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COMPUTATIONAL MODELING OF FIRE SPRINKLER SPRAY CHARACTERISTICS USING THE FIRE DYNAMICS SIMULATOR

A Major Qualifying Project Report
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Abstract

Large-scale testing is necessary to verify a specific sprinkler's performance in order for the sprinkler to become listed and approved. An example of a sprinkler certification test is an actual density delivered (ADD) test. An ADD test requires the use of a large lab space, lab assistants, and expensive lab equipment. By using computational fluid dynamics, the cost and time of this certification process could be reduced. The goal of this project is to determine how accurately the Fire Dynamics Simulator (FDS) 6 can predict the distribution of water of an automatic fire sprinkler by inputting the manufacturer's specifications and measured characteristics: spray angle, spray offset, initial velocity and droplet size. A sensitivity analysis was completed to document the relative importance of each model input in the FDS 6 simulation. These model inputs were measured through use of Particle Image Velocimetry, digital images of spray, and historical data. The FDS 6 output of water flux distribution was compared to experimental results of a bucket test. Future testing should include more accurate and simpler methods for obtaining the model inputs as well as a larger sample size of different fire sprinklers.

1.0 Introduction

The purpose of this project is to determine how accurately the Fire Dynamics Simulator (FDS) 6 can predict the distribution of water of an automatic fire sprinkler by inputting the manufacturer's specifications and measured characteristics: spray angle, spray offset, initial velocity and droplet size. By using computational fluid dynamics the process of measuring water flux distributions can be more efficient. Testing in a laboratory can become very expensive and an alternative way to test these sprinklers is needed. An upright extended coverage k-25.2 sprinkler and a k5.6 pendant standard coverage sprinkler were selected for observation. Experimental data for the model inputs were found at Underwriter's Laboratories in Northbrook, Illinois as well as at Tyco in Cranston, Rhode Island. After collecting the data needed to input into FDS and gathering the manufacturer's data on the specific sprinkler, FDS testing was conducted. The water flux distributions produced by FDS were compared to experimental bucket tests to measure the accuracy of FDS. A flow rate was calculated over each area underneath the sprinkler using 16 buckets in the experiment and using 16 measuring devices in FDS. Furthermore a sensitivity analysis was completed to gain an understanding of the relative importance to each model input. Each major input was raised and lowered from the true value to observe the fluctuation of water flux distribution. Further research in this area is needed to validate the FDS characterization of a fire sprinkler by including various types and orientations of sprinklers.

2.0 Background

Sprinkler testing is an expensive and time consuming process. By using Fire Dynamics Simulator (FDS), the cost and time of this process for large scale testing can be reduced. However, for FDS to accurately model sprays, the spray characteristics needed to be studied. Dave Sheppard completed his PhD dissertation at Northwestern, with a goal to "measure the sprinkler spray characteristics required as input for computational sprinkler spray models [1]." This project was funded by National Institute of Standard and Technology (NIST) with the intentions of modifying and updating their sprinkler setup [1-2]. Therefore Sheppard wanted to understand which inputs were required and important to replicate a sprinkler test in FDS. Sheppard studied nine pendant and six upright sprinklers with varying k-factors and orifice sizes. To conduct testing Particle Image Velocimetry (PIV) and Phase Doppler Anemometer (PDA) were used to study initial spray characteristics.

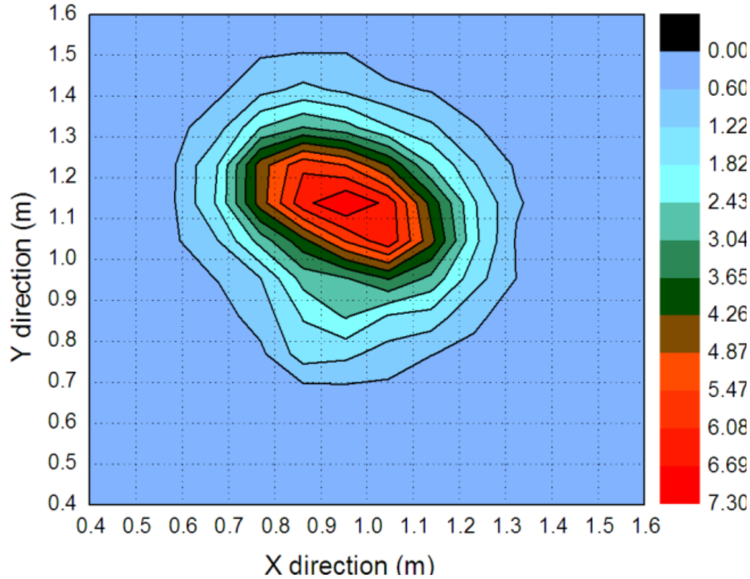
Some of the main findings that Sheppard found were:

- The major characteristics for characterizing a spray were droplet size, droplet velocity, and water flux
- Radial droplet velocity at a distance 0.2m from the sprinkler orifice is 53% of the water velocity through the orifice with a 0.08 standard deviation.
- Radial velocity is dependent on the elevation angle meaning measurements of spray angles are important.
- The median droplet diameter increases with elevation angle and decreases with increasing water pressure.
- Water flux is dependent on elevation angle an azithumal angle

- It is possible to predict water flux distributions from a PIV

These findings help prove that knowing the sprinkler offset distance is important to modeling. Also, elevation angle can affect droplet velocities, water flux, and droplet diameters. Lastly, Sheppard concluded if the initial droplet velocity, droplet direction, number of droplets, and droplet size were known, a water flux distribution could be predicted. Kevin McGrattan at NIST used Sheppard's findings to write a complex detailed file format for inputting sprinkler data such as spray pattern, droplet size, and droplet velocity for FDS 3. This file format is similar to the TABL function in FDS 6, but more complicated. However to create this data file, data from PIV and PDA would need to be used. Before validating this new sprinkler algorithm, it was removed due to the high cost and inconvenience to running tests in order to gather the inputs. The sprinkler model was brought back to what it was in FDS 2 where it was simpler and easier to input values.

