utilizing Nozzle Cone-4B1

The same experimental procedure outlined in the Cone-4B measurements was utilized for the Cone-4B1 measurements. Figure 6-9 shows the SMD, U and V velocity components measured for Cases 005, 006, and 007 centerline scan experiments. Case 005 produced the smallest droplets at the nozzle centerline with droplet SMD’s ranging from 100 to 118 µm. The droplet SMD profile along the centerline for Cases 005 and 006 show an increasing SMD with increasing axial distance from the nozzle. However, Case 007 exhibited a jagged up and down centerline profile. The U and V velocity
profiles along the centerline for Case 007 show similar trends. A much more flat velocity profiles are evident in Figure 6-9 compared to those shown for Cone-4B. The relatively uniform droplet SMD profiles and uniform velocity profiles along the spray centerline were attributed to the more efficient atomization of the Cone-4B1 nozzle. The audible and visual stability of this spray was much more prevalent than any of the other sprays using different nozzles.

Figure 6-10 summarizes the radial scan measurements taken at 0° and 16 in. below the nozzle exit. All three SMD profiles indicate a sharp peak to the maximum droplet diameter then a decline in SMD. This sharp peak represents the outer fringes of the spray where the largest droplets were concentrated. Once the fringes of the spray have been traversed the droplet diameter and velocity decrease. The radial U and V velocity profile of Case 005 shows a peak, corresponding to the same peak in the SMD profile, at which a maximum velocity is reached and then the velocities decrease in magnitude. Again, it is theorized that these velocity and SMD maxima lie on the outer fringes of the spray. In this case the highest momentum area of the spray is located along the fringes. Cases 006 and 007 exhibit flat U and V radial velocity profiles. This flat velocity profile along with the small droplet SMD range is indicative of a well atomized spray. Case 006 and 007 have relatively uniform droplet momentum along the radius of the spray. This well atomized, uniform spray was attractive to be studied further for fire suppression applications.

Spray symmetry was checked and Figure 6-11 summarizes the measurements taken on the 90° radial scan. Comparing Case 005 in the 0° scan with the 90° scan it is revealed that the only similarities are in the trends the curves exhibit. Both the SMD and
Figure 6-9 Nozzle Cone-4B1 Centerline Profiles of SMD, U, and V Mean Velocities

Figure 6-10 Nozzle Cone-4B1 Radial Profiles of SMD, U, and V Mean Velocities

Figure 6-11 Nozzle Cone-4B1 Radial Profiles of SMD, U, and W Mean Velocities
U velocity curves do not agree in magnitude. The asymmetry shown by these two radial scans is again attributed to the non-uniform flow within the nozzle/atomizer and the asymmetry within the nozzle construction. Case 006 exhibits little symmetry between the $0^\circ$ and $90^\circ$ radial scans. The $90^\circ$ scan shows a jagged SMD profile that is in contrast of the single peak shaped curve for the $0^\circ$ scan. A similar relationship is shown for the U velocity profiles. The $90^\circ$ scan reveals a bell shaped curve while the $0^\circ$ profile is flat. Case 007's $90^\circ$ profiles exhibit a similar relationship to it's $0^\circ$ profile that Case 006 exhibits. The asymmetries shown in Cases 006 and 007 were attributed to the aforementioned parameters.

As was reported for Nozzle Cone-4B the W velocity components in the $90^\circ$ scans were small. This indicates the PDA transmitting optics were lined up on the nozzle centerline and very little swirl is contained in this region of the spray.

Using the data obtained from the PDA measurements an effective cone angle was calculated. Table 6-2 shows the calculated cone angles for Nozzle Cone-4B1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cone Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>005</td>
<td>78.2</td>
</tr>
<tr>
<td>006</td>
<td>86.4</td>
</tr>
<tr>
<td>007</td>
<td>86.4</td>
</tr>
</tbody>
</table>

6.5 Multi-Hole Nozzle Measurements Utilizing Nozzle Cone-5A

Experiments using Nozzle Cone-5A were conducted using the same experimental parameters as described in Section 6.3. Cases 008, 009, and 010 flow conditions were used to characterize the spray. Figure 6-12 shows the SMD, U and V velocity components measured for Cases 008, 009, and 010 centerline scan experiments. It can be
seen from the Figures that Case 010 produced the smallest droplet SMD profile. SMD’s ranged from 78 µm to 105 µm. The curves for all cases indicate, in general, an increase in SMD with increasing axial distance. This relationship is evidence that droplet coalescence was occurring and there is some swirling motion within the core of the spray. For each of these three cases there is a peak at x = 18 in. After examining the U and V velocity profiles it can be seen for Cases 009 and 010 that at x = 18 in. the U velocities are negative indicating a recirculation region. It was possible that this recirculation region promoted droplet coalescence thus the peak in SMD’s at x =18. However, this relationship is not shown in the Case 008 measurements. The V velocity profiles show a general increase in V velocity with increasing axial location. This indicates the presence of swirl within the core of the spray. It was observed visually during the experiments that with increasing axial distance from the nozzle more swirl was present in the spray.

Plotted in Figure 6-13 are the SMD’s, U, and V velocities measured in the 0° radial scan performed 16 in. below the nozzle exit. The SMD’s for Cases 008 and 010 increase with increasing r then reach a maximum at r = 12 in. and r = 13.5 in. respectively. Case 009 exhibits the same trend with the exception no peak is indicated on the plot. This is because beyond r = 12 in. no measurements could be made for this case. The PDA receiving optics received no signal beyond this point due to the dense fog created by the spray. It is assumed however that Case 009 would have a similar SMD profile as Cases 008 and 010 based on visual observations. Both the U and V profiles for all three cases indicate a bell shaped curve. The maximum U and V velocities are shown to be at approximately r = 10.5 in. Cases 008 and 009 indicate maximum U velocities around 7 m/s while Case 010 indicates a maximum U velocity of 6.2 m/s. Also, Cases
Figure 6-12 Nozzle Cone-5A Centerline Profiles of SMD, U, and V Mean Velocities

Figure 6-13 Nozzle Cone-5A Radial Profiles of SMD, U, and V Mean Velocities

Figure 6-14 Nozzle Cone-5A Radial Profiles of SMD, U, and W Mean Velocities
008 and 009 show maximum V velocities of approximately 4.5 m/s and Case 010 show a maximum velocity of 3.5 m/s. Based on the SMD, U, and V profiles it can be stated that Case 010 exhibited the most efficient atomization. The smaller SMD’s and V velocities measured in Case 010 are indicative of well-atomized sprays where the bulk flow is more monodispersed. The radial scans again prove that the concentrations of larger, high momentum droplets are concentrated around the outer fringes of the spray.

Radial scans were performed at 90° to check the spray for symmetry. Figure 7-14 summarizes the SMD, U, and W velocity measurements. The 90° scan for Case 008 differs from the 0° scans both in the SMD and U profiles. The 90° scan measured SMD’s ranging from 100 to 120 µm and U velocities ranging from 0 to 1 m/s. This is in contrast to the 0° scan where SMD’s and U velocities of 3 to 4 times this magnitude where measured. The Case 008 radial scan showed a more well atomized spray. Case 009’s 90° scan showed similar profiles for both the SMD’s and U velocities as was measured in the 0° scan. Case 009 in Figure 6-14 shows a maximum SMD of 280 µm at r = 12 in. and a maximum U velocity of 6.8 m/s at r = 12 in. The Case 010 90° SMD profile closely approximates what was measured in the 0° profile indicating droplet diameter symmetry. Although, the 90° U velocity profile closely resembles the 0° profile in shape they do not agree in magnitude. In the 90° scan a maximum velocity of 3 m/s was measured at r = 10 in. as opposed to a maximum velocity of 6.2 m/s in the 0° case.

As was the case for Nozzle Cone-4B and 4B1 the W velocity components in the 90° scans were small. This indicates the PDA transmitting and recieving objects were lined up on the nozzle centerline and very little swirl is contained in this region of the spray.
Using the data obtained from the PDA measurements an effective cone angle was calculated. Table 6-3 shows the calculated cone angles for Nozzle Cone-5A.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cone Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>008</td>
<td>80.2</td>
</tr>
<tr>
<td>009</td>
<td>73.8</td>
</tr>
<tr>
<td>010</td>
<td>86.4</td>
</tr>
</tbody>
</table>

6.6 Multi-Hole Nozzle Measurements Utilizing Nozzle Cone-5B

Experiments using Nozzle Cone-5B were conducted using the same experimental parameters as described in Section 6.3. Cases 011, 012 and 013 flow conditions were used to characterize the spray. Figure 6-15 shows the SMD, U and V velocity components measured for Cases 011, 012, and 013 centerline scan experiments. It can be seen from the Figures that Case 011 contained the smallest droplet SMD measured along the spray centerline. SMD’s ranged from 98 µm to 105 µm. An increase in SMD with increasing axial location was reported for all three cases. This indicates the presence of droplet coalescence along the spray centerline. The U and V velocities were relatively constant along the centerline as shown in Figure 6-15. The U velocities show a slight decrease in magnitude with increasing axial location. This result is intuitive as the droplets get larger the aerodynamic drag created by the free falling droplet was increased thus reducing the droplet velocity. The V velocities reported along the centerline are small in magnitude averaging approximately 0.0625 m/s indicating primarily vertically downward flow.

Plotted in Figure 6-16 are the SMD’s, U, and V velocities measured in the 0° radial scan performed 16 in. below the nozzle exit. From the figures it can be seen that
Figure 6-15 Nozzle Cone-5B Centerline Profiles of SMD, U, and V Mean Velocities

Figure 6-16 Nozzle Cone-5B Radial Profiles of SMD, U, and V Mean Velocities

Figure 6-17 Nozzle Cone-5B Radial Profiles of SMD, U, and W Mean Velocities
the SMD’s for all three cases were strongly dependant on radial location. In each case the SMD’s increase with increasing r. A maximum droplet SMD of approximately 300 µm was reported for each case. This was indicative of poor atomization compared to the SMD’s produced by Nozzle Cone 4B1 Section 6.4. There are no peaks shown in any of the SMD curves shown in Figure 6-16. Therefore, the outer fringes of the spray were never traversed during the PDA experiments. From the U and V velocity profiles it can be seen they all have a bell shaped curve. The maximum velocities reported are much larger that those shown for Nozzle Cone-4B1. The larger velocities indicate the spray was not as well atomized with this nozzle.

Figure 6-17 show the results from the 90° radial scan at x = 16 in. to check for spray symmetry. Plots of the Case 011 90° scan reveal a rapid increase in SMD from r = 6 in to r = 12 in. The 0° scan shows an increase in SMD over this range but the maximum SMD measured was 325 µm as opposed to 430 µm in the 90° scan. The U velocities have a similar profile with maxima near r = 9 in. but the magnitudes do not agree with 11.8 m/s in the 90° scan and 9 m/s in the 0° scan. Similar results for Case 012 were reported for the 90° scan as was reported for Case 011. Although both scans exhibit similar trends, the magnitudes for both SMD’s and U velocities differed. Comparing Figures 7-16 and 7-17 for Case 013 a much more symmetric spray was observed. Both SMD’s and velocities matched more closely over the range reported. Due to the symmetry reported for Case 013 flow conditions and the asymmetry reported for Cases 011 and 012 it is suggested that the resulting spray from Nozzle Cone-5B is dependent upon the flow pattern within the nozzle and atomizer.
As was the case for the previous three nozzles the W velocity components in the 90 upon scans were small. Therefore little swirl was present in this region of the spray.

Using the data obtained from the PDA measurements an effective cone angle was calculated. Table 6-4 shows the calculated cone angles for Nozzle Cone-5A.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cone Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>011</td>
<td>80.2</td>
</tr>
<tr>
<td>012</td>
<td>80.2</td>
</tr>
<tr>
<td>013</td>
<td>82.2</td>
</tr>
</tbody>
</table>

6.7 Summary

6.7.1 Single-Hole Exit Orifice Summary

A one-component Phase-Doppler system has been employed to measure droplet diameters and velocities produced by a twin-fluid atomizer with a single-hole exit orifice. This study investigated the twin-fluid atomizer’s ability to produce a droplet distribution with a wide range of droplet diameters. Also of interest was to determine the velocity profile within the spray to show the variation in droplet momentum. The experiments discussed above were performed using Case 001 flow conditions.

The presented measurements proved the twin-fluid atomizer’s ability to produce a spray with both a relatively large droplet distribution and velocity profile. These are common traits of sprays that have been reported as being effective when used in fire suppression applications. Although the flow conditions, droplet diameters, droplet velocities, and cone angle were all smaller than that required for fire suppression applications, much was learned about the spray produced by twin-fluid atomizers. Most
importantly it was shown that the high velocity droplets were concentrated within the core of the spray. This information was used in the design of the multi-hole water mist fire suppression atomizer.

6.7.2 Multi-Hole Exit Orifice, Nozzle Summary

A two-component PDA system has been employed to measure droplet diameters and velocities for multi-hole exit orifice twin-fluid atomizers. Four nozzle geometries were used to study the effects of nozzle geometry on the water spray characteristics. The flow conditions for each nozzle/atomizer combination were varied until three different flow conditions were found to produce stable internal flow and spray. Centerline and radial scans were performed to characterize the spray’s droplet and velocity distributions.

It was determined that the stability of the atomizer internal flow and resulting spray were strongly dependent on the nozzle geometry. Flow conditions could not be matched for each nozzle. One set of flow conditions for one nozzle that produced a stable flow and spray could not do the same for another nozzle. The SMD’s produced by the four nozzle/atomizer combinations did not agree with the results published by Lefevbre (1993) where he reported SMD’s from air-assist atomizers could be written as:

$$\text{SMD} = \left(14 \cdot x \cdot 10^{-6} \cdot d_o^{0.75}\right) \cdot \left(\frac{m_L}{m_A}\right)^{0.75}$$

The equation implies that that increasing the atomizing gas mass flow will reduce the spray’s SMD. However, the data obtained in this study did not display this relationship throughout our measurements. In fact, the contrary was observed for some cases in this study.

The results presented here did indicate where the high momentum regions within the spray were located. This is a very important parameter when designing fire
suppression systems and determining atomizer spacing. Results indicated that the high momentum regions of the spray were typically located away from the nozzle centerline in the range \( r = 12 \) to \( r = 14 \) in. Recirculation regions were reported for several cases. These regions were a result of poor atomization where vortex shedding was observed due to the lack of high momentum droplets in the spray’s core. In the cases where no recirculation was reported, the droplet movement was downward in the core of the spray indicative of good atomization.

It was determined that Nozzle Cone-4B1 performed most favorably in terms of fire suppression applications. The spray produced by Cone-4B1 was the most stable and best matched the design objectives outlined during the atomizer development. Cone-4B1 demonstrated good atomization evidenced by the SMD radial profiles. From Figure 6-10 it can be seen that for Cases 005 and 007 that relatively flat profiles were reported. This indicated good atomization and is in contrast to that reported for Nozzles Cone-5A and 5B. Their radial profiles indicate a large increase in SMD with increasing radial location. The strong dependency on radial location is indicative of poor atomization and that distinctive jets were discharged from the nozzle.
CHAPTER 7 PHASE III EXPERIMENTAL RESULTS

7.1 Experimental Conditions

The measurements presented in this phase of the study were conducted in order to satisfy the NFPA 750 characterization requirement. The experiments were conducted using Nozzle Cone-4B1 and three different atomizing gases specifically, Carbon Dioxide, Helium and Nitrogen. In order for the twin-fluid atomizer to be classified as a water mist, per NFPA 750’s definition, the droplet diameters had to be measured at the coarsest part of the spray in a plane 3.3 ft (1m) below the nozzle and the $D_{v0.9}$ had to be less than 1000 µm.