A recent study was conducted using the latest version of the computational fluid model, FDS 6 Beta [3]. Recently a Victoria University group in Australia has tried to characterize a water-mist spray using FDS 6[3]. To gather their basic sprinkler inputs, manufacturer data sheets were used. The group then measured outside spray angle by observing a picture and assumed the inside spray angle was zero. Then the DV50 number was found through "a function of nozzle orifice diameter, operating pressure, and geometry." They also assigned the location of the initial velocity at the orifice in FDS instead of the offset. The group did not specify what was used as an offset or if it was even measured. However, since it is a nozzle making mist, the offset will not be very large, which also limits the error of setting the initial velocity at the orifice. Therefore these errors are minor. The output was a water flux density distribution which was compared to the one measured with a bucket test. The result was decently successful.



Figure

1: Contour map of bucket test water flux density distribution in L/m^2 [3]

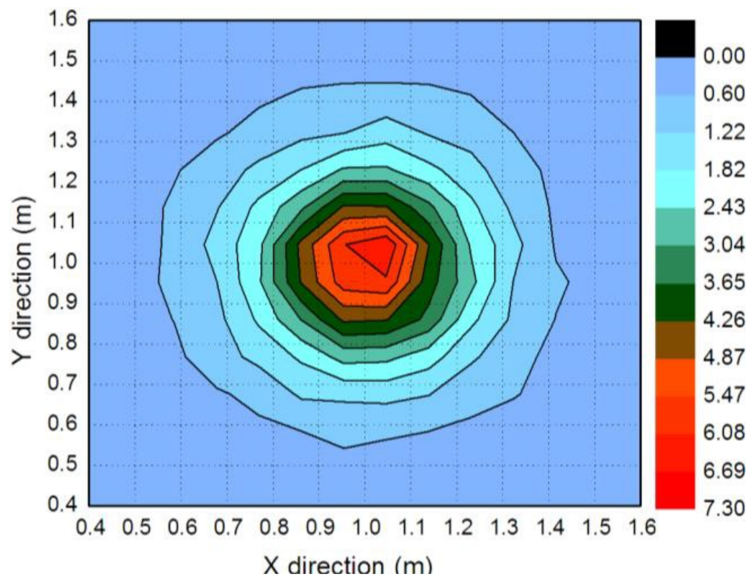


Figure 2: Contour map of FDS water flux density distribution in L/m^2 [3]

As can be observed in figure 2, the bucket test distribution was slightly shifted to the northwest of the contour map. This error was believed to be caused by a draft. Other than this shift and a slight elliptical shape, the two distributions are respectively similar. The studies done by Dave Sheppard and Victoria University are good foundations to build upon for FDS 6 sprinkler testing. As of now, there are no completed studies validating and verifying FDS 6 for automatic fire sprinklers.

The scope of the project was to determine the predictive capability of the FDS 6 sprinkler spray algorithm given a full set of best available input data and to document the relative importance of each model input. To conduct this project a single extended coverage upright k-25.2 sprinkler was analyzed. Research identified droplet size, velocity, spray angle and spray offset as key parameters to classify a fire sprinkler spray distribution. Using Particle Image Velocimetry, Phase Doppler Anemometry, digital images and historical data, these parameters were found. . These parameters were inputted into FDS 6 to predict a spray distribution. This predicted distribution was compared to an experimental bucket test to determine how accurately FDS 6 can predict the distribution of water from a particular fire sprinkler head. A sensitivity analysis was completed to determine the relative importance of each model input.

3.0 Research Plan

To reach the goal of this project, a 10-step research plan was designed:

1. Conduct literature review
2. Document sprinkler spray characteristics
3. Research state-of-the-art measurement techniques
4. Evaluate the physics of FDS 6 spray algorithm
5. Gather manufacturer's data for selected sprinkler head
6. Conduct experiments to measure both spray characteristics of sprinkler head and ADD test
7. Run FDS with full set of best available input data
8. Compare measured ADD to predicted ADD in FDS
9. Determine the relative importance of each model input through a sensitivity analysis
10. Make recommendations leading towards the development of methodology for assembling a minimum set of necessary FDS input parameters useful for predicting for predicting spray characteristics

4.0 Spray Characteristics

4.1 Shape of Spray (Spray Angle)

The shape of the spray patterns of the various sprinklers is shown below in figure 3. Each spray pattern is tailored toward a desired need such as coverage, water-flux, or spray angle. Upright sprinkler heads provides fire protection to the ceiling, where-as a pendent style sprinkler head does not. Early suppression (fast response) sprinkler heads provide increased water-flux over a smaller area.