The three atomizing gases were chosen to investigate if the spray characteristics, SMD’s and velocities, were dependent on the atomizing gas density. CO$_2$ with a molecular weight of 44.01 was the most dense gas used, He with a molecular weight of 4.00 was the least dense gas used, and N$_2$ with a molecular weight of 28.02 was in between the other two gases. Experiments were performed for three different flow conditions for each of the three atomizing gases, Cases 014-022 Table 5-1. The flow conditions for CO$_2$ were first established and the volumetric flowrates for the other two gases were matched to that of the CO$_2$. Also, the water volumetric flowrate was matched in each case. A two component PDA system was used to measure droplet diameters and velocities. One radial scan was made at 3.3 ft below the nozzle exit at the coarsest location within the spray.

7.2 Effects of Gaseous Phase at Constant Operating Volume Flow Rate

7.2.1 Intermediate Liquid Operating Flowrate (Cases 014, 015, and 016)

Droplet diameter distributions for each spray produced from Cases 014, 015, and 016 are shown in Figure 7-1(a-l) and Figure 7-2(a-l). Figure 7-1(a-l) shows the droplet
diameter distributions for each atomizing gas along the radius of the spray from \( r = 18.25 \) in. to \( r = 22.75 \) in. Figure 7-2(a-l) shows the droplet diameter distributions along the radius of the spray from \( r = 24.25 \) in. to \( r = 27.73 \) in. The droplet diameter distributions indicated are expressed as a frequency and the number of droplets occurring in each size range are shown as a percentage of the total droplets counted in the sample. Also, shown on each plot in Figures 7-1 and 7-2 are curves that indicate the cumulative volume of the droplets. The data indicate similar droplet distributions for all three atomizing gases. All the distributions indicate a relatively large range of droplet diameters produced ranging from 5 \( \mu \text{m} \) to 500 \( \mu \text{m} \), with Case 014 consistently producing the smallest distributions and Case 016 the largest. Bimodal droplet diameter distributions were measured for Cases 014 and 015 with increasing radius. These bimodal distributions show one predominant frequency in the range from 50 to 100 \( \mu \text{m} \), and another in the range from 250 to 300 \( \mu \text{m} \). Bimodal droplet distributions were attributed to instability within the water spray. Instabilities in the water spray were caused by pulsations resulting from the internal two-phase flow. The spray oscillated between good and poor atomization resulting in varying droplet diameters that varied with the frequency of the internal pulsations. These droplet distributions are consistent with distributions reported by Braidech (1955). The \( D_{0.9} \) droplet diameters as measured in the coarsest part of the spray per NFPA 750 for Cases 014, 015, and 016 are 338, 342, and 402 \( \mu \text{m} \) respectively. Therefore, all the sprays at these flow conditions were classified as water mist sprays. All three \( D_{0.9} \) diameters are smaller than 500 \( \mu \text{m} \) reported by Pepi (1997) of a commercially available atomizer.

Figure 7-3 shows the radial SMD, \( U \), and \( V \) velocity profiles measured 3.3 ft below the nozzle. These measurements were taken coincidentally with the data measured
Figure 7-1 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-2 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-3 SMD, U-Velocity, and V-Velocity Profiles 3.3 ft Below the Nozzle

for the droplet diameter distributions. Figure 7-3 indicated similar profiles for each atomizing gas. The SMD profiles each show an increase in SMD with increasing radius up to $r = 24.25$ in at which point a maximum was reached and then a decrease in SMD. The bell shaped curve is evidence that the coarsest part of the spray was traversed. Droplet SMD’s measured ranged from 160 to 280 $\mu$m. The $U$ and $V$ velocities measured have similar ranges in magnitude but differ in profile as indicated in Figure 7-3. Cases 014 and 015 profiles show a decrease in $U$ and $V$ mean velocities with increasing $r$ that is
in contrast to that of Case 016. Case 016 U and V velocities increase up to \( r = 22.75 \) in and then decrease with increasing \( r \). Case 016 curves indicate that the high momentum droplets were concentrated in the core of the jet in contrast to the other two cases where slightly more monodisperse droplets were observed. The GLR’s for Cases 014, 015, and 016 were 0.024, 0.002 and 0.015 respectively. The spray characteristics indicated no dependency on GLR. This is contrary to most twin-fluid atomizers (Lefebvre 1993).

### 7.2.2 High Liquid Operating Flowrate (Cases 017, 018, and 019)

Droplet diameter distributions for each spray produced from Cases 017, 018, and 019 are shown in Figure 7-4(a-l) and Figure 7-5(a-l). Figure 8-4(a-l) shows the droplet diameter distributions for each atomizing gas along the radius of the spray from \( r = 18.25 \) in to \( r = 22.75 \) in. Figure 7-5(a-l) shows the droplet diameter distributions along the radius of the spray from \( r = 24.25 \) in to \( r = 27.73 \) in. As was measured for Case 014, 015, and 016 the droplet diameter distributions for these cases are similar for each atomizing gas. Droplet diameters ranged from 5 to 500 \( \mu m \) for all gases along the radius of the spray. Bimodal distributions were reported for Case 018. The bimodal distribution was attributed to the unstable pulsations of the water spray at these operating conditions. The cumulative volume plots indicate that CO\(_2\) produced the smallest D\(_{0.9}\) diameters and N\(_2\) produced the largest as was observed previously. The largest D\(_{0.9}\) values were reported to be 296 \( \mu m \) at \( r = 27.25 \) in, 398 \( \mu m \) at \( r = 27.73 \) in, and 394 \( \mu m \) at \( r = 24.25 \) in for Cases 017, 018, and 019 respectively. Again all these values were smaller than those reported by one commercially available atomizer (Pepi 1997).

Figure 7-6 shows the radial SMD, U, and V velocity profiles measured 3.3 ft below the nozzle. The curves indicate a much more uniform spray than was reported for Cases 014, 015, and 016. The diameter and velocity profiles did not vary considerably
Figure 7-4 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-5 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-6 SMD, U-Velocity, and V-Velocity Profiles 3.3 ft Below the Nozzle

with increasing r for Case 017. The monodisperse spray was indicative of a well-atomized stable spray. SMD’S were smallest for Case 017 ranging from 160 to 180 µm. The SMD curve for Case 018 shows a large increase in size from r = 27.25 in to r = 27.73 in. This large increase in diameter was due to an inefficiently atomized spray that concentrated larger droplets around the outer fringes of the spray. The U velocity profile for Case 019 shows a velocity less than zero at r = 27.25 in. This is indicative of a region of recirculation that was observed in Phase II. This area of recirculation most probably resulted from a small area within the spray void of high momentum droplets. As was
reported above, the spray characteristics did not show a dependency on the fluid GLR’s. Cases 017, 018, and 019 had GLR’s of 0.021, 0.002, and 0.013 respectively, yet produced quite similar sprays.

7.2.3 Low Liquid Operating Flowrate (Cases 020, 021, and 022)

Droplet diameter distributions for each spray produced from Cases 020, 021, and 022 are shown in Figure 7-7(a-l) and Figure 7-8(a-l). Figure 7-7(a-l) shows the droplet diameter distributions for each atomizing gas along the radius of the spray from \( r = 18.25 \) in to \( r = 22.75 \) in. Figure 8-8(a-l) shows the droplet diameter distributions along the radius of the spray from \( r = 24.25 \) in to \( r = 27.73 \) in. As was reported for the previous two flow conditions, the droplet diameters distributions exhibit similar ranges. The distributions range from 5 to 515 µm. Case 020 produced the most uniform spray under these conditions evidenced by the small range of droplet diameters measured. At each radial location Case 020 produced the smallest droplets. Case 021 with He used as the atomizing gas again shows bimodal distributions. The bimodal distributions were again attributed to instability within the spray. Maximum \( D_{0.9} \) diameters for Cases 020, 021, 022 were reported to be 305, 402, and 394 µm respectively. The spray pattern produced by the atomizer for each of these Cases was hollow coned. The majority of the droplets were concentrated in a conical pattern with few high momentum droplets in the core.

Figure 7-9 shows the radial SMD, U, and V velocity profiles for Cases 020, 021, and 022. The SMD profile for Case 020 is quite uniform with increasing \( r \). Cases 021 and 022 indicate an increasing SMD with increasing \( r \) to a maximum and then a decrease in SMD from there. This was indicative of less efficient atomization than that of Case 020.
Figure 7-7 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-8 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft Below the Nozzle
Figure 7-9 SMD, U-Velocity, and V-Velocity Profiles 3.3 ft Below the Nozzle

The U and V mean velocities are similar for all three Cases. Each U and V profile shows an increase in velocity with increase in r to some maximum value. The U and V velocity profiles also indicate whether or not the outer fringes of the spray were traversed. For Cases 020 and 021 the velocity profiles show that the outer fringes were not traversed as evidenced by the large velocities at the largest radial location. This was attributed to poor atomization for Cases 020 and 021. At r = 18.25 in, Case 022 indicates a negative U velocity and V = 0 indicating an area of recirculation and the droplets were
traveling upward. GLR’s of 0.017, 0.002, and 0.011 were used for Cases 020, 021, and 022 respectively. Data for these cases indicated more dependence of GLR than shown for the other two flow conditions.

7.3 Water Distribution Experimental Results

Water distribution tests were conducted on the water sprays produced by the LSU atomizer under various flow conditions and utilizing CO₂ and N₂ as the atomizing gases. This part of the study was conducted to study the profile of the actual water delivered along the radius of the spray at a distance of 3.3 ft below the atomizer nozzle. Figure 2-9 shows the experimental setup for the water distribution tests. The water distribution tray was divided into 24 equal volume bins that were sealed watertight such that water in one bin could not leak into another. Figure 7-10(a-c) indicates the results obtained from the water distribution experiments. In these tests the water distribution tray was centered directly underneath, 3.3 ft below, the atomizer. The fluid delivery system was activated and allowed to spray over a period of time ranging from 3 to 8 minutes depending on the total water flowrate. Water discharged from the atomizer fell into the equally divided bins within the distribution tray. Over time the volume of water in each bin increased such that the volume contained in each could be measured. From the measured volume in each bin and the length of time the water was allowed to spray, a volume flowrate profile along the radius of the spray was calculated. Figure 7-10(a) shows the results from the water distribution experiments conducted for flow conditions Case 014 and 016. It can be seen from the Figure that Case 016 delivered the larger quantity of water to the center portion of the tray compared to Case 014. However as the distance from the nozzle centerline increased Case 014 delivered more water to these regions. The larger
Figure 7-10  Water Spray Distribution at 3.3 ft Below the Atomizer
volume flowrates of water delivered to the center of the tray indicated a greater concentration of droplets in the core of the spray thus a more fully dispersed spray pattern. Lower volume flowrates within the core indicated a more hollow-cone spray pattern. The spray patterns become important in fire suppression applications when describing the effectiveness of a water spray. Both Cases produced similar profiles with increasing volume flowrates delivered to bins at increasing radial distance. This characteristic was expected and was attributed to the conical shaped nozzle installed on the atomizer. The water sprays initial momentum was directed radially away and downward from the nozzle. This creates a core containing droplets that come from the outer fringes of each jet or droplets ejected from the recirculation regions described previously.

Figure 7-10(b) contains the water distribution profiles for Cases 017 and 019. The distributions for these two Cases were very similar to those reported for Cases 014 and 015. Case 019 delivered the larger quantity of water to the center of the distribution tray while Case 017 delivered more at the ends of the tray. Figure 7-10(c) shows the water distribution profiles for Cases 020 and 022. From the Figure it can be seen that the water distribution was very similar for both Cases near the center of the tray. The volume flowrates delivered near the center in these Cases was much smaller than that delivered in the previous Cases. This was attributed to the inefficient atomization of the water. Because the atomization in Cases 020 and 022 was not as efficient there was fewer droplets contained in the core of the spray. Therefore, the majority of the droplets contained in this region were those ejected from the recirculation regions on the inner fringes of the jet.
7.4 Summary

The requirements of NFPA Standard 750 were satisfied in this phase of the study. All the sprays produced in this phase were considered to be water mist sprays per NFPA 750 (1996). In fact all the sprays produced would be either Class 2 or Class 3 sprays using the classifications proposed by Mawhinney, Dlugogorski and Kim (1996). Class 2 sprays were produced for all Cases except Cases 016 and 021. Under these two conditions the sprays were borderline Class 2 sprays, where Class 2 spray criteria was $200 \mu m \leq D_{0.9} \leq 400 \mu m$ and Class 3 was $D_{0.9} > 400 \mu m$. The results obtained from this phase of the study were compared to other atomizers used for fire suppression. A summary of the flow conditions and droplet characteristics was included in Table 8-1 of commercially available atomizers.

<table>
<thead>
<tr>
<th>Author / Organization</th>
<th>Atomizing Gas</th>
<th>$P_{gas}$ (psig)</th>
<th>$P_{water}$ (psig)</th>
<th>$Q_{gas}$ (SCFH)</th>
<th>$Q_{water}$ (gpm)</th>
<th>Droplet Diameters (mm)</th>
</tr>
</thead>
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<tr>
<td>Cousin</td>
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<td>NA</td>
<td>44</td>
<td>NA</td>
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<tr>
<td>Grosshandler, et al.</td>
<td>NA</td>
<td>NA</td>
<td>798</td>
<td>NA</td>
<td>2.6</td>
<td>58 (SMD)</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>Air</td>
<td>82</td>
<td>84</td>
<td>NR</td>
<td>1.6</td>
<td>40 (D$_{0.9}$)</td>
</tr>
<tr>
<td>Grinnell Corp.</td>
<td>NA</td>
<td>170</td>
<td>NA</td>
<td>1.6</td>
<td>480 (D$_{0.9}$)</td>
<td></td>
</tr>
<tr>
<td>Securiplex Inc.</td>
<td>Air</td>
<td>175</td>
<td>175</td>
<td>3.2</td>
<td>480 (D$_{0.9}$)</td>
<td></td>
</tr>
<tr>
<td>LSU</td>
<td>CO$_2$</td>
<td>220</td>
<td>215</td>
<td>3.2</td>
<td>289 (D$_{0.9}$)</td>
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<tr>
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<td>N$_2$</td>
<td>198</td>
<td>195</td>
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<td>LSU</td>
<td>He</td>
<td>158</td>
<td>153</td>
<td>3.2</td>
<td>398 (D$_{0.9}$)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7-1 Nozzle Comparison Data

where, NA = Not Applicable, NR = Not Reported

The sprays reported for the Grinnell and Securiplex atomizers produced the most comparable droplet diameters to those reported for this study. The data shows that when CO$_2$ and N$_2$ were used as the atomizing gases the $D_{0.9}$ diameters decreased or remained relatively uniform with decreasing GLR. When He was used as the atomizing gas the data suggest the $D_{0.9}$ diameters increased with decreasing GLR. This observation was
attributed to at low GLR’s the flows within the atomizer using CO₂ and N₂ were more stable resulting in more stable, uniform atomization. The opposite was observed for He. As the He GLR was decreased the flow became more unstable resulting in less efficient atomization. This is evidenced by the bimodal distributions reported for Cases 018 and 021. The characterization data obtained in this phase of the study was used in analysis of the Phase IV full-scale fire suppression experiments.
CHAPTER 8 FULL-SCALE FIRE TESTS OF TWIN-FLUID WATER MIST FIRE SUPPRESSION SYSTEMS

8.1 Experimental Flow Conditions

The measurements presented in this phase of the study were conducted to examine the effectiveness of the LSU developed twin-fluid water mist atomizer in small Class B hydrocarbon pool and spray fire applications. Also, the same experiments conducted with the LSU atomizer were conducted with the commercially available Grinnell AquaMIST AM10 atomizer. A comparison of the results determined the effectiveness of the LSU atomizer’s fire extinguishing capabilities. The experiments were conducted inside the LSU Fire Testing Facility using three different water spray flux densities 0.086, 0.075, and 0.065 GPM/ft$^2$. With each spray flux density, the quantity and type of atomizing gas was varied. CO$_2$ and N$_2$ were used as the atomizing gases, when required. The fire testing began with baseline tests on 225 kW ethyl alcohol pool fires without any water spray discharging into the facility. The dry pool fire tests were conducted to establish a reference in which the water spray tests could be compared. Once the baselines were established, full-scale 225 kW ethyl alcohol pool fire tests were conducted with application of the various water spray conditions. Water spray experiments on 200 kW ethyl alcohol spray fires were next conducted to study the atomizers ability to suppress Class B spray fires. Also, 55 kW propane fire experiments were conducted to study the effects of water mist on a gaseous fuel. Simulated machinery space fire tests were conducted on 425 kW combined ethyl alcohol pool and spray fires. Finally fire tests were conducted on 280 kW combined ethyl alcohol pool fires and propane spray fires. Temperatures throughout the fire testing chamber were measured along with the time to extinguishment. Also, the water and atomizing gas flowrates and pressures were measured and recorded throughout each experiment.
8.2 Baseline Pool Fire Experiments

Fire testing began by conducting dry, experiments on 225 kW pool fires. (3) Three quarts of ethyl alcohol were poured into the pool fire container and placed centrally within the fire testing facility. The fuel was ignited and allowed to burn without any application of water, gas, or water spray. Table 8-1 lists the parametric variations investigated throughout the fire tests. Figure 8-1 shows the temperature versus time curves within the fire testing facility for Case 8-1 listed in Table 8-1. It can be seen that the maximum temperature measured by TC1 was 530 °F. The other six thermocouples measured maximum temperatures ranging from 400 °F to 1160 °F. The maximum temperature was measured at t = 10 min. This was attributed to the process of fuel heating throughout the experiment. As the ethyl alcohol burns throughout the experiment a thicker and thicker layer of fuel is heated near its flash point thus increasing the combustion rate and heat release rate. The time to extinguishment was 20:18 min. Inspection of the pool fire container after the fire was extinguished revealed the liquid ethyl alcohol fuel was completely consumed. The ethyl alcohol combustion rate was computed to be 0.0369 GPM.

A series of baseline experiments were next conducted on 225 kW ethyl alcohol pool fires with the pool fire container placed centrally within the fire testing facility. CO₂ gas was discharged into the chamber at varying volume flow rates. These experiments were conducted to determine the effects of CO₂ in the extinguishment of pool fires. Two volume flow rates of CO₂ were chosen for these experiments, 310 SCFH and 183 SCFH. These flow rates were chosen to match the volume flow rates of the atomizing gas used during the water spray experiments. Figure 8-2 shows the temperature versus time curves at seven locations within the facility. Figure 8-2(a) shows the curves for Case 8-2. 310
SCFH of CO₂ was discharged into the facility once the pool fire was ignited. TC1’s maximum measured temperature was 550 °F and the other six thermocouples measured maximum temperatures ranging from 500 °F to 1075 °F. The time to extinguishment was 20:08 min:sec. As in the case of the dry pool fire experiment all of the ethyl alcohol was consumed. Therefore, the pool fire combustion rate was determined to be 0.0341 GPM. The combustion rate was lower in this case due to the CO₂ discharging into the facility. The lower combustion rate was attributed to the CO₂ discharged into the facility serving to slow down combustion. However, it was determined that the CO₂ did little for extinguishment. The maximum temperature measured was lower because of the added mass of cool CO₂ gas discharged into the facility. Figure 8-2(b) shows the curves for Case 8-3. 183 SCFH of CO₂ was discharged into the facility once the pool fire was ignited. TC1’s maximum measured temperature was of 545 °F. The six other thermocouples measured maximum temperatures ranging from 420 °F to 1115 °F. The time to extinguishment was 19:10 min:sec and the fuel combustion rate was 0.0391 GPM. Temperatures within the facility were greater in the 183 SCFH case than in the 310 SCFH case because of the smaller quantity of CO₂ that was discharged into the facility. Temperatures within the facility for both these cases were less than that measured in the dry fire test experiments. The time to extinguishment for the dry experiment and CO₂ experiments closely approximated one another. It was determined that CO₂ discharged into the facility alone at the volume flowrates used in the experiments had little effect on the pool fire extinguishment.

The next phase of the fire testing was conducted on 225 kW pool fires with the pool fire container placed centrally within the fire testing facility. Using nozzle CONE-4B1 on the LSU atomizer, water alone was discharged into the facility at three different
volume flow rates. These experiments were conducted to establish a baseline for comparison with the water mist experiments. Flowrates of 2.4 GPM (0.065 GPM/ft$^2$), 2.8 GPM (0.075 GPM/ft$^2$), and 3.2 GPM (0.086 GPM/ft$^2$) were chosen to match the water volume flowrates that were used in the water mist fire tests. Because only water was used for these experiments, 8 distinct jets were observed discharging from the nozzle. There was no atomization of the water and the cone angle of the water jet pattern was large such that none of the water was discharged into the pool fire container. The nozzle and pool fire container were located centrally within the fire testing facility. The nozzle was mounted 3.3 ft (1.0 m) vertically above the pool fire oriented vertically downward.

Figure 8-3(a) shows the temperature versus time curves within the fire testing facility for Case 8-4. 0.065 GPM/ft$^2$ of water was discharged from the nozzle into the facility. TC1’s maximum measured temperature during the experiment was 562 °F at $t = 21:47$ min:sec after the pool fire was ignited. The other seven thermocouples measured maximum temperatures ranging from 400 °F to 940 °F. The time to extinguishment was 36:30 min. Observation of the pool fire container after the fire burned out revealed all the ethyl alcohol had been burned. The ethyl alcohol combustion rate was calculated to be 0.0205 GPM.

Figure 8-3(b) indicates the temperature profile within the fire testing facility for Case 8-5. Once the pool fire was ignited 0.075 GPM/ft$^2$ of water was discharged from the nozzle. The maximum temperature measured by TC1 was 518 °F at $t = 21:40$ min:sec. Maximum temperatures measured by the other seven thermocouples ranged from 300 °F to 889 °F. The pool fire burned out in 36:42 min:sec after ignition. After the fire burned out, visual inspection of the pool fire container revealed all of the ethyl
Table 8-1 Full-Scale Fire Tests Flow Conditions and Experimental Setup

<table>
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<tr>
<th>Case</th>
<th>Fire Type</th>
<th>Fuel</th>
<th>Fuel Volume (Gal)</th>
<th>Fuel Flowrate (GPM/SCFH)</th>
<th>Fire Location</th>
<th>Atomizer</th>
<th>Atomizing Gas</th>
<th>$Q_{H2O}$ (GPM)</th>
<th>$Q_{gas}$ (SCFH)</th>
<th>$D_{0.9}$ (µm)</th>
<th>TE (min:sec)</th>
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Table 8-1 con’t

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<th>Atomizer</th>
<th>Atomizing Gas</th>
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<th>$D_{0.9}$ (µm)</th>
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* indicates Simulated Machinery Space Fires
Figure 8-1 Case 8-1 Dry Ethyl Alcohol Pool Fire Temperature Profile

Fuel = Ethyl Alcohol
Type = Pool Fire (Dry)
$V_{\text{fuel}} = 0.75 \text{ gal}$
Figure 8-2 CO₂ Effects on Ethyl Alcohol Pool Fires
alcohol had been combusted. Therefore, the combustion rate was calculated to be 0.0204 GPM.

Figure 8-3(c) shows the temperature profile within the fire testing facility for Case 8-6. The pool fire was ignited, and then the water delivery system was activated to discharge 0.086 GPM/ft^2 of water into the facility. The water flow rate was increased and consequently the water supply pressure increased. Increasing the pressure caused the water to break-up somewhat as it was discharged from the nozzle. The 8 distinct jets that were observed in the previous two experiments were less defined in this case. The cone angle of the water spray decreased causing some of the discharged water to fall into the pool fire container. The maximum temperature measured by TC1 was 427 °F occurring 21:20 min:sec after the fire was ignited. Maximum temperatures measured by the other six thermocouples ranged from 300 °F to 860 °F. The time to extinguishment was 27:34 min:sec. Also, from Figure 8-3(c) it can be seen that the measured temperatures fluctuated over time much more than in the previous experiments. This was attributed to the water discharging directly into the pool fire container. The fire was much more unstable than was observed in the other cases. The flame fluttered within the pool fire container, traveling around the perimeter of the rectangular container as the water impacted the liquid ethyl alcohol. Because the water from the nozzle fell into and accumulated in the pool fire container, the combustion rate could not be determined.

Comparing the dry fire baseline tests to the water only tests it was determined that the water in Cases 8-4, 8-5 and 8-6 served to decrease the temperatures within the fire testing facility. Increased times to extinguishment for Cases 8-4 and 8-5 were attributed to the decreased ethyl alcohol combustion rate. Visual observation of the flames in these
two Cases revealed a stable flame that seemed to be unaffected by the water discharging into the facility. In Case 8-6 the temperature within the facility was decreased further than those measured in the above two cases and the flames inside the container became unstable due to the water impacting the ethyl alcohol free surface. This can be seen from the fluctuating temperatures shown in Figure 8-3. The time to extinguishment was decreased in Case 8-6 because of the cooling effect the water had on the liquid ethyl alcohol.

### 8.3 Full-Scale Water Mist Pool Fire Results

Temperature profiles within the facility are shown in Figure 8-4(a-c) for fires test Cases 8-7, 8-8, and 8-9 conducted on 225 kW ethyl alcohol pool fires. Table 8-1 indicates the testing conditions under which these experiments were conducted. Three quarts of ethyl alcohol were placed centrally within the fire testing facility, ignited, and were given a two-minute pre-burn time before introducing the water sprays. Temperatures throughout the facility were measured and recorded, See Figure 2-8 for thermocouple locations. Also, water and atomizing gas (if applicable) volume flow rates were measured. Figure 8-4(a) shows the experimental results obtained from pool fire tests using Case 8-7 experimental conditions. 0.086 GPM/ft² of water and 310 SCFH of CO₂ were discharged as water spray from the atomizer that was placed centrally within the facility. Measured data and visual observation revealed that once the automated fluid delivery system was activated, the fire was extinguished in 8.0 sec. A total of 0.43 gallons was discharged to extinguish the fire. The temperature within the facility continually increased throughout the two-minute pre-burn period and the baseline temperature of 540 °F was measured by TC1 located directly over the pool fire container,
near the top of the facility. From visual observation of the experiment, the entire free surface of the ethyl alcohol was burning during the two-minute pre-burn period. Once the atomizing gas was initiated to pressurize the fluid delivery system, the flames inside the container immediately decreased in intensity and the flames went from filling the pool fire container to being isolated to the outer perimeter of the container. Finally, after the water spray was introduced into the facility the flames were immediately extinguished without any re-ignition. Rapid extinguishment of ethyl alcohol pool fires by water mist atomizers was consistent with findings of Braidech and Neale (1955).

From visual observation the flames looked to have been “blown out” by the initial surge of water spray discharged from the nozzle. Fire blow out was reported by Leeds (1994) in water mist fire suppression applications. The initial surges in atomizer fluid flowrates were attributed to the high differential pressure across the ON/OFF solenoid valves when the valve was in the OFF position. Upon the signal to activate, the solenoid valve quickly opened causing a short surge of gas and liquid. Figure 8-4(a) shows the initial surge of CO₂ and water as they were activated and after the initial surge both of the fluids approached their set points. The fire blow out mechanism of fire extinguishment was attributed to the distortion of the combustion zone or flame, reducing its thickness so that the vapors have a much shorter time to react. This technique is commonly used to control oil-well fires. If the combustion zone becomes too thin, combustion will be incomplete, the flame will be cooled below the flash point and therefore the reaction cannot be self-sustaining thus extinguishing the fire.

Data indicates that once the water spray was introduced into the facility, the temperature immediately began decreasing throughout. This was indicative of space
cooling and was evidence of the atomizer’s ability to attenuate heat throughout the facility. Furthermore, steam was observed filling the facility upon extinguishment of the fire adding to the evidence of space cooling. Water mist cools the gaseous combustion zone or flame. Combustion requires high temperatures to sustain itself. The combustion reaction must produce enough heat to compensate for heat losses and maintain the necessary high temperatures in the reaction zone. A small reduction in flame temperature causes a large decrease in the reaction rate. When the water mist is discharged into the combustion zone, it upsets this relatively sensitive balance and extinguishes the fire.

The combustion reaction requires that oxygen be present. When the water mist enters the combustion zone it rapidly absorbs heat or energy and is converted to steam. The change is state from liquid to steam results in the expansion of the water nearly 1700 times its liquid volume. This rapid expansion displaces oxygen in the combustion zone and prevents additional oxygen from entering the combustion zone.

Upon closer inspection of Figure 8-4(a) it can be seen that the temperature within the facility began to decrease once the atomizing gas was initiated prior to application of the water. This is evidence that the initial surge of gas decreased the fires intensity and blocked the fire’s heat from radiating throughout the space. Therefore, the modes of extinguishment identified for this test were fire blow out and space cooling.

The spray produced by the atomizer under these conditions was classified as a Class 2 Spray (Kashiwagi, 1994) with a $D_{0.9} = 289 \mu m$. Referring to Figure 7-10(b) for Case 017 in the range from $-18 \text{ in.} \leq x \leq 18 \text{ in.}$ it can be seen that only a small volume of water discharged from the atomizer actually could have penetrated to the seat of the fire. This is further evidence of space cooling and demonstrates the atomizer’s
Figure 8-3 Effect of Water Only on Ethyl Alcohol Pool Fires
ability to extinguish pool fires with small quantities of water actually delivered to the seat of the fire.

Temperature and fluid volumetric flowrate profiles are shown in Figure 8-4(b) for pool fire test Case 8-8. This experiment was identical to Case 8-7 with the exception that N\textsubscript{2} was used as the atomizing gas. This experiment was conducted to determine if the spray produced using N\textsubscript{2} had varying effects on fire extinguishment compared to sprays produced using CO\textsubscript{2}. From Figure 8-4(b) it can be seen that the fire was ignited at t=0 sec and the fire was given a 2 min pre-burn time prior to activation of the fluid delivery system. TC1, located directly over the pool fire container, measured the baseline temperature of 547 °F. After initiation of the fluid delivery system the pool fire was extinguished in 9.0 sec. Therefore a total volume of 0.48 gallons of water was required to extinguish the 225 kW pool fire. The spray produced by the atomizer for this Case was classified as a Class 2 spray Kashiwagi, (1994) with a D\textsubscript{0.9} = 394 µm. Similar conclusions were made for this Case as were discussed for Case 8-7. The flames seemed to have been “blown out” due to the initial surge of water spray from the atomizer. Also, it was observed that steam filled the room upon completion of the experiment and the facility door was opened. Therefore it was concluded that both the effects of fire blow out and space cooling were the two primary modes of fire extinguishment. The water distribution shown in Figure 7-10(b) for Case 019 revealed a greater volume of water was delivered to the region of the pool fire container, -18 in.≤x≤18 in., than that for fire Case 8-6. However almost identical results were recorded. This was attributed to the effects the initial high momentum spray had on the extinguishment. The initial surge decreased
Figure 8-4 Centrally Located Pool Fires with 0.086 GPM/ft² Water Spray Application
the fire’s intensity to the point where only a smaller confined pool fire had to be extinguished. Then space cooling extinguished the small remaining fire.