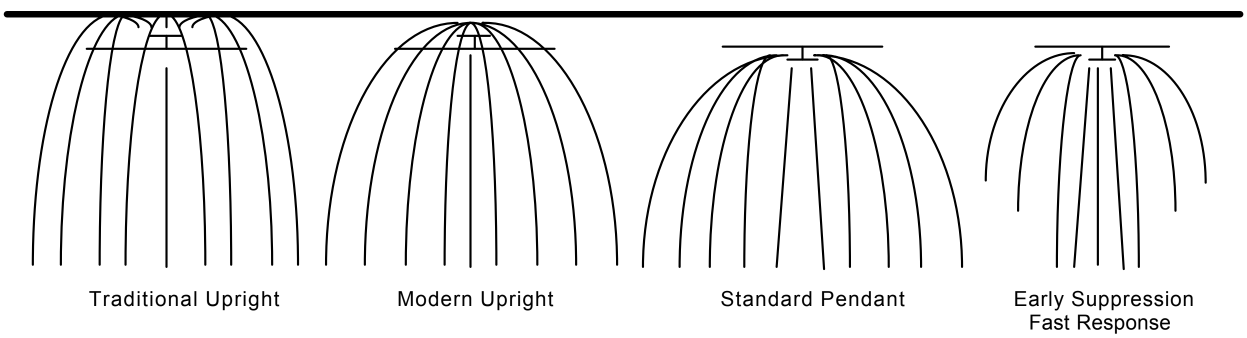


Figure 3: Sprinkler Spray Shapes [1]

A main characteristic of the shape of spray of a sprinkler is the spray angle. There are two different types of spray angles. There is an inner spray angle and an outer spray angle. The outer spray angle is the angle of the outer boundaries of the spray. The inner spray angle is the boundary of the area inside the spray where there is no water (figure 4). These spray angles influence the spray distribution of water and governs the coverage. A lower outer spray angle will have a higher water flux over a small area.

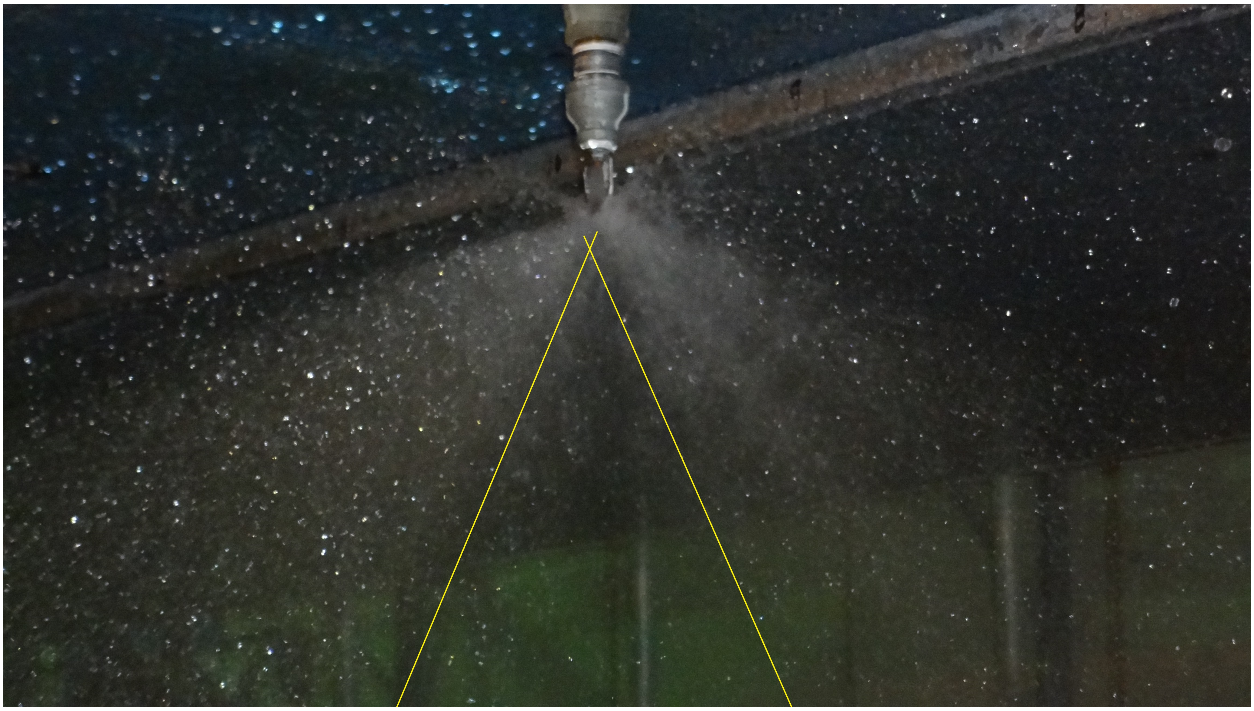


Figure 4: Inner Spray Angle

4.2 Velocity

Droplet Velocity is an important spray characteristic when determining if the sprinkler will be able to extinguish a fire. Fire plumes have an upward velocity, and if the water droplet does not have enough downward vertical velocity and momentum, it will not be able to penetrate the plume and reach the base of the fire. Also the longer it takes the droplet to penetrate the plume, the higher the chance the droplet will evaporate. Since rooms with higher ceiling will have higher fire plumes, the velocity will need to be larger than in a room with lower ceilings. Dave Sheppard in his report on sprinkler spray characteristics was able to find some general drop velocity facts for sprinklers.

Droplet Diameter (m)	Reynolds Number	Terminal Velocity, ($m \cdot s^{-1}$)
1.00E-06	1.89E-06	3.0E-05
1.00E-05	1.89E-03	3.0E-03
1.00E-04	1.57E+00	0.24691
0.001	227.1	3.564
0.002	751	5.89
0.003	1467	7.67
0.004	2336	9.16
0.010	9906	15.54

Table 1: Droplet Diameter vs. Reynolds Number vs. Terminal Velocity [1]

Table 1 shows that the larger the droplet diameter, the higher the terminal velocity, and the higher the Reynolds number. As stated before the Reynolds number shows the effect of air on the droplets. The terminal velocity is an important characteristic to determine if the droplet will end up with enough velocity to penetrate the upward plume velocity.