Figure 8-4(c) shows the temperature and water flowrate curves for pool fire test Case 8-9. The Grinnell AM-10 (AquaMist) atomizer was used to produce the water spray for this fire test Case. Temperatures within the facility steadily increased once the pool fire was ignited and reached a maximum of 500 °F when the water delivery system was activated. The fire was extinguished in 5 sec after water activation. A total volume of 0.19 gallons of water was discharged to extinguish the fire. The published $D_{0.9}$ droplet diameter for the AM-10 was 480 µm thus classifying the spray as a Class 3 Spray (Kashiwagi, 1994). Observation of the experiment revealed the fire seemed to be “blown out” by the initial surge of water spray. Once the water spray was activated, the flames inside the pool fire container rolled up along the perimeter of container and were instantaneously extinguished. From Figure 8-4(c) it can be seen that the water flowrate initially overshot its set point of 3.2 GPM due to the large $\Delta P$ across the solenoid valve. A few seconds after water flow initiation the fluid delivery control system adjusted the water flowrate near the set point.

In all three experiments shown in Figure 8-4(a-c) rapid extinguishment of ethyl alcohol pool fires were observed. In all three Cases 3.2 GPM of water was discharged from their respective atomizers. The total volume of water required to extinguish the 225 kW pool fires were small. Less than one-half gallon of water was required to extinguish all three fires. This was attributed to the effective use of the high momentum spray and the effective fire suppression characteristics of the atomized water. The two primary modes of fire extinguishment were identified to be flame blow out and space cooling. In
all three Cases it can be seen that upon initialization of the fluid delivery system a large surge of water and atomizing gas resulted. Moreover, the surge pushed high momentum water droplets and atomizing gas vertically downward towards the pool fire container causing the oxygen surrounding the flames to be displaced, thus blowing out the fire. It was also observed for each Case that steam filled the facility upon extinguishment of the fire. This was an indication that heat produced by the fire was transferred to the falling water droplets vaporizing them. Transferring of the heat from the fire to the water served to cool the fire and surrounding atmosphere aiding in fire suppression and preventing fire re-ignition.

Temperature and fluid flowrate profiles are shown in Figure 8-5(a-c) for experiments conducted on 225 kW ethyl alcohol pool fires located centered against the east wall of the fire testing facility. The atomizer was located central to the fire testing facility, 3.3 ft (1 m) above the container, oriented vertically downward. Experimental conditions for Cases 8-10, 8-11, and 8-12 are shown in Table 8-1. Figure 8-5(a) contains profiles for fire test Case 8-10. Temperatures within the facility reached a maximum of 500 °F located near the center of the facility. 0.086 GPM/ft² of water was discharged along with 310 SCFH of atomizing CO₂ gas to produce the water spray. Upon initiation of the fluid delivery system, the fire was extinguished in 9 sec. 0.5 gallons of water was discharged to extinguish the fire. Observation of the pool fire after activation of the fluid delivery system revealed the pool fire was immediately reduced in size and intensity. This immediate reduction in fire intensity was attributed to the high momentum spray resulting from the surge in water flow. Upon activation of the fluid delivery system heat from the fire and surrounding walls. The center of the pool fire container was located
(a) Case 8-10

(b) Case 8-11

(c) Case 8-12

Figure 8-5 Wall Pool Fires with 0.086 GPM/ft² Water Spray Application
16.75 in east of the nozzle and from Figure 7-10(b) for Case 017 it can be seen that the pool fire was located near the region of greatest volume distribution. Therefore a greater volume of water was delivered to the seat of the fire. However, the water mist behaved in the same manner in this Case as was observed for the centrally located fire. This was attributed to the high momentum surge that significantly suppressed the fire and for all practical purposes blew the fire out. After the initial surge only small pool fires concentrated in the corners remained. The water mist easily extinguished the remaining fires. Therefore, the two modes of extinguishment were identified as fire blow out and space cooling.

Figure 8-5(b) contains profiles for fire test Case 8-11. In this experiment 0.086 GPM/ft² of water and 290 SCFH of N₂ were discharged from the atomizer as a water spray. After ignition of the ethyl alcohol pool fire a maximum temperature of 548 °F was measured within the facility. Time to extinguishment was 9.0 sec after initiation of the fluid delivery system. Therefore, 0.48 gallons of water was required for extinguishment. Similar fire behavior and facility temperature profiles were observed for this Case as were reported for Case 8-10. The water distribution profile for these flow conditions closely resembled that for Case 8-10. Fire blow out and space cooling were identified as the primary modes of extinguishment.

Results for fire test Case 8-12 are shown in Figure 8-5(c). This experiment consisted of discharging 0.086 GPM/ft² of water from the AM10 atomizer. Similar results observed for Cases 8-10 and 8-11 were observed for this Case. A maximum temperature of 483 °F was measured and a time to extinguishment of 5 seconds was recorded. The pool fire was extinguished with 0.24 gallons of water. Flame blow out and space cooling were again identified as the primary modes of extinguishment.
Results from the 225 kW ethyl alcohol corner pool fire tests, Cases 8-13, 8-14, 8-15 are shown in Figure 8-6(a-c). The pool fire container was located in the northwest corner of the fire testing facility with the atomizer located centrally as shown in Figure 2-4. Water spray was discharged vertically downward onto the corner pool fires. The pool fires were given a two-minute pre-burn time before activation of the fluid delivery system. Figure 8-6(a) shows the results from fire test Case 8-13. The reference temperature measured by TC1 measured a maximum temperature of 500 °F. Thermocouple TC1 was used as the reference temperature throughout this study. The time to extinguishment for this Case was 5:36 min:sec after activation of the fluid delivery system. Therefore 17.9 gallons of water was required to extinguish the fire. Visual observation of the corner pool fire revealed the container was engulfed in flames prior to water spray activation. Once the water spray was initiated the flames within the container were immediately suppressed in intensity. The flames went from fully engulfing the container to being concentrated along the north side of the container. Flame intensity continued to decrease throughout the experiment until the flames were concentrated only in the northeast and northwest corners of the pool fire container. Finally, the remaining flames in the corners were extinguished. Three modes of extinguishment were identified in this Case working in concert to extinguish the fire. From Figure 7-10(b) for Case 017 it can be seen that the greatest concentration of water was discharged near 18 in from the atomizer centerline. In this fire test Case the pool fire container was located outside this range. Hence, the pool fire was located outside the high momentum region and thus fire blow out played a lesser role in extinguishment. However, it was observed that the intensity of the fire was immediately reduced due to
Figure 8-6 Corner Pool Fires with 0.086 GPM/ft² Water Spray Application
the initial surge but it was not sufficient to extinguish the fire. Also, space cooling was identified as a mode of extinguishment evidenced by the immediate reduction in facility temperatures upon activation of the water spray. Further evidence of space cooling was the observation of steam filling the facility. The third mode of extinguishment was identified as fuel cooling. Water; was sprayed into the pool fire container thus diluting and cooling the liquid ethyl alcohol over time. Once the fuel and surrounding atmosphere were cooled to below the flash point of the fuel the fire was extinguished.

Figure 8-6(b) shows the temperature and flowrate curves of fire test Case 8-14. From Figure 8-6(b) it can be seen that the reference temperature within the facility reached a maximum of 509 °F at t=2 min at which time the fluid delivery system was activated. The time to extinguishment was 5:20 min:sec. 19.0 gallons of water was discharged into the facility to extinguish the pool fire. Flames fully engulfed the pool fire container during the pre-burn period and once the fluid delivery system was activated the fire was immediately suppressed. However, flames were concentrated in the northwest and northeast corners of the container until they were extinguished. In this Case the water atomization was not as good as in Case 8-13 and distinct jets discharging from the nozzle were observed. The distinct jets were indicative that the spray pattern was not well dispersed and the spray coverage was not as uniform as in the previous Case. Figure 7-6, Case 019, provides further evidence that the water was not as well-atomized in this Case revealing the SMDs were nearly 100 µm larger over the range measured compared to Case 017. This caused the water to impact the corner pool fire container in a small concentrated area, near the edge, thus resulting in the flames being pushed into the container corners. Although, there was no rapid extinguishment of the flames the fire was suppressed and in control immediately after activation of the fluid delivery system.
The three modes of extinguishment described for Case 8-13 were identified as the primary modes of extinguishment in this Case. Figure 7-10(b) for Case 019 shows the highest concentration of water delivered near r = 18 in. Therefore, the pool fire container was located outside of the high momentum range.

Fire test Case 8-15 results are plotted in Figure 8-6(c). The Grinnell AM-10 atomizer was used for this experiment. After activation of the fluid delivery system the fire was immediately extinguished in 7:50 min:sec. Therefore, 21.9 gallons of water was discharged into the facility to extinguish the fire. TC1’s maximum temperature measured was 550 °F. The spray pattern produced by the AM-10 was well dispersed and the spray coverage was full. Fire blow out, space cooling, and fuel cooling were identified as the primary modes of extinguishment.

Comparing Cases 8-13, 8-14, and 8-15 for corner pool fires it was determined that all three Cases performed similarly. Similar temperature profiles and times to extinguishment were measured for all Cases. The corner pool fire tests differ from the previous centrally located fires and single wall fires because in these tests the initial momentum surge of the water spray was the primary mode of extinguishment. This mode did not have such a pronounced effect in the corner fire tests. Without fire blow out being the primary mode much more water was required to extinguish the fire. However space and fire cooling were identified as the primary modes of extinguishment. The mixing of the water spray in the combustion zone served to cool the fuel and surroundings to the point were combustion could no longer be sustained. Also, the actual contact of the water and liquid fuel resulted in cooling of the fuel. The combination of fuel and space cooling working together to extinguish the fire.
The next series of fire tests were conducted using reduced water and atomizing gas volumetric flowrates. Temperature profiles within the facility are shown in Figure 8-7(a-b) for fires test Cases 8-16 and 8-17 conducted on 225kW ethyl alcohol pool fires. Table 8-1 indicates the testing conditions under which these experiments were conducted. Three quarts of ethyl alcohol were placed centrally within the fire testing facility, ignited, and were given a two-minute pre-burn time before introducing the water sprays. Temperatures throughout the facility were measured and recorded. Also, water and atomizing gas volume flowrates were measured. Figure 8-7(a) shows the experimental results obtained from pool fire tests using Case 8-16 experimental conditions. 2.8 GPM (0.075 GPM/ft²) of water and 306 SCFH of CO2 were discharged from the atomizer that was placed centrally within the facility. Measured data and visual observation revealed that once the automated fluid delivery system was activated, the fire was extinguished in 10.0 sec. Therefore the pool fire was extinguished by 0.47 gallons of water. The temperature within the facility continually increased throughout the two-minute pre-burn time and a maximum of 578 °F was measured by TC1 located above the pool fire (See Figure 2-8 for thermocouple locations). From visual observation of the experiment, the entire free surface of the ethyl alcohol was burning during the two-minute pre-burn period. Once the atomizing gas was initiated to pressurize the fluid delivery system, the flames inside the container immediately decreased in intensity and the flames went from filling the pool fire container to being isolated to the outer perimeter of the container as was reported above for Cases 8-7, 8-8, and 8-9. Finally, after the water spray was introduced into the facility the flames were immediately extinguished without any re-ignition. The primary mode of fire suppression was flame blow. From Figure 8-7(a) it
Figure 8-7 Centrally Located Pool Fires with 0.075 GPM/ft² Water Spray Application
can be seen that there was an initial surge of CO₂ and water upon fluid delivery system activation. The initial high momentum flux of water spray served to instantaneously reduce the fire’s intensity, the secondary mode of extinguishment, flame cooling, extinguished the small remaining fire. It was noted after the fire was extinguished and conformation that there was no fire re-ignition, the testing chamber door was opened and the chamber was filled with steam. Thus confirming that flame cooling due to evaporation of the liquid droplets was a secondary mode of extinguishment. The spray produced by the atomizer under these conditions was classified as a Class 2 Spray (Kashiwagi, 1994) with a D₀,₉ = 338 µm. The water distribution for this Case is shown in Figure 7-10(a) for Case 014. From the Figure it can be seen that the water distribution in the region of the pool fire container, -18 ≤ x ≤ 18, was small in terms of the volume delivered to the container. Therefore, a small volume of water was discharged directly onto the fire and actually penetrated the fire plume to the seat of the fire.

Figure 8-7(b) indicates the temperature profiles within the facility for fire test Case 8-17. The same experimental procedure was followed as described for Case 8-16 with the exception of 290 SCFH of N₂ was used as the atomizing gas. Similar results were obtained for Case 8-17 as were reported for Case 8-16. The maximum temperature measured within the facility measured was 580 °F and a time to extinguishment of 12 sec was observed. This time to extinguishment corresponds to 0.54 gallons of water discharged to extinguish the fire. The slightly longer time to extinguishment was attributed to the larger droplet distribution produced under these flow conditions. Identical primary and secondary modes of extinguishment were identified for this Case as reported above. A Class 3 spray was produced from the atomizer under these conditions
with a $D_{0.9} = 402 \, \mu m$. From Figure 7-10(a) for Case 016 it can be seen that the water distribution played a small role in fire extinguishment. Only a small volume of water was actually discharged to the region of the pool fire container.

Comparing Cases 8-16 and 8-17 to Cases 8-7, 8-8, and 8-9 similar results were observed. The 14% reduction in water flowrate in 8-16 and 8-17 had little effect on the fire suppression characteristics of the sprays. Two modes of fire extinguishment were identified namely flame blow out and fire cooling. These two modes were also identified and described in the previous Cases.

Temperature and fluid flowrate profiles are shown in Figure 8-8(a,b) for experiments conducted on 225 kW ethyl alcohol pool fires located centered against the east wall of the fire testing facility. The atomizer was located central to the fire testing facility, 3.3 ft (1 m) above the container, oriented vertically downward. Experimental conditions for Cases 8-18, and 8-19 are shown in Table 8-1. Cases 8-18 and 8-19 differ from 8-10, 8-11, and 8-12 by reducing the water and atomizing gas flowrates. Figure 8-5(a) contains temperature and flowrate profiles for fire test Case 8-18. The maximum reference temperature measured throughout the experiment was 500 °F measured by TC1. 2.8 GPM (0.075GPM/ft²) of water was discharged along with 306 SCFH of atomizing CO2 gas to produce the water spray. Upon initiation of the fluid delivery system, the fire was extinguished in 3:17 min:sec. Therefore, 9.0 gallons of water was discharged to extinguish the wall pool fire. Because the fluid flow conditions were reduced compared to previous tests, the water spray cone angle was not as great. This smaller cone angle resulted in less high momentum water droplets penetrating to the seat of the fire. From visual observation once the fluid delivery system was activated, the
Figure 8-8 Wall Pool Fires with 0.075 GPM/ft² Water Spray Application
high momentum spray caused the fire to go from completely engulfing the pool fire container to only occupying the two eastern corners. Although blow out aided in reducing the fire’s size and intensity it was not sufficient to extinguish the fire. The primary modes of fire extinguishment were space and fuel cooling. Once a sufficient quantity of water was sprayed into the container the fuel was cooled to below its flash point thus aiding extinguishment. Evidence of fuel cooling was obtained from visual observation of the fire. The fire went from fully engulfing the container to being confined to the eastern corners (two independent fires) to slowly reducing in size until they were extinguished. This indicates that the fuel was being cooled over time to the point in which the fuel could no longer support combustion.