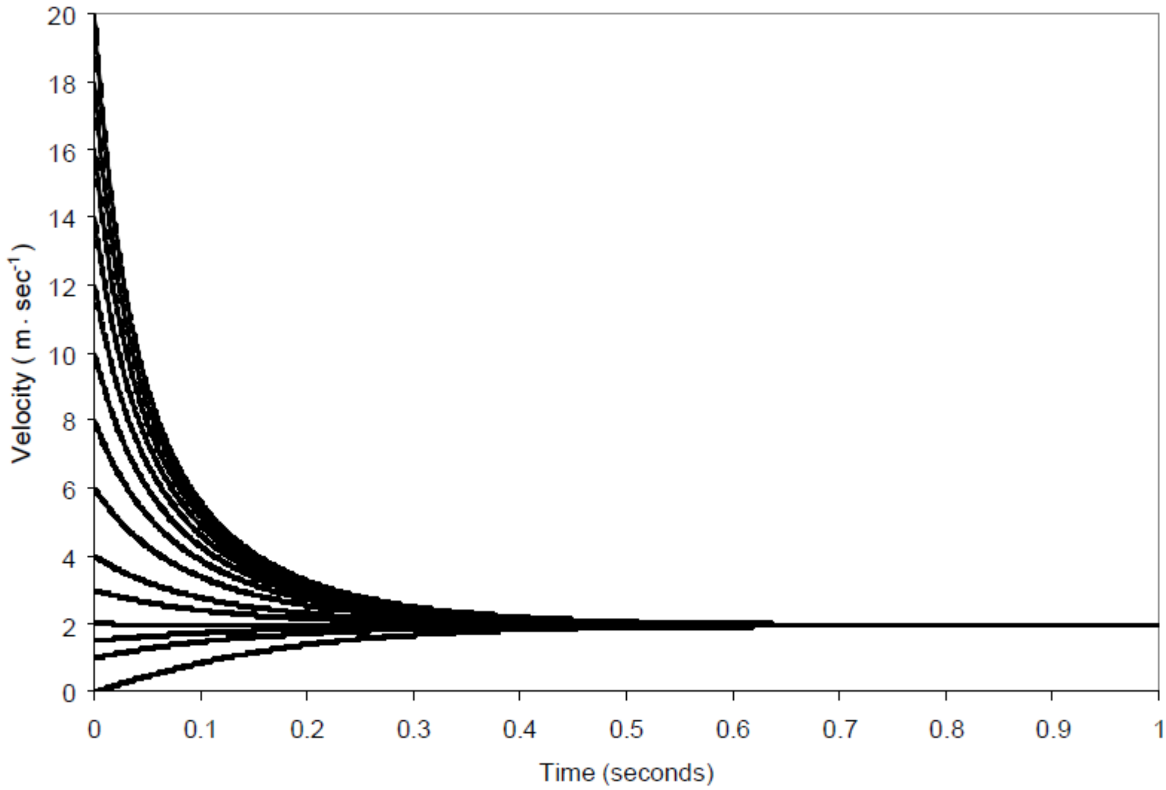


Figure 5: Initial Velocities vs. Terminal Velocity [1]

Figure 5 is another graph compiled by Dave Sheppard. This graph compares droplets of the same size with different initial vertical velocities. From this graph it is seen that the initial vertical velocity does not alter the terminal velocity of the droplet.

	Initial Droplet Velocity					
Droplet Diameter	0.1 m/s	1 m/s	2 m/s	5 m/s	10 m/s	20 m/s
0.000001 m	3.53E-07	3.5E-06	6.96E-06	1.71E-05	3.35E-05	6.47E-05
0.00001 m	3.54E-05	0.000299	0.00057	0.00130	0.00237	0.00414
0.0001 m	0.002378	0.013203	0.0240	0.0512	0.0869	0.140
0.001 m	1.73	1.678333	1.47	1.77	3.43	4.83
0.01 m	13.0	13.9	14.7	16.4	16.2	18.7

Table 2: Vertical Distances [1]

Table 2 above is a table showing the vertical distance it takes for different diameter droplets to reach their terminal velocities at different initial droplet velocities. One finding is that the larger the droplet, the farther the vertical distance to terminal velocity. Another finding is the higher the initial droplet velocity, the farther the vertical distance to terminal velocity. An average ten feet tall ceiling is approximately 3 meters. As you can see in this table a .01m droplet would not reach its terminal velocity in this room. Therefore in a typical 10 feet tall room, a smaller droplet would be more ideal for its cooling properties.

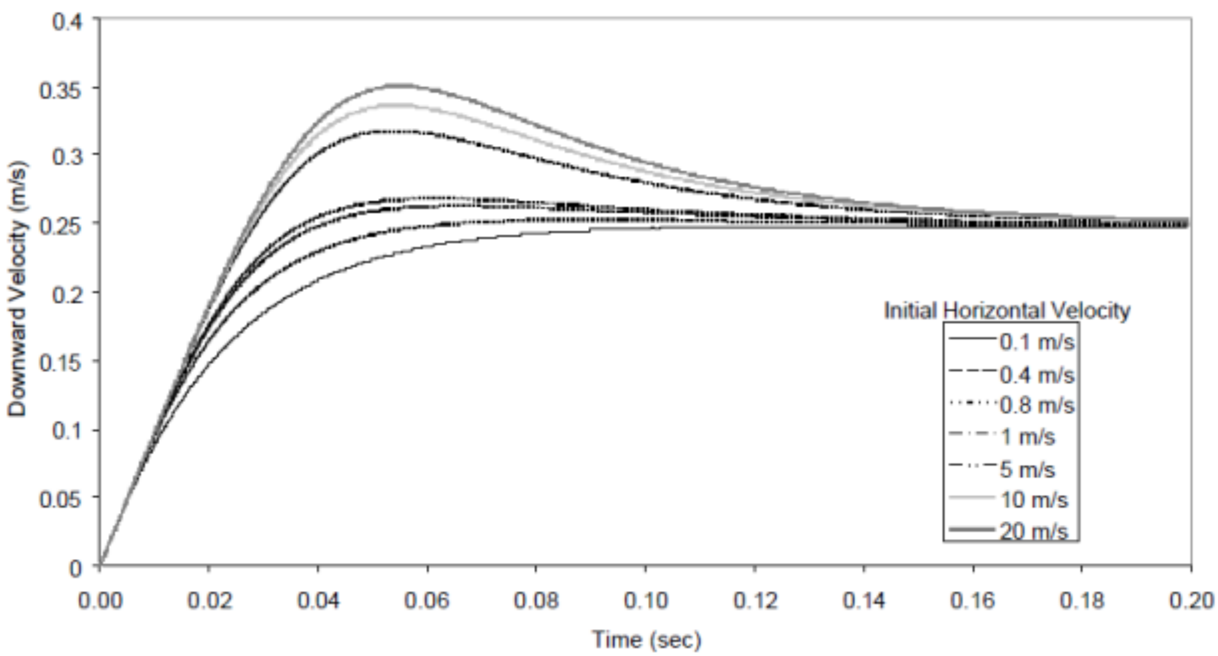


Figure 6: Initial Horizontal Velocity [1]

In figure 6, different initial horizontal velocities are graphed to show how they change downward velocities. The graphs shows that the higher the initial horizontal velocity of the droplets, the higher the absolute maximum velocity of the droplets. However, they all end up with the same terminal velocity. Therefore, initial horizontal velocity does not affect the terminal vertical velocity.

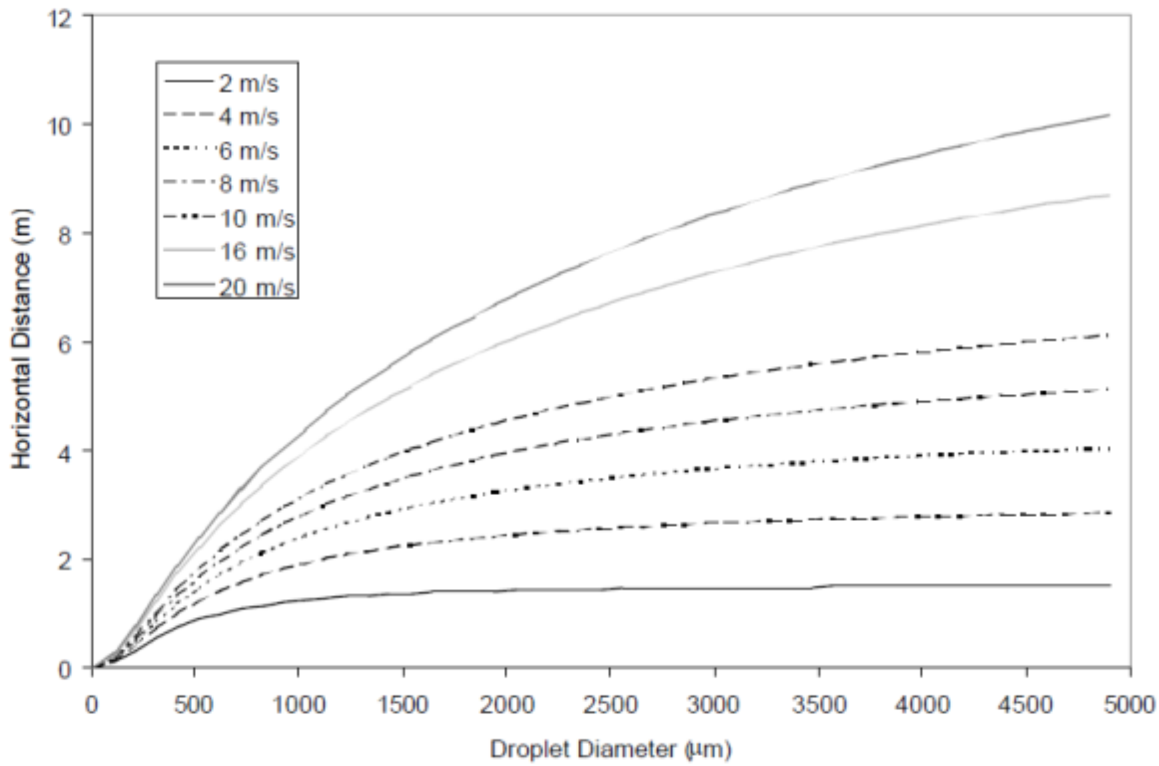
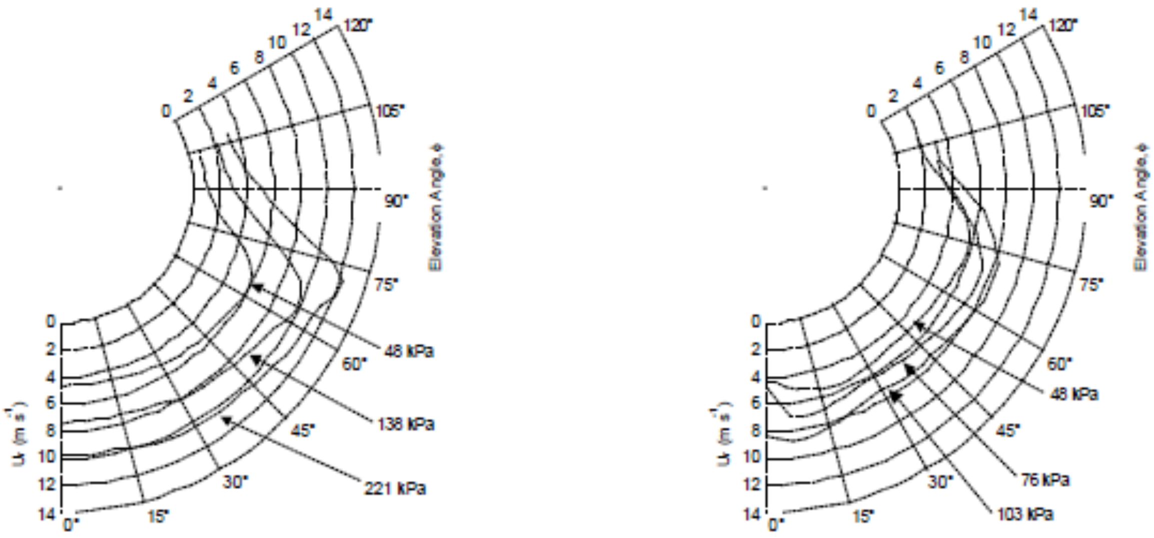