Figure 8-8(b) shows the temperature and flowrate profiles for fire test Case 8-19. The experimental conditions and procedure were identical to Case 8-18 with the exception of N₂ was used as the atomizing gas at a flowrate of 290 SCFH. Results from Case 8-19 were similar to those for Case 8-18. The maximum measured reference temperature was 486 °F by TC1 located centrally within the facility. The time to extinguishment was 3:15 min:sec. 9.3 gallons of water was discharged extinguish the fire. After the two minute pre-burn, the fluid delivery system was activated and the fire was suppressed and confined to the two eastern corners of the fuel container. Over time the fires slowly reduced in size until they were extinguished. The primary modes of extinguishment were identified as space and fuel cooling.

Comparing Cases 8-18 and 8-19 with 8-10, 8-11, and 8-12 it was determined that the lower water and gas flowrates used in 8-18 and 8-19 served to diminish the water spray’s ability to rapidly extinguish the pool fire. In the previous three Cases, the fires were extinguished rapidly due to two primary modes of extinguishment; fire blow out
and space cooling. In 8-18 and 8-19 these modes aided in fire suppression but were not sufficient to extinguish the fire. Moreover, the reduced fluid flowrates resulted in decreased momentum of the water spray. The water spray did not have sufficient momentum or spray cone angle to penetrate the fire and essentially blow it out. However, the momentum of the spray did suppress the fire sufficiently to reduce the fire to two small pool fires located in the eastern corners of the container. Because the fire was not rapidly extinguished the water spray was allowed to spray into the pool fire container thus cooling the ethyl alcohol below its flash point.

Experiments conducted on 225 kW ethyl alcohol pool fires were next studied where the pool fire container was located in the northwest corner of the fire testing facility. Figure 8-9(a,b) shows temperature and flowrate profiles for Cases 8-20 and 8-21. These experiments were conducted to determine the effectiveness of the atomizer under these fluid flow conditions on corner pool fires. In both of the corner pool fire experiments the fire was located farther away from the atomizer than in any of the other Cases, See Figure 2-4 for pool fire locations. Figure 8-9(a) indicates the results obtained from Case 8-20. The ethyl alcohol pool fire was given a two-minute pre-burn before the fluid delivery system was activated. A maximum temperature of 500 °F was measured within the facility at the end of the pre-burn. TC2 measured the maximum temperature located above the pool fire. The time to extinguishment was 3:38 min:sec. Therefore, 10.2 gallons of water was discharged into the facility to extinguish the corner pool fire. Upon activation of the fluid delivery system, the pool fire went from engulfing the pool fire container to being confined to a line along the northern side of the container. The fire remained in a line along the northern side until it was extinguished. Flames slowly decreased in intensity over time until they were extinguished. The water spray was not
directly impacting the fire along the northern side of the container. Therefore, the fire blow out mode of extinguishment was not a dominant mode of extinguishment in this case. Fuel cooling was identified as the primary mode of extinguishment. Also, space cooling was a secondary mode of extinguished evidenced by the rapid decrease in temperature throughout the facility and the observation of steam filling the facility. This result indicates the twin-fluid atomizer’s ability to suppress fires and attenuate heat throughout the space even when the fire is located outside of the high momentum zone. Figure 8-9(b) shows the temperature and flowrate profiles for Case 8-21. In this Case 290 SCFH of N\textsubscript{2} was used as the atomizing gas. At the end of the pre-burn a maximum temperature of 600 °F was measured by TC2. The time to extinguishment was 5:53 min:sec. Therefore, 16.5 gallons of water was required to extinguish the corner pool fire. Again, in this Case the fire was not rapidly extinguished due to the fire being located outside of the high momentum spray region. From the water and droplet distribution results for Case 016 reported in Chapter 7, it can be seen that the corner pool fire was located outside both the largest volume distribution region and largest droplet momentum region. However, the fire was rapidly suppressed in size and reduced to being located only along the northern edge of the pool fire container. Fuel cooling was determined to be the primary mode of extinguishment.

Comparing Cases 8-20 and 8-21 it was determined that the time to extinguishment was longer for 8-21 because of the smaller cone angle produced in 8-21. Using N\textsubscript{2} as the atomizing gas the water was not as well atomized and consequently produced a smaller cone angle. The reduced cone angle allowed a smaller percentage of water to fall into the pool fire container, thus lengthening the time required to cool the fuel below its flash
Figure 8-9 Corner Pool Fires with 0.075 GPM/ft² Water Spray Application
Comparing Cases 8-20 and 8-21 to 8-13, 8-14, and 8-15 it was determined that the time to extinguishments was dependent on the spray flux density. In Cases 8-20 and 8-21 the spray flux densities were smaller thus lengthening the time to extinguishments. In all Cases the pool fires were “controlled” immediately following activation of the fluid delivery system. The initial surge of water spray reduced the fully developed pool fires to small controlled fires within the fuel container.

225 kW Ethyl alcohol pool fire experiments were next conducted using experimental flow conditions described in Table 8-1 for Cases 8-22 and 8-23. In these experiments the twin-fluid atomizer was placed centrally within the facility, mounted 3.3 ft (1 m) above the facility’s platform. The pool fire container was located centrally within the facility centered under the atomizer. Figure 8-10(a,b) contains results obtained for fire test Cases 8-22 and 8-23. The pool fires were ignited and given a pre-burn period prior to activation of the fluid delivery system. 2.4 GPM (0.065 GPM/ft²) of water along with 183 SCFH of CO₂ were discharged vertically downward toward the pool fire. Figure 8-10(a) shows the temperature and flowrate profiles obtained during the Case 8-22 experiment. Temperatures within the facility reached a maximum of 500 °F at the end of the pre-burn. The time to extinguishment was 4:15 min:sec. Therefore, 11.9 gallons of water were discharged into the facility to extinguish the fire. Immediately after the water spray was activated the fire went from fully engulfing the pool fire container to being reduced to two small independent pool fires located in both the north and south ends of the container. The initial pool fire was blown out in the center and greatly suppressed on both ends. However, unlike the other centrally located pool fire test, the initial high momentum surge was not sufficient to extinguish the fire. From Figure 7-10(c) for Case
in can be seen that very little water was discharged into the region of the pool fire container. Therefore, the actual water that impinged on the pool fire was small resulting in a longer time to extinguishment. Fuel cooling was identified as the primary mode of extinguishment evidenced by visual observation of the gradual reduction in fire intensity over time. The fire, after being isolated to two small independent fires, slowly was suppressed until the all the fuel in the pool fire container was cooled below the flash point.

Temperature and flowrate curves are shown in Figure 8-10(b) for fire test Case 8-23. In this case 2.4 GPM (0.065 GPM/ft²) of water along with 175 SCFH of N₂ were discharged from the atomizer. The same experimental procedure and setup was used for this Case as described above for Case 8-22. A maximum temperature of 508 °F was measured by TC1 located directly above the pool fire container. The fire was extinguished in 4:02 min:sec. Therefore, 9.68 gallons of water were discharged into the facility. Similar fire behavior was observed for this experiment as described for Case 8-22. Fuel cooling was identified as the primary mode of extinguishments. The lower time to extinguishments in this Case compared to Case 8-22 was attributed to the higher volume of water delivered to the fire. Figure 7-10(c) for Case 022 indicates a higher volume of water was delivered to the region of the fire thus providing more water to cool the fuel.

Comparing Case 8-22 to Case 8-23 it can be seen that the time to extinguishment was nearly a minute longer for Case 8-22. This was attributed to the water distribution produced in Case 8-22. A finer atomized water spray was produced and less volume of the water spray reached the pool fire container. The water spray was characterized as a
Figure 8-10 Centrally Located Pool Fires with 0.065 GPM/ft² Water Spray Application
hollow cone where the majority of the water spray was concentrated in a conical shape void in the center of high momentum droplets. More of the droplets were either vaporized as they were discharged toward the fire or they completely missed the container due to the hollow cone spray pattern. Since Case 8-23’s spray was not as well atomized more of the larger droplets were discharged into the container thus cooling the fuel. The initial surge of water spray was not sufficient in either Case to cause fire blow out. However, it was able to significantly reduce the fire’s intensity. More steam was visually observed after the fire was extinguished for Case 8-22 than in 8-23 indicated more space cooling.

After the centrally located 225 kW ethyl alcohol pool fire experiments were completed the pool fire container was moved to the center of the facility’s eastern wall where fire test Cases 8-24 and 8-25 were conducted. Figure 8-11(a,b) shows temperature and flowrate curves for test Cases 8-24 and 8-25. The same experimental conditions and procedure were used for these Cases as described above for 8-22 and 8-23. Figure 8-11(a) shows the results obtained from fire test 8-24. 2.4 GPM (0.065 GPM/ft²) of water and 183 SCFH of CO₂ were discharged from the atomizer. A maximum temperature of 600 °F was measured by TC3 at the end of the two-minute pre-burn. The fire was extinguished in 12.0 sec after initiation of the fluid delivery system. 0.40 gallons of water were required to extinguish the 225 kW wall pool fire. The primary mechanism of extinguishment was fire blow out. Fire blow out was achieved in this Case and not in Case 8-22 because the highest droplet momentum and spray flux density were directed near the center of the container. Space cooling was also a secondary mode evidenced by steam filling the testing facility after the fire was extinguished.
Figure 8-11(b) shows the temperature and flowrate curves for Case 8-25. 2.4 GPM (0.065 GPM/ft²) of water and 175 SCFH of N₂ were discharged from the atomizer. The time to extinguishment was 10 sec after initiation of the fluid delivery system. This corresponds to 0.42 gallons of water discharged to extinguish the fire. The maximum temperature was measured to be 500 °F by TC3. Fire blow out was identified as the primary mode of extinguishments as described for Case 8-24.

Comparing Cases 8-24 and 8-25 it was determined that both performed similarly in the wall pool fire experiments. Because both sprays had a hollow cone pattern, the high momentum droplets were concentrated near the center of the pool fire container. The high momentum droplets blew out the fire. However space cooling was also identified as a mode of extinguishment evidenced by the steam present within the facility. Results from 8-24, and 8-25 are similar to those obtained for Cases where a flux density of 0.086 GPM/ft² of water was discharged. Although, the spray patterns produced from the atomizer in these Cases were different, the modes of extinguishment observed were identical. This result was attributed to the location of the high momentum droplets. As long as the pool fire was located within a region of high droplet momentum rapid extinguishment by fire blow out was observed.

225 kW corner pool fires were studied next for Cases 8-26 and 8-27. The pool fire container was moved to the corner of the facility to study the effectiveness of the atomizer on corner fires. The atomizer was centrally located and oriented vertically downward. Located 3.3 ft (1 m) above the facility’s platform. Figure 8-12(a,b) contains the results obtained from the tests. Figure 8-12(a) shows the curves for Case 8-26. It can be seen from the Figure that rapid extinguishment was not achieved under these
Figure 8-11 Wall Pool Fires with 0.065 GPM/ft² Water Spray Application
conditions. The time to extinguishment was 2:01 min:sec corresponding to a volume of 4.8 gallons of water discharged to extinguish the fire. TC-2 located over the pool fire measured the maximum temperature within the facility of 648 °F. Visual observation of the fire revealed that upon initial activation of the fluid delivery system the fire was suppressed greatly. If went from engulfing the container to being controlled and contained along the north edge of the container. The fire slowly decreased in intensity until it was extinguished at t=2:01 min:sec. As mentioned previously in the above Cases the spray pattern was of the hollow cone type. A large percentage of the initial high momentum droplets impacted the fire near the southern edge of the container. Therefore, fire blow out was a contributing mode of extinguishment but ultimately fuel cooling was the primary mode. Because of the spray was not well-atomized resulting in a hollow cone spray pattern, a majority of the water directed at the northwest corner of the facility actually fell into the container thus cooling the fuel.

Figure 8-12(b) shows the results from Case 8-27. 2.4 GPM (0.065 GPM/ft²) of water and 175 SCFH of N₂ were discharged from the atomizer to study the resulting spray’s effects on corner pool fires. A maximum temperature of 575 °F was measured by TC2 located directly above the pool fire. The time to extinguishment was 2:19 min:sec. Therefore 5.6 gallons of water were discharged to extinguish the pool fire. The ethyl alcohol pool fire was extinguished in the same manner described for Case 8-26.

Comparing Case 8-26 to 8-27 it can be seen that similar results were obtained. In both Cases fuel cooling was the primary mode of extinguishment. The hollow cone spray pattern discharged from the atomizer directed the initial high momentum droplets towards the pool fire container, thus greatly suppressing it. The initial surge immediately
Figure 8-12 Corner Pool Fires with 0.065 GPM/ft² Water Spray Application

(a) Case 8-26

(b) Case 8-27
reduced the facility and fuel temperature thus aiding in extinguishment. Then overtime accumulated in the fuel container reducing the fuel temperature to the point where combustion could no longer be maintained. Comparing Cases 8-26 and 8-27 to the other corner pool fires it can be seen that in some Cases, 8-26 and 8-27 have shorter times to extinguishments, even though Cases 8-26 and 8-27 had the smallest spray flux densities. The shorter times to extinguishment were attributed to the hollow cone spray pattern and the fact that a large quantity of the water was directed directly into the fuel container.

8.4 Full-Scale Water Mist Spray, Jet, and Machinery Space Fire Results

Class B spray fires were investigated in the next phase of the research. This phase of experiments were conducted to test the CONE-4B1’s ability to suppress spray fires and compare its performance with the commercially available AquaMist AM10 atomizer. Figure 8-13(a,b) contains temperature and flowrate curves for test Cases 8-28 and 8-29. The tests were conducted on 200 kW ethyl alcohol spray fires. A Lawrence 0-1 gpm fuel injector was used to produce the fuel spray. 0.164 GPM of ethyl alcohol was sprayed from the fuel injector located centrally within the fire testing facility, See Figure 2-5 for fuel injector location. The atomizers were located centrally within the facility, oriented vertically downward, and 3.3 ft (1 m) above the facility’s platform. In each Case the spray fires were ignited and given a two-minute pre-burn prior to activation of the fluid delivery system. Figure 8-13(a) shows the curves for test Case 8-28. In this Case 3.2 GPM (0.086 GPM/ft²) of water and 310 SCFH of CO₂ were discharged into the facility. A maximum temperature of 223 °F was measured by TC1 located above the spray fire. The spray fire was not as intense as the pool fires reported above and was extinguished in 17 sec after initiation of the fluid delivery system. 0.91 gallons of water were discharged
to extinguish the fire. Upon fluid activation, the flames went from fully developed and stable with a conical flame pattern to significantly suppressed and unstable. The high momentum spray suppressed the fire’s ability to burn away from the injector and localized the flames near the exit. Instability of the fire was observed with the flames rapidly fluctuating in intensity and direction. When the fire was extinguished it seemed to have been blow out due to the instability.