Figure 7: Horizontal Distances [1]

In figure 7, horizontal distances are graphed for water droplets with different initial horizontal velocities. What can be concluded from the graph is that the larger the droplet, the higher the horizontal distance.



P10A U25A

Figure 8: Droplet Velocity vs. Water Pressure [1]

Lastly shown here in figure 8 is pressure versus droplet velocity. The two graphs are representing two different sprinklers. Both the graphs are showing 3 different pressures. By looking at the graphs, it is shown that the higher the pressure the higher the velocity. Also it can be seen that the pressure relatively does not change the velocity distribution as all three lines are generally the same shape and have the same peaks and valleys.

4.3 Droplet Size

A calculated water droplet size is critical while designing a fire sprinkler system to ensure it can effectively pass through the fire plume. As this fire plume continues its upward velocity approaching the ceiling, the emitted water droplets need to penetrate and pass-through this obstacle. A major concern is that the water droplet could evaporate before reaching the base of the fire. A space with a greater fire load typically requires larger droplets depending on the height of the ceiling as well as the fire plume resistance. The water droplet size is determined based on several factors.

First, there is a generally accepted correlation between pressure and water droplet size. Typically higher the pressure the smaller the water droplets are. Pressure provided from the water source may need to be altered to achieve the desired water droplet size.

Second is the deflector of the sprinkler head. The deflector is main differentiating factor in choosing and designing a sprinkler system. Shape of the spray pattern, water-flux, and water droplet size are dependent upon the deflector. The offset is the measure of distance from where the water leaves the sprinkler head out of the orifice to the point where physical and individual water droplets are formed after the atomization process. The deflector plays a key role in the formation of water droplets by changing the water flow from a stream, to water sheets to water droplets.

Lastly, location of the spray refers to the consistency of the water droplets within the boundary of the coverage. There is a great variance of the water droplet distribution within the shape of the spray pattern. Larger water droplet size is capable of greater velocity and farther travel distance from the sprinkler head. An industry standard has been established for general distribution patterns however in the field experimental testing is required to confidentially understand actual distribution compared to expected distribution.

4.4 Water Flux

The final characteristic is water flux of the fire sprinkler. Flux is a measure of volumetric flow rate over the area. This is the amount of water that is discharged beneath the protected sprinkler area. By determining the water flux it is possible to see how much water can be delivered to the fire in order to extinguish it. The distribution of fluxes changes dramatically when pressure is fluctuating. There is not a consistent water flux below the sprinkler coverage.

For example the water flux at the outer limits of the spray could be higher or lower than the flux below the sprinkler depending on the type of sprinkler and pressure.

4.5 Spray Offset

Spray offset is a distance away from the sprinkler head in which atomization is complete, forming droplets. Atomization is the process in which water droplets are created (Marshall). There are three stages of atomization. They are sheet formation, sheet breakup, and ligament breakup. The three stages are illustrated in figure 9. The first stage is sheet formation. The sheet formation begins at the stagnation point where the water jet initially hits the deflector. When the water jet collides with the deflector it forms a water sheet. This water sheet stays steady across the deflector, but once the sheet leaves the deflector the second stage called sheet breakup begins. Sheet breakup starts when the water sheet is no longer in contact with the deflector. The sheet becomes unstable flowing through air and waves begin to form. These waves eventually break up into ligaments. This is the beginning of the third stage named ligament breakup. In this stage, waves once again are formed, however, this time they are formed in each individual ligament. These waves cause break up again and form individual water droplets, completing the process.

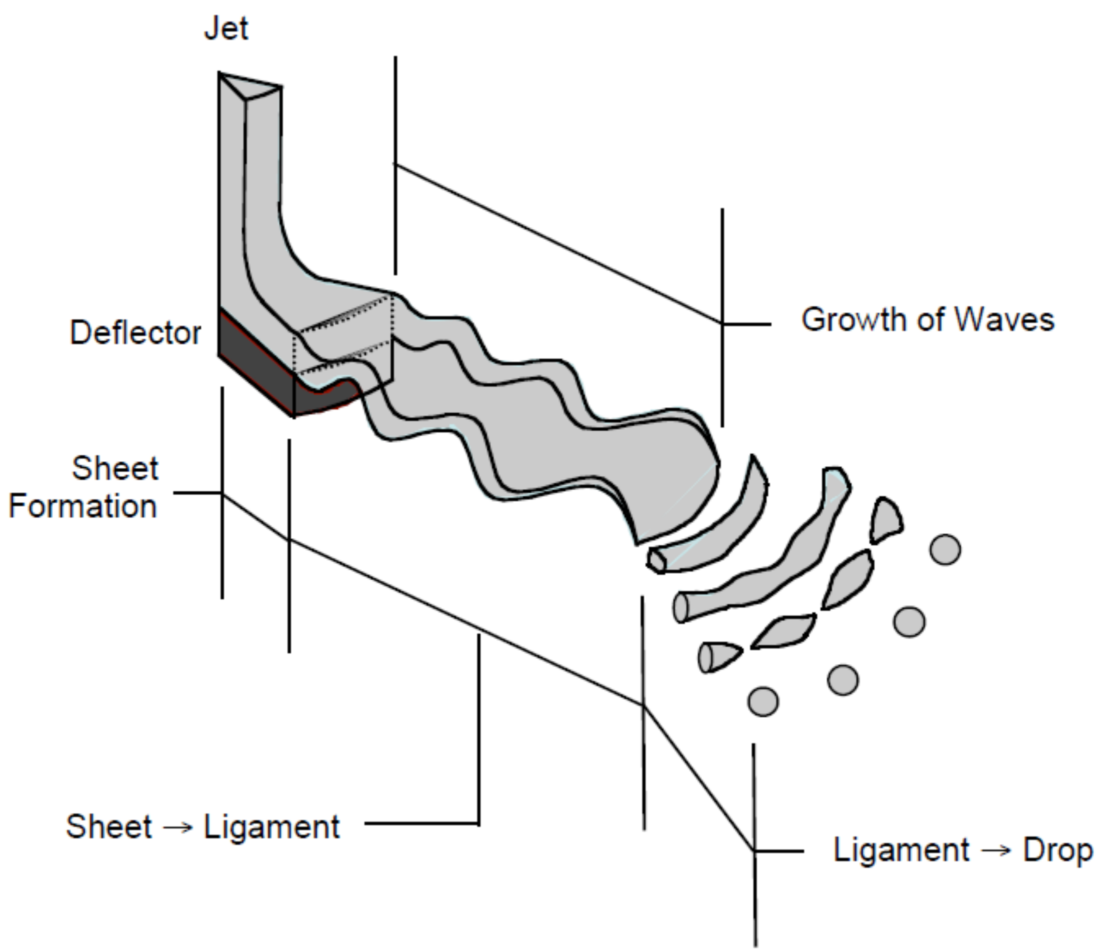


Figure 9: Ligament Breakup (Marshall)

5.0 Measurement Methods

5.1 Particle Image Velocimetry

Particle Imaging Velocimetry is a relatively new technology enabling researchers to understand flow characteristics. This technology is growing especially the last couple years due to advances in technology involved in the process. The PIV setup can be seen in figure 10.

In the majority of particle imaging velocimetry systems, seeding particles are added to the fluid under examination [9]. The type of seeding particle varies depending on what fluid is present. The particles must match the characteristics of the fluid to prevent disturbing the natural flow. When choosing particles, it is important to make the seed small enough to not disrupt the flow, but large enough to be seen and reflect the light. After the seeds have been properly mixed with the fluid or gas, the process can begin. A laser beam is pointed towards a special type of lens, which expands the laser beam into a "light sheet" creating a viewing plane. The light sheet illuminates the particles flowing across the plane. A synchronizer must be used with the laser and the high speed camera. The laser will go off micro seconds before the camera is shot to illuminate the seeds. The laser is then turned off, but the seeds stay illuminated as the camera takes a picture. This is then done a second time immediately after. The less time it takes for these two pictures to be taken, the easier it is to compute the velocity. If the second image is taken immediately after the first image, it is possible to calculate the velocity by measuring the distance over the time lapse. Average velocities of the areas are then calculated and used to develop a velocity vector field (Figure 11), which can then be used to analyze flow patterns and characteristics.

Due to the high cost of PIV systems, many educational facilitates cannot afford to implement a PIV system. There are many different uses for the PIV technology. It is used to analyze any type of flow including but not limited to medical related flows, wind, aerodynamics of air, and the flow of various liquids. A PIV system can also be used to analyze sprinkler spray characteristics.