The AM10 atomizer was next tested, Case 8-29, under the same conditions as 8-28. Figure 8-13(b) shows the temperature and flowrate curves. It can be seen from the Figure that the maximum temperature within the facility was 165 °F measured by TC1. Similar results were obtained for Case 8-29 as were reported for 8-28. The time to extinguishment was 23 sec which corresponds to 1.2 gallons of water discharged to extinguish the fire. Again, upon activation of the fluid delivery system the fire went from stable and fully developed to very unstable and burning only near the exit of the fuel injector. Moreover, the flame’s discharge direction went from horizontal, parallel with the facility’s platform, to angled sharply downward towards the platform. It was theorized the spray fire was blown out caused by the instability created by the water mist.

Since water mist technology in the application of machinery spaces is currently a topic of much interest, a simulated machinery space was constructed and placed within the fire testing facility. Test Case 8-30, summarized in Table 8-1, lists the experimental parameters and flow conditions for the machinery space test. The machinery space mock-up consisted of an 8 in. diameter by 12 in. long stainless steel cylinder with end caps welded on each end. The mock-up was placed directly beneath the atomizer that was located centrally to the facility. The spray fire fuel injector was mounted 10 in.
Figure 8-13 Ethyl Alcohol Spray Fires
above the facility platform and oriented such that the ethyl alcohol would spray directly onto the mock-up. Figure 2-6 shows the experiment layout for Case 8-30. 0.164 GPM of ethyl alcohol was sprayed onto the cylinder. The spray fire was ignited and given a 1.5-minute pre-burn prior to activation of the fluid delivery system. Results from Case 8-30 are shown in Figure 8-14. After ignition of the spray fire the temperature within the facility began to increase. TC1 measured the maximum temperature of 545 °F at a location 10 in. above the top of the machinery mock-up. The fire was extinguished 19 sec after initiation of the fluid delivery system. Therefore, a total of 1.0 gallon of water was required to extinguish the 200 kW machinery space fire. After the fire was ignited the spray fire engulfed the mock-up. Flames covered the mock-up with the maximum fire intensity along the south side. Upon activation of the water mist the fire intensity was greatly suppressed and confined to being located only near the fuel injector exit. The fire exhibited the same behavior described above for Cases 8-28 and 8-29. Re-ignition of the spray was a concern due to the mock up’s added mass within the facility. Although the mock-up was heated throughout the pre-burn period it was rapidly quenched upon initiation of the water mist thus preventing re-ignition. The water mist sufficiently cooled the mock-up to below the flash point of the fuel. The rapid extinguishment of the spray fires by the twin-fluid atomizer agrees with research published by Ziu, Kim, and Li (1998). Ziu et al studied the effects of water mist produced by twin-fluid atomizers on simulated machinery space spray fires. In their study, the atomizers were located farther away from the spray fire and machinery mock-up than in this study. The water mist did not have the same momentum effects on the fire as reported in this study. The authors identified space cooling as the primary mode of extinguishment.
The next series of experiments consisted of 425 kW simulated machinery space fire tests. Pool and spray fires were simultaneously ignited and the machine mock-up was placed inside the pool fire container. The mock-up was oriented such that the ethyl alcohol sprayed directly onto it. This experimental setup was designed and constructed to simulate a machinery space fire consisting of fuel spilled on the floor along with a break in a fuel line spraying on a hot metal surface. Figure 2-6 shows the experimental setup and fire arrangement. Figure 8-15(a,b) contains the temperature and flowrate curves for experimental test Cases 8-31 and 8-32. In both Cases 3 quarts of ethyl alcohol was used for the pool fire fuel and 0.164GPM of ethyl alcohol was sprayed from the fuel injector. The atomizers were centrally located, 3.3 ft (1 m) above the platform and oriented vertically downward. The pool fire was ignited and then the ethyl alcohol spray was activated thus igniting the spray fire. After the spray fire ignited and was fully developed the combined spray and pool fires were given a one-minute pre-burn before activation of the fluid delivery system. Figure 8-15 (a) shows the measurements obtained from the Case 8-31 experiment. 3.2 GPM (0.086 GPM/ft²) of water and 310 SCFH of CO₂ were discharged from the atomizer onto the simulated machinery space fire. TC1 measured the maximum temperature within the facility of 1060 °F located directly above the pool fire and machine mock-up. This temperature was significantly larger than reported in any of the previous Cases indicated a more intense fire. The time to extinguishment was 21 sec. Therefore, only 1.1 gallons of water were discharged to extinguish the 425 kW fire. The short time to extinguishments for the increased power fire suggests that the extinguishment of the fires is primarily dependent on the initial high momentum surge of water mist and space cooling in the combustion zone near the fuel source. Evidence of
Figure 8-14 Case 8-30; Simulated Machinery Space Spray Fire

this is the behavior of the fire and temperatures recorded throughout the facility. From visual observation of the experiment it was determined that fire blow out and space cooling were the primary modes of extinguishment. As was reported in the previous pool fire Cases the initial high momentum water mist greatly suppressed the pool fire and extinguished the spray fire. The pool fire was instantaneously suppressed then space
cooling took over and extinguished the fire. Evidence of space cooling was the observation that the fire testing facility was completely filled with steam upon extinguishment of the fire. Moreover, from Figure 8-15(a) it can be seen that the temperature throughout the facility rapidly decreased once the water mist was discharged indicating heat absorption from the fire to the water mist. The spray fire was extinguished in the same manner as described for Case 8-30.

Figure 8-15(b) contains the measurements obtained during the Case 8-32 fire test. The same experimental procedure and setup was used for this Case as described for Case 8-31 with the exception of the AM10 atomizer was used to produce the water mist. 3.2 GPM (0.086 GPM/ft²) of water was discharged from the AM10 onto the machinery space fire. Figure 7-15(b) indicates the maximum temperature measured within the facility was 890 °F at the end of the pre-burn period. The time to extinguishment was 11 sec, which corresponds to a total volume of 0.7 gallons of water discharged to extinguish the fire. Fire blow out was identified as the primary mode of extinguishment. Upon activation of the fluid delivery system the spray fire was immediately extinguished and the pool fire was instantaneously suppressed. The pool fire went from engulfing the fuel container and machinery mock-up to being concentrated in the four corners of the container. The remaining four small pool fires were very unstable. It was theorized that the small fires were extinguished due to the instability created by the high momentum water mist.

Comparing Case 8-31 to 8-32 it can be seen that similar results were obtained. However, their modes of extinguishment were slightly different. In Case 8-32 it was proposed that the fire’s instability caused by the high momentum water mist was the primary mode of extinguishment causing the fire to blow out. In Case 8-31 there was
Figure 8-15 Simulated Machinery Space Fire Test Results
two primary modes of extinguishment, i.e., fire blow and space cooling. It was reasoned that in Case 8-31 space cooling was a primary mode due to the behavior of the fire. The fire was quickly suppressed after initiation of the fluid delivery system and then the fire gradually became smaller and smaller until it was extinguished. There was little fire instability noted during the experiment.

The effectiveness of water mist in 55 kW propane spray fire applications was next studied. The Lawrence fuel injector was mounted 10 in above the fire testing facility’s platform and 20 in south of the atomizer’s centerline. Figure 2-5 shows the experimental setup and equipment arrangement. The atomizers were mounted 3.3 ft (1 m) above the platform and oriented vertically downward. Figure 8-16(a,b) shows the temperature and flowrate curves for fire test Cases 8-33 and 8-34. See Table 8-1 for Case experimental flow conditions. In both Cases 75 SCFH of propane gas was discharged from the fuel injector. The propane was ignited and given a one-minute pre-burn prior to activation of the fluid delivery system. Figure 8-16(a) contains the results from Case 8-33. 3.2 GPM (0.086 GPM/ft²) of water and 310 SCFH of CO₂ were discharged from the atomizer. The maximum temperature measured during the experiment was 188 °F by TC1 located directly above the core of the spray fire. The time to extinguishment was 21 sec corresponding to a total volume of 1.1 gallons required for fire extinguishment. During the pre-burn period the propane fire was fully developed with stable flames, and the flame pattern was conical in shape. After the fluid delivery system was activated the fire was instantaneously suppressed and the spray fire pattern was downward toward the platform. Instability in the fire was observed as the water mist was applied to the fire. Throughout the experiment the instability became greater until the fire was extinguished.
The instability of the fire caused by the water mist resulted in the propane spray fire being blown out. Therefore, primary mode of extinguishment was fire blow out.

Figure 8-16(b) depicts the measurements obtained for fire test Case 8-34. For this fire test the LSU atomizer was replaced by the AM10 atomizer. 3.2 GPM (0.086 GPM/ft²) was discharged from the AM10 onto the propane spray fire. From Figure 8-16(b) it can be seen that at the end of the pre-burn the maximum temperature within the facility was 175 °F measured by TC1. The spray fire was extinguished in 11 sec after initiation of the fluid delivery system. 0.59 gallons of water were required for fire extinguishments. The fire characteristics and mode of extinguishment were identical to that described for Case 8-33.

For both propane spray fire Cases rapid extinguishment was observed. Fire blow out was identified as the primary mode of extinguishment. From Figure 8-16(a,b) it can be seen that the temperatures throughout the fire testing facility were much less than in the pool fire Cases. This indicates that the water mist would not have as great of an effect in cooling the space as was observed for pool fire experiments.

The next series of fire tests combined propane pool fires with ethyl alcohol pool fires for an estimated power of 300 kW. These tests were designed and constructed to simulate machinery space type fires. The pool fire represented some type of fuel spilled onto the machinery space floor while the propane spray fire represented a gaseous fuel spraying from a broken pipe or a broken piece of equipment. The experimental flow conditions are shown in Table 8-1 for fire test Cases 8-35 and 8-36. 3 quarts of the ethyl alcohol were placed inside the pool fire container and the container was placed in the center of the facility. 75 SCFH of propane was discharged from the Lawrence fuel injector. The fuel injector was mounted 10 in. off the facility platform and was located
Figure 8-16 Propane Jet Fire Test Results

(a) Case 8-33

Fuel = Propane
Type = Spray Fire
Q_{CO2} = 310 SCFH
Q_{H2O} = 3.2 GPM

(b) Case 8-34
just south of the pool fire container. Figure 2-6 depicts the experimental setup and equipment arrangement. In each Case the pool fire was ignited and then the propane spray was activated thus igniting the spray fire. The fires were given a one-minute pre-burn prior to activation of the fluid delivery system. Figure 8-17(a) shows the temperature and fluid flowrate curves for test Case 8-35. In this Case 3.2 GPM (0.086 GPM/ft$^2$) of water and 310 SCFH of CO$_2$ were discharged from the atomizer. Thermocouple TC1 located directly above the propane fire measured the maximum temperature within the facility of 503 °F. The time to extinguishment was 22 sec corresponding to a total volume of 1.2 gallons required to extinguish the fire. Observation of the experiment revealed that the fires were extinguished in the same manner as reported previously for Cases 8-7, 8-8, and 8-9. Instantaneous suppression of the fires was observed. The spray fire went from a fully developed, stable fire to a very unstable, fluctuating flame pattern. The pool fire went from fully engulfing the fire container to being located only in the four corners of the container. Fluctuation of the spray fire flames became so great the fire went out. Therefore, fire blow out was identified as the primary mode of extinguishment of the spray fire. The pool fire was suppressed greatly by the initial surge of high momentum water mist. Then the water droplets cooled the four remaining fires such that the surrounding atmosphere could no longer support combustion. Flame blame out and space cooling were the primary modes of extinguishment for the pool fire.

Figure 8-17(b) contains the temperature and water flowrate curves for test Case 8-36. In this Case 3.2 GPM (0.086 GPM/ft$^2$) of water was discharged from the AM10 atomizer. TC1 measured the maximum temperature within the facility of 500 °F. After
initiation of the fluid delivery system, the fires were extinguished in 27 sec. Therefore a total of 1.4 gallons of water were required for fire extinguishment. Identical results were obtained for this Case as was reported for Case 8-35. The two primary modes of extinguishment were identified as fire blow out and space cooling. Fire blow out was identified as being the primary mode of extinguishment of the propane spray fire.

Comparing the results obtained for Cases 8-35 and 8-36 it can be seen that both Cases performed similarly. The temperature profiles throughout the experiment closely approximate one another as can be seen in Figure 8-17(a,b). Rapid extinguishment of combination spray and pool fires by water mist was observed and the results reported agree with the findings of Braidech (1955) and Liu, Kim, and Su (1996).

8.5 Summary

Experiments were conducted to study the effectiveness of water mist when applied to small hydrocarbon fires. Fire tests conducted with water mist produced by the LSU developed atomizer was compared to that of the commercially available Grinnell AquaMIST AM10 atomizer. In a majority of the Cases rapid extinguishment of the fires was observed. It was concluded that the primary modes of fire extinguishment by water mist were fire blow out, space cooling, and fuel cooling. Because the atomizers were mounted 3.3 ft (1m) above the fires, the initial high momentum surge of water mist resulted in greatly suppressing the fires and in some Cases completely extinguishing them. Space cooling was also identified as a primary mode evidenced by the large quantity of steam observed within the fire testing facility once the fires were extinguished. Oxygen displacement was most probably another mode of extinguishment but due to the limited instrumentation it could not be verified. Oxygen displacement
Figure 8-17 Combination Ethyl Alcohol and Propane Fire Test Results
occurs when the liquid droplets discharged from the atomizer are evaporated as they approach the fire. The evaporation expands the droplets approximately 1700 times its liquid volume thus displacing oxygen. Local displacement of oxygen starves the fire of oxygen aiding in extinguishment. Also, in Cases where rapid extinguishment was not obtained fuel cooling was a primary mode of extinguishment. In these Cases the water mist was sprayed into the fuel container and over time the water mist cooled the fuel to below its flash point.

The results reported herein indicate that extinguishment of small hydrocarbon fires by Class 2 and 3 water mists was readily achievable. Also, it was shown that very small volumes of water, typically less than one gallon, in some Cases were required to completely extinguish the fires and prevent re-ignition. The results were compared to those reported by Braidech (1955) where he described the extinguishment of hydrocarbon pool and spray fires in terms of water droplet diameters and spray flux densities. Figure 8-18 was taken from Braidech’s paper that indicates the dependence of fire extinguishment on the spray flux density and average volume droplet diameter. If we plot our spray flux density and average droplet diameter points on his graph it can be seen that our points lie in his nonextinguishment zone. However, we observed extinguishment under these conditions. Therefore, this work served to extend his boundary where fire extinguishment can be achieved relative to the spray flux density. The extension of the extinguishment zone was indicative that extinguishment had to be dependent on something else in addition to water droplet diameters. It was theorized that the primary dependence on fire extinguishment was the placement of the fires relative to the atomizers.
Wighus reported that the absorption of heat from a fire by a water spray is a function of water discharge rate and mean water droplet diameter. He also reported that the effectiveness of the spray action is also especially dependent of the location of the atomizer relative to the fire. He continued by stating that a spray directly impinging the base of the fire was much more effective than one not impinging the base. His statements agree with the results we have reported with the exception of dependence on water droplet diameter. Our experiments were performance based tests rather than droplet diameter studies.

Gameiro and Girard (1993) reported rapid extinguishment of pool and spray fires by twin-fluid atomizers conducted on fires ranging from 3 to 20 MW. The author reported a rapid decrease in temperatures throughout the experimental facility upon activation of the fluid delivery system. This find was in strong agreement of all of our
results reported. The water mist, upon discharging into the facility, absorbs heat from the fire and surrounding facility walls thus reducing the temperature.

Comparing the results of the LSU atomizer and the AquaMIST AM10 it can be seen that they performed similarly when the spray flux densities were matched. Tests utilizing the AM10 had slightly shorter times to extinguishment in a majority of the Cases. Although in the corner pool fires tests, Cases 8-13 and 8-15, the LSU atomizer had a shorter time to extinguishment. The LSU atomizer out performed the AM10 in this Case due to the wider cone angle and the spray pattern was such that more of the water droplets were concentrated along the spray’s perimeter. In the spray fire tests and simulated machinery space tests the LSU and AM10 produced similar results and fire extinguishing characteristics. In all Cases were 0.086 GPM/ft² flux density was discharged flame blow out was the primary mode of extinguishment. This phenomenon was primarily due to the location of the atomizers relative to the fires. This information is valuable for determining atomizer spacing and locations when designing fire protection systems.

The results obtained using the AM10 were in concurrence with results published by the Naval Research Laboratory (1995). In their research 0.046 GPM/ft² from multiple AM10’s were applied to hydrocarbon pool fires and times to extinguishment ranged from 0:50 to 4:00 min:sec.

The fire tests revealed the dependence of the atomizer’s fire suppression capability on the relative position of the atomizer and the fire. As was expected, the further the fires were located from the atomizers the more difficult they were to suppress. There was no splashing of the liquid ethyl alcohol observed causing the fire to spill over
the pool fire container as was reported by Kokkala (1998). Since no spilling was observed, this was evidence that the water droplets were not so large as to cause splashing and spilling of the fuel. Also discovered in this study were the spray pattern effects on the atomizer’s capability to suppress fires. It was reported that in some Cases the spray patterns prevented rapid extinguishment because the concentration of the droplets were not conducive for extinguishment. Again, the spray pattern and height of the atomizers above the plane of protection are key pieces of design data required to design complete fire protection systems.
CHAPTER 9 CHARACTERIZATION OF AN ELECTROSTATIC SPRAY SUBJECTED TO VARIOUS ELECTRICAL BOUNDARY CONDITIONS

9.1 Introduction

In order to atomize any liquid a disturbance must be introduced into the liquid’s surface area. The disturbance causes the surface to rupture resulting in the formation of ligaments, which subsequently break up and form droplets. Electrostatic atomization is characterized by the energy causing the surface disturbance or disruption comes from the mutual repulsion of like charges that accumulate on the free surface of the liquid. Thus an electrical pressure is created that tends to expand the surface area. The electrical pressure is opposed by surface tension forces, which tend to contract or minimize the surface area. When the electrical pressure exceeds the surface tension forces, the surface becomes unstable and droplet formation begins. If the electrical pressure is maintained above the critical value consistent with the liquid flow rate, then atomization occurs and is continuous Lefevbre (1989).

The electrical pressure, $P_e$, has been derived by Graf (1962) as

$$P_e = \frac{F V^2}{2\pi D^2}$$

where $V$ is the applied voltage, $D$ is the drop diameter, and $F$ is a charging factor that represents the fraction of the applied potential attained on the drop surface.

Kelly (1994) reported that the charged droplet spray could be characterized by the distribution of drop diameters and the distribution of charge over a droplet population. Kelly’s theoretical work resulted in the simple relation between the mean values of the two distributions:
\[ D = \frac{K}{\sqrt{\rho_e}} \]

where \( D \) is the mean droplet diameter and \( \rho_e \) is the mean droplet charge density. Choosing units of \( \text{C/m}^3 \) for \( \rho_e \) and \( \mu\text{m} \) for \( D \) the value of the constant \( K \) is 84 for conventional electrostatic spray liquids. The constant is independent of liquid properties such as conductivity and surface tension.

Electrical sprays differ from conventional sprays by the presence of free charge on the droplet’s free surface. As will be demonstrated from the results herein the presence of the charge has profound implications on the behavior of the spray. Unlike conventional, uncharged, droplet sprays that are dominated by purely aerodynamic effects as they are discharge and projected from the atomizer, charged droplet sprays are driven by strong electrical force.

The electrical force is intense and of long range, generated by the charge on the droplets’ free surface. The charge produces vigorous droplet/droplet repulsion and intense spray dispersion. Because the droplets contain an electrically non-neutral charge, they generate large “space charge” electric fields that completely fill the volume in which they are generated. Consequently, they fill and interact with all the objects within the volume and provide electric field line paths for the conveyance of charged droplets.

Of practical interest, when the charged droplet spray is directed towards an object the electric fields lines are not limited to the front surface of the object. Rather, the electric field lines extend around all sides of the object and provide a guidance path by which the charged droplets will travel. These field lines provide the spray the ability to wrap around objects.
The following are unique characteristics of electrically charged sprays:

- Automatic droplet dispersion
- Droplets have the ability to flow to conventionally inaccessible spaces
- Electrostatic atomizers intrinsically produce narrow droplet size distributions
- Electrostatic atomization is the most efficient atomization process
- Droplet size is independent of flow rate and fluid properties
- Generated by compact devices operating at arbitrarily high flow rates

Conventional atomizers operate at an efficiency of approximately 1%. This implies that 1% of the total energy input into the atomization process actually is utilized to disperse the liquid into droplets. However Kelly (1997) reported electrostatic atomization has an efficiency of 25%. The remaining 75% of the electrical input energy drives the droplet dispersivity.

9.2 Description of the Electrostatic Atomizer

The electrostatic atomizer utilized throughout this Part of the study was the SPRAY TRIODE® provided by Charged Injection Corporation. The schematic of the SPRAY TRIODE® is shown in Figure 9-1. In this device, two submerged electrodes form a self-contained field emission electron gun assembly. A centrally located emitter electrode is positioned immediately upstream of a grounded orifice plate through which the atomizing fluid exists. If no voltage is applied to the emitter, the fluid simply discharges from the orifice without disruption, i.e. a stream of liquid is discharged. However, if negative voltage is applied to the emitter it is possible to drive free charge into the exiting fluid Kelly (1997). Once free of the confines of the interelectrode region, the charged fluid undergoes disruption and spray formation. Charge is returned to the circuit by a collector
electrode. A resistor is placed between the orifice electrode and ground to limit electrode current in the event of an internal breakdown in the fluid.

The SPRAY TRIODE® requires application of a modest input voltage on the order of 10 kV. This applied voltage permits the injection of small amounts of free charge (3µA per mL/s is all that is required for vigorous atomization) and the development of very high electric fields (5 to 15 MV/m is typical). It is the presence of this space electric field that drives the charged droplets outward from the atomizer. Once the charged droplets are discharged from the atomizer, no longer do aerodynamic or fluid dynamic forces
govern the flow of the droplets. Throughout this study Grade A kerosene was used as the atomization fluid.

9.3 Experimental Facility

An electrostatic spray testing facility was designed and constructed such that charged droplet velocity field experiments could be conducted and the electrical boundary conditions near the atomizer could be varied. Figure 9-2 contains the electrostatic spray testing facility schematic.

On the liquid side of the experimental facility, nitrogen gas provided the pressure to force the liquid kerosene through the atomizer. The nitrogen cylinder was equipped with a standard industrial inert gas regulator to set the pressure inside the kerosene pressure vessel. Grade A kerosene was stored inside the kerosene pressure vessel that was constructed from clear acrylic piping components. From the pressure vessel the liquid kerosene was conducted through ¼” tubing to the SPRAY TRIODE® atomizer. The liquid traveled through the atomizer where it was electrically charged and then discharged into the droplet collector. 3x3x1/4” angle structural steel formed the frame for the collector Figure 9-3 depicts the Electrostatic Spray Testing Facility. The facility had dimensions of 1220x610x610 mm (L_xL_yL_z). Electrically grounded ¼” wire mesh lined the facility on all sides, including the bottom, to collect the charge on the droplets. Clear glass comprised the four outer sides of the facility so that CCD camera images could be obtained. A 4” by 12” hole was cut into the wire mesh on the side facing the camera to provide an unobstructed view of the flow field during the PIV measurements.

On the electrical side of the experimental facility a high voltage power supply provided the 10 kV voltage to the SPRAY TRIODE® as required for vigorous
Figure 9-2 Electrostatic Spray Testing Experimental Facility Schematic
Between the power supply and the nozzle, a multi-meter was placed to measure the input current into the fluid. The charge was placed into the flowing kerosene as it discharged through the exit orifice. From there the charged droplets impacted the wire mesh where the charge was returned to ground. A multi-meter was placed between the nozzle and ground to measure the spray current. Also, a 100 MΩ resistor was placed between the nozzle and ground to limit electrode current in the event of an internal breakdown in the fluid.

9.4 Instrumentation and Data Acquisition

A schematic of the instrumentation used for the electrostatic spray characterization measurements is shown in Figure 9-4. PIV measurements were conducted to measure the velocity field produced by the electrostatic atomizer. The PIV system employed used the standard PIV measuring technique where the velocities of the liquid droplets were measured by recording the displacement of the droplets and subsequently analyzing the
recorded displacements. Two short laser pulses fired with a known time separation illuminated droplets dispersed in the region of interest. The droplet positions are recorded by means of the CCD camera.

The droplet displacements are calculated from the displacements in the image plane. Knowing the magnification of the imaging and the time separation between laser pulses, the velocity projections on the measuring plane are calculated.

To conduct the PIV experiments four basic parameters were required for successful measurements. These four parameters are list below:

(1) Seeded flow, the charged droplets provided the light scattering particles.

(2) Illumination of a cross section of the flow, the laser light sheet provided the illumination.

(3) Capturing and recording of the scattered laser light, laser light was recorded by the CCD camera placed at 90° to the laser sheet.

(4) Analysis of the recordings, analysis of the data was performed with “in house” data processing programs.

9.5 Experimental Conditions

Table 9-1 lists the experimental flow conditions utilized for Part II of this investigation. The Spray Triode® was mounted centrally within the facility at a height of 508 mm above the wire mesh bottom. The supply pressure was set to 40 psig in all experiments resulting in a kerosene volume flow rate of 24 mL/min. The mass averaged
Figure 9-4 Particle Image Velocimetry Instrumentation and Data Acquisition Schematic
velocity of the kerosene discharged from the atomizer’s orifice was \( V_m = 8.15 \) m/s. The nozzle and spray currents were measured and are indicated in Table 9-1. Three cases were utilized and each differed by the electrical boundary conditions near the atomizer. In the first case the charged droplets were discharged into the facility without any obstructions. Secondly, experiments were conducted with a grounded conducting obstruction placed 75 mm away from the atomizer. This obstruction was placed near the atomizer to change the electrical boundary conditions and to study the effects the obstruction had on the resulting droplet velocity field. The third experimental setup consisted of placing a non-conducting obstruction 75 mm from the atomizer. The non-conducting obstruction was placed near the atomizer to study the effects on the charged droplet spray. The size and location of the obstructions for each case is indicated in Table 9-1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Volume Flowrate (mL/min)</th>
<th>Supply Pressure (psig)</th>
<th>Nozzle Current* (µA)</th>
<th>Spray Current** (µA)</th>
<th>Atomizer Location X,Y,Z (mm)</th>
<th>Obstruction Dimensions, (HxW(mm))</th>
<th>Location Dimensions, (HxW(mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unobstructed</td>
<td>24</td>
<td>40</td>
<td>0.6</td>
<td>0.4</td>
<td>610,508,305</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Gnd Cond-Obstr</td>
<td>24</td>
<td>40</td>
<td>0.6</td>
<td>0.3</td>
<td>610,508,305</td>
<td>178 x 457</td>
<td>686,496,305</td>
</tr>
<tr>
<td>Non Cond-Obstr</td>
<td>24</td>
<td>40</td>
<td>0.6</td>
<td>0.3</td>
<td>610,508,305</td>
<td>178 x 457</td>
<td>686,496,305</td>
</tr>
</tbody>
</table>

*Current measured between the nozzle and ground  
**Current measured between the wire mesh within the facility and ground

9.6 Characterization of a Charged Droplet Spray

9.6.1 Characterization of the Unobstructed Spray

Figure 9-5 shows the dispersion of charged droplets emanating from the Spray Triode® in an unobstructed spray facility. Figure 9-6 depicts the scaled mean velocity field for the unobstructed charged droplet case. The velocity field was produced by averaging 200 instantaneous PIV images. The X and Y length scales were scaled by
Figure 9-5 Dispersion of Droplets Emanating from the Spray Triode®

Figure 9-6 Unobstructed Planar Velocity Field of Electrostatically Charged Droplets
From Figure 9-6 it can be seen that near the center of the jet the droplets were traveling vertically downward with velocities approximating $V_m$. However with increasing $X$ the velocity vectors indicate that the droplets were traveling away from the atomizer centerline. Moreover, from $0 \leq \frac{Y}{L_y} \leq 0.12$ the velocity vectors indicate that the droplet movements were counter to the streamwise direction. This counter gravity flow of the charged droplets was attributed to the strong electromagnetic forces produced by the droplets. Since each droplet contains a net negative charge that is distributed along the free surface of the droplet, the charged droplets repel one another driving them in all directions. The droplets travel along the electric field lines that completely fill the facility.

The scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled axial velocity component ($V/V_m$) is shown in Figure 9-7. It can be seen from the Figure that the spray’s $V$ velocity was relatively symmetric about the atomizer centerline. The upper corners of the contour plot indicate that the droplets were being accelerated upward and outward away from the atomizer. The upward droplet movement was evidence that the flow was governed by electrostatic forces rather than aerodynamic forces.

The scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled radial velocity component ($U/V_m$) is shown in Figure 9-8. Again, the $U$ droplet velocities were symmetric about the atomizer centerline. Figure 9-8 reveals that the droplets were being dispersed away from the centerline driven by the repulsive electromagnetic forces within the droplet flow field. The center core of the contour plot indicates that the droplets were moving horizontally in this region parallel to
the bottom of the facility. This was further evidence that the charged droplet spray pattern was independent of the aerodynamic and gravitational effects that govern conventional sprays.

### 9.6.2 Characterization of a Charged Droplet Spray in the Presence of a Grounded Conducting Obstruction

The electrical boundary conditions were changed for the next series of experiments by placing a grounded, conducting obstruction 75 mm from the Spray Triode®. The grounded obstruction was placed at the location indicated in Table 9-1. Figure 9-9 shows the planar scaled velocity field for the grounded obstruction case. The bold vertical line in the figure represents the position of the grounded obstruction. The
nozzle was located at 0,0. It can be seen from the Figure that the grounded obstruction had a profound effect on the droplet velocity field. On the atomizer side of the obstruction the charged droplets were accelerated towards the obstruction. This strong droplet attraction to the grounded obstruction was attributed to the electromagnetic field resulting from the presence of the obstruction. The close proximity of the obstruction created a short path to ground for the charged droplets thus attracting them altering the spray pattern compared to the unobstructed case. On the shielded side of the obstruction the droplets wrap around and travel upward and towards the obstruction. The charged droplets sustain counter gravity motion thus defying the properties of conventional gravitational sprays.
Figure 9-9 Planar Velocity Field of Electrostatically Charged Droplets Near a Grounded Conducting Obstruction

Figure 9-10 shows the scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled axial velocity component ($V/V_m$). The contour plot reveals that the maximum axial velocity was contained in the core of the jet near the atomizer centerline. However, on the shielded side of the obstruction the plot is flooded with shades of blue indicating negative (upward) motion of the charge droplets. This is evidence of the principle of electrostatic paint spraying, where charged paint droplets are sprayed from one side of an object but due to the wrap around effect of the droplets both sides are deposited with paint droplets.

Figure 9-11 shows the scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled radial velocity component ($U/V_m$). The
Figure 9-10 Axial Velocity Field and Color Flooded Contour Plot of Electrostatically Charged Droplets Near a Grounded Conducting Obstruction

contour plot indicates that the grounded obstruction had a strong influence on the radial velocity. On the atomizer side of the obstruction the droplets were accelerated towards the obstruction while on the shielded side the droplets were traveling towards the obstruction.

Comparing the grounded conducting obstruction case to the unobstructed case it was noted that the charged droplet spray pattern was strongly dependent on the electrical boundary conditions. This was indicative of the influence of the electromagnetic field on the resulting spray pattern. Since the charged droplets travel along the electric field lines any disruption to the electric field affects the spray pattern. This property of charged droplet sprays could be used in their design and application to optimize the spray pattern.
9.6.3 Characterization of a Charged Droplet Spray in the Presence of a Non-Conducting Obstruction

The electrical boundary conditions were modified from the previous experiment by replacing the grounded conducting obstruction with a non-conducting (plexi-glass) obstruction. The non-conducting obstruction was placed 75 mm from the Spray Triode®. The size and location of the obstruction is outlined in Table 9-1. Figure 9-12 contains the planar scaled velocity field for the non-conducting obstruction case. The bold vertical line in the Figure indicates the location of the non-conducting obstruction. From Figure 9-12 it can be seen that the non-grounded obstruction caused the charged droplets to be repelled near the obstruction. This was in contrast to the conducting obstruction where
the droplets were attracted to the obstruction. Examination of the velocity field near the obstruction reveals the droplets were actually driven away from the obstruction. Since the obstruction was non-conducting the charge was allowed to build-up on the surface thus repelling the droplets from the surface. Near the upper portion of the obstruction, on the atomizer side, the vector field is nearly vertically upward indicating the droplets were being driven upward away from the obstruction. The velocity field near the center of the obstruction was almost stagnant in the plane illuminated. The stagnation was attributed to the local electrical boundary conditions where the droplets were in electrostatic equilibrium. On the shielded side of the obstruction it can be seen that there was no wrap around effect as observed in the grounded obstruction case. There was no short-circuit to
ground in this case near the obstruction thus eliminating the spray’s ability to wrap around the obstruction.

Figure 9-13 shows the scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled axial velocity component (V/V_m). The contour plot shows the maximum velocity was contained in the core of the jet and was accelerated with increasing axial distance. Left of the atomizer centerline, the droplet spray pattern closely resembles that of the unobstructed case. However, on the right side of the centerline the spray indicates a strong dependence on the electrical boundary condition. The resulting velocity field near the obstruction is further evidence of the electrical driving force that governs charged droplet sprays. The contour plot shows that
on the shielded side of the obstruction there were few droplets contained in this region. Near the end of the contour plot on the atomizer side there was a region of interaction between the droplets near the obstruction and the freestream droplets near the atomizer centerline. The non-conducting obstruction created a bottleneck near the end where the freestream droplets were being driven away from the centerline but the droplets along the obstruction were being repelled in the opposite direction towards the centerline. This interaction between the two competing electric fields served to create a region of deceleration of the charged droplets.

Figure 9-14 shows the scaled mean spray-droplet velocity vector field superposed on a color-flooded contour plot of the scaled radial velocity component (U/Vm). Evidence of the dependence of the charged droplet spray on the electrical boundary conditions is further shown in the radial velocity contour plot. On the atomizer side near the obstruction, the radial velocities were approximately zero. This is indicative of the repulsive nature of the non-conducting obstruction.

Comparing the non-conducting obstruction case to the conducting case it was evident that the charged droplet spray was strongly dependent on the electrical boundary conditions near the atomizer. The non-conducting obstruction disrupted the droplet dispersion setting up an electrical obstruction as well as a physical obstruction. The charge was allowed to build up on the surface of the obstruction resulting in a strong electrical boundary. This electrical boundary resulted in the repulsion of the droplets emanating from the atomizer. A stagnation region was identified in this case that was not observed in the grounded obstruction case. The stagnation region was attributed to the local electrical boundary conditions that resulted in electrostatic equilibrium of the
droplets. Also identified in the non-conducting case was the bottleneck in the velocity field created by the end effect of the obstruction.

9.7 Summary

Experiments have been conducted to characterize electrostatically charged droplet spray fields and the effects of various electrical boundary conditions near the electrostatic atomizer. PIV measurements were conducted for data acquisition and post processing of the PIV data was performed with “in house” data processing programs. Results reveal the dependence of charged droplet sprays on the electrical boundary conditions near the atomizer exit. Charged droplets have been shown to wrap around grounded conducting obstructions and sustain counter gravity motion. In all cases the droplets exhibit counter
gravity flow. This was attributed to the strong electromagnetic fields created within the testing facility. It was the electric fields that provided the driving potential to force the droplets in counter gravity motion. The results reported herein provide additional evidence to the results reported by Kelly (1994) where he reported that charged droplet sprays cannot be described by conventional aerodynamic and gravitational mechanics that govern conventional sprays.

The results presented herein are useful in the design of electrostatic applications. Whether the applications are paint spraying, fire suppression, agricultural spraying, etc. the electrostatic atomizer can be used to supply charged droplets to areas that are inaccessible to conventional atomizers.
CHAPTER 10 RESEARCH SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

10.1 Summary

10.1.1 Part I Summary

A twin-fluid water mist fire suppression atomizer was successfully designed developed and tested. The objective of this Part of the study was to develop a water mist fire suppression atomizer that met the requirements of NFPA 750 and was effective in suppressing Class B fires. Also as part of the objective was to fully characterize the sprays throughout the development of the atomizer.

Phase I of the investigation began with the design and development of the atomizer. Design of the atomizer began by defining design objectives for the atomizer. Outlined in the design objectives was the atomizer’s ability to produce a large droplet distribution, maximize the liquid flow rate while minimizing the gas flow rate, and produce a sufficient cone angle to be effective in fire suppression applications. Initially, problems with internal two-phase flow and spray instabilities slowed the development of the atomizer. It was discovered that the instabilities in the atomizer were two fold. First the gas injector geometry was not conducive to stable flow. Secondly, the mixing volume inside the atomizer was too large. The gas injector geometry problem was addressed by designing and constructing a conical injector based on Chin and Lefebvre’s (1993) injector. Designing and constructing an atomizer by which the mixing volume could be varied while in operation solved the mixing volume problem. This gave the atomizer the ability to optimize the spray characteristics for a given set of flow conditions.
One and two-component Phase-Doppler Particle Analysis (PDA) water spray experiments were next conducted in Phase II to characterize the sprays produced by the developed atomizer and atomizer/nozzle combinations. Five different atomizer nozzles were designed and constructed each designed to produce different sprays with varying cone angles. Characterization of the single-hole orifice atomizer utilized a one-component PDA system to measure droplet diameters and mean velocities. The measurements revealed the atomizer’s ability to produce a spray with a large droplet and velocity distribution. Also, reported was the region of large droplet diameters and high velocity was concentrated near the atomizer centerline. However, the single-hole orifice did not produce sufficient water flow rates and spray cone angles to be considered for fire suppression applications.

Phase II consisted of the characterization of the multi-hole nozzles utilizing a two-component PDA system to measure droplet diameters and mean velocities. Four different multi-hole nozzle geometries were used to study the effects of nozzle geometry on the spray produced. Results indicated that nozzle Cone-4B produced on average the smallest SMD droplets. However, Cone-4B1 performed similarly and from visual observation produce a higher quality atomization. Nozzles Cone-5A and 5B performed poorly. Their atomization quality was much less than that of 4B and 4B1 evidenced by the large droplets in the radial profiles reported. All the nozzles demonstrated that strong dependence of droplet momentum on radial position. Also, all nozzles showed some asymmetry from both radial profiles reported. The asymmetry was attributed to the nozzle construction and non-uniform internal two-phase flow.
The spray characterization requirements of NFPA 750 were satisfied in Phase III of the study. All of the sprays produced by the LSU developed atomizer were deemed a water mist per the definition outlined in NFPA 750. The effects of atomizing gas density were studied in this Phase of the study. It was reported that the gas density did not sufficiently affect the droplet diameters produced. However, since the gas volume flow rates were matched for each flow condition the atomizing gas did affect the stability of the spray. The data shows that when CO₂ and N₂ were used as the atomizing gases the D₀.₉ diameters decreased or remained relatively uniform with decreasing GLR. When He was used as the atomizing gas the data suggest the D₀.₉ diameters increased with decreasing GLR. The results reported for Phase III indicated the atomizer’s ability to produce large droplet diameter and velocity distributions which was outlined as a design objective in the developmental stage.

Full-scale fire suppression performance tests were performed in Phase IV. The atomizers developed in Phases I-III were used in full-scale Class B fires. Also, a commercially available Grinnell AquaMIST AM10 single fluid atomizer was used as a baseline comparison. Results from the experiments indicated that the LSU developed atomizer performed similarly in all Case as the AM10 atomizer. Three modes of extinguishment were identified that played key roles in the suppression of the Class B fires: fire blow out, space cooling (oxygen displacement), and fuel cooling.

10.1.2 Part II Summary

Particle Image Velocimetry (PIV) measurements were conducted to characterize the charged droplet spray emanating from an electrostatic atomizer. The purpose of this Part of the study was to examine the effects of varying electrical boundary conditions on
the resulting charged droplet spray. Instantaneous droplet velocities were measured by capturing two successive images and using cross-correlation to calculate the droplet speed and direction of movement.

The PIV velocity fields have proven the charged droplets’ ability to sustain counter gravity motion. Charged droplet sprays were proven to be independent of gravitational forces rather they are governed by electromagnetic forces. When a grounded conducting obstruction was placed near the atomizer the charged spray was shown to be accelerated towards the obstruction on the atomizer side of the obstruction. On the shielded side of the obstruction the velocity field indicated the charged droplets’ ability to wrap around the obstruction and impact it on the other side.

When a non-conducting obstruction was placed in the flow field the charged spray was repelled by the obstruction due to the build-up of charge on the surface of the obstruction. In this case the spray did not exhibit the wrap around effect reported in the conducting obstruction case.

10.2 Recommendations for Future Work

The spray characterization experiments conducted in Part I of this study were for the most part qualitative in nature. To fully characterize the sprays produced by the LSU developed atomizer it will be necessary to conduct PDA measurements over a larger range of GLRs. This data will be useful in fully describing the behavior of sprays produced by twin-fluid atomizers designed for applications in fire suppression. Also, a computational analysis of the internal two-phase flow within the atomizer will be useful in understanding the atomizing mechanisms involved in water mist atomization.
It is apparent from our experiments that there was no evident relationship between GLR and SMD as suggested by the literature for sprays used in spray combustion applications. For quantitative information, it will be necessary to perform PDPA measurements over a large range of GLRs to gain an understanding of the GLR/SMD relationship with the multi-hole nozzles.

From the results reported herein, it is apparent that water mist is effective in suppressing Class B fires. However to further understand the water mist/fire interaction it will be necessary to obtain data for many more fire scenarios. Examples of other fire scenarios include but are not limited to: varying spray flux densities, varying atomizer to fire height, increased and decreased fire power, ventilation effects on fire suppression, etc. Of primary interest is the effects of water mist on other class fires, i.e., Class A and C fires. Also, to be considered is the gas species analysis in the water mist applications.

The PIV techniques employed in this study for the charged droplet characterization are only applicable for two-dimensional flow. To extend this technique it will be necessary to implement another camera and laser sheet to perform three-dimensional PIV measurements. This would be useful in fully characterizing the velocity field of charged droplets with varying electrical boundary conditions. Also of interest are different obstruction configurations and understanding the relationship of the wrap around effect to obstruction orientation.

Of primary interest is extending the application of charged droplet sprays. The use of charged droplet sprays in water mist applications is of paramount importance because of the charged droplets ability to arrive at spaces that are inaccessible to conventional water sprays.
REFERENCES


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Figure A-27 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray at 20 in. Below the Nozzle, X-Axis Scan, Cone-5B
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Figure A-29 Nozzle Cone-4B Radial Profiles of SMD, U, and V Mean Velocities, 20 in. Below The Nozzle

Figure A-30 Nozzle Cone-4B1 Radial Profiles of SMD, U, and V Mean Velocities, 20 in. Below The Nozzle
Figure A-31 Nozzle Cone-5A Radial Profiles of SMD, U, and V Mean Velocities, 20 in. Below The Nozzle

Figure A-32 Nozzle Cone-5B Radial Profiles of SMD, U, and V Mean Velocities, 20 in. Below The Nozzle
Figure A-33 Nozzle Cone-4B Droplet Diameter Distributions at Various Radial Locations, 3.3 ft (1 m) Below The Nozzle

Figure A-34 Nozzle Cone-4B1 Droplet Diameter Distributions at Various Radial Locations, 3.3 ft (1 m) Below The Nozzle
Figure A-35 Nozzle Cone-5A Droplet Diameter Distributions at Various Radial Locations, 3.3 ft (1 m) Below The Nozzle

Figure A-36 Nozzle Cone-5B Droplet Diameter Distributions at Various Radial Locations, 3.3 ft (1 m) Below The Nozzle
Figure A-37 SMD Versus GLR for Phase II Flow Conditions Listed in Table 5-1
B. Phase III, Characterization of a Twin Fluid Atomizer

The following results were obtained as part of Phase III described in Chapter 7.

In the following results the mass flow rates of the atomizing gases were matched as opposed to the volume flow rates in Chapter 7.

Figure B-1 SMD versus GLR for Phase III Experimental Flow Conditions Listed in Table 5-1
Figure B-2 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft (1 m) Below the Nozzle, Cone-4B1
Figure B-3 Droplet Diameter Distributions and Cumulative Volume Curves Along the Radius of the Spray 3.3 ft (1 m) Below the Nozzle, Cone-4B1

Figure B-4 SMD, U-Velocity, and V-Velocity Profiles 3.3 ft Below the Nozzle
Figure B-5 Water Spray Distribution at 3.3 ft Below the Atomizer With the Water Distribution Tray Oriented 90° From That Shown in Figure 7-10
C. Phase IV Full-Scale Fire Tests

Figure C-1 Louisiana State University’s Fire Testing Facility

Figure C-2 Grinnell AquaMist AM10 Atomizer Mounted Inside the Fire Testing Facility
Figure C-3 Human Machine Interface Control Panel Utilized in the Phase IV Fire Suppression Experiments
VITA

Chad Moore was born June 8, 1974 in Jackson, MS. He was raised in Byram, MS where he attended and graduated from Byram High School. He received his Bachelor of Science degree from the University of Southern Mississippi (USM) in Hattiesburg, MS in May 1997. Upon graduating from USM he continued his studies at Louisiana State University in the Department of Mechanical Engineering. He studied as a full-time graduate student for two years before accepting the position of Senior Engineer in Stone & Webster’s Baton Rouge Office. While with Stone & Webster he worked as a design engineer with responsibilities in the design of fossil fueled power plants. Chad is currently employed as a project mechanical engineer with Cooke, Douglass, Farr, Lemons LTD, Architects and Engineers in Jackson, MS.

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