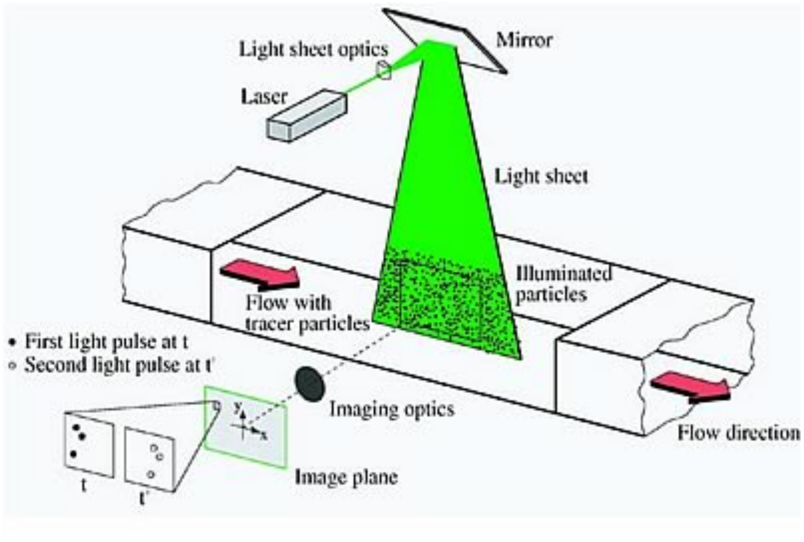


Figure 10- PIV Setup

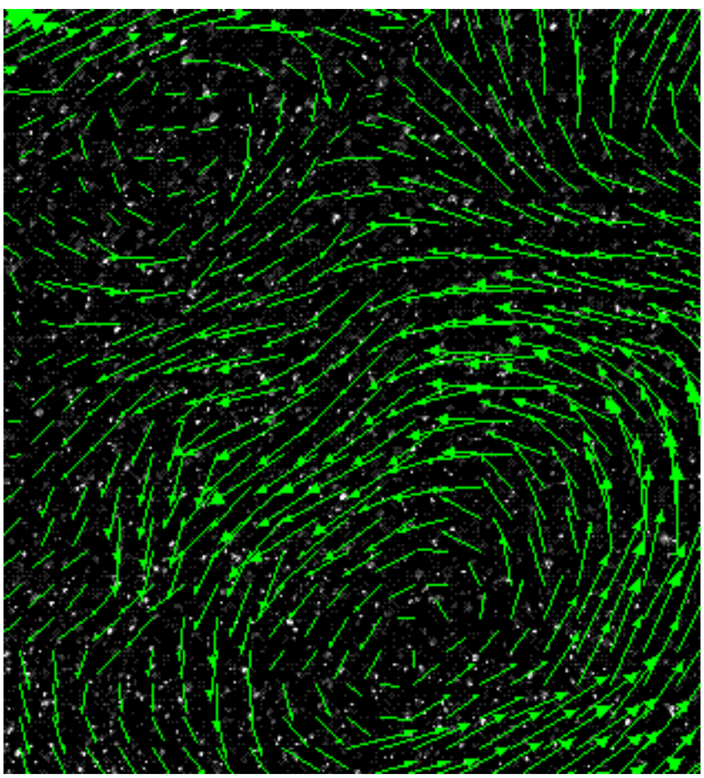


Figure 11- Vector Field [10]

5.2 Phase Doppler Anemometry

Another measurement method is a Phase Doppler Anemometer (PDA). Similar to the PIV, the PDA is another laser based measurement system [14]. As shown in figure 12, it starts with a laser being split in a beam splitter. These lasers are pointed inward and where they cross becomes the control volume. When a particle flows through this control volume it creates a shadow onto the detectors. The detectors then count the number of the pixels of the shadow to calculate the diameter. They also count how long the shadow is there to record individual droplet velocity.

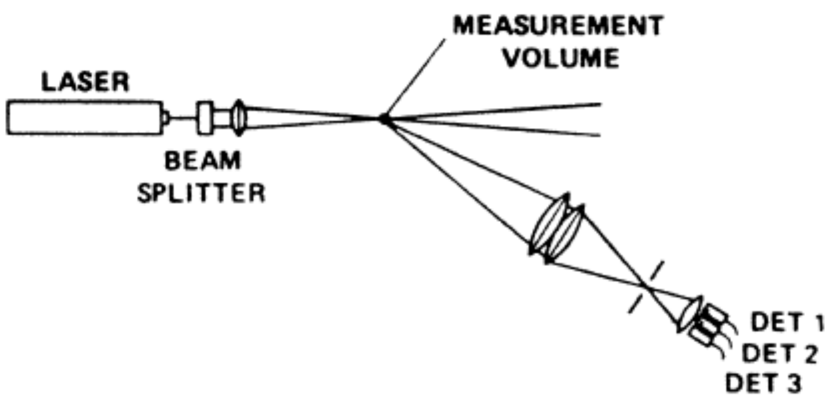


Figure 12: Phase Doppler Anemometer Diagram [14]

Due to having such a small measurement volume, a PDA system is inefficient. It is good at finding average droplet size diameters and velocities at one given point, but to accurately portray a whole sprinkler spray field, it will take a long time since each control volume is small.

5.3 Direct Image Particle Analysis (DIPA)

The last measurement system is Direct Image Particle Analysis (DIPA). DIPA is similar to the PIV system. It also uses a light sheet to illuminate particles and image pairs. After the image pairs are taken the software can then analyze the image pairs. The user inputs the calibration of the images i.e. um/pixel and size of image into the software. The software by conducting a cross analysis between the two images can tell what is a particle and what is not a particle [4]. The number of pixels in the particle is then counted and the size of the particle is outputted. Analysis is then conducted on the output file to determine key characteristics such as DV50 number and flux over a specified area.

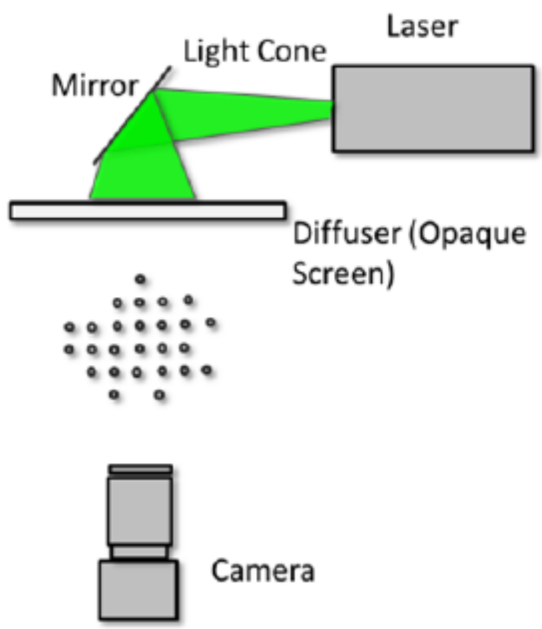


Figure 13: DIPA Setup [4]

6.0 The Fire Dynamics Simulator

6.1 Physics and Underlying Equations in FDS 6

There are many inputs for sprinklers in FDS; however some have a more drastic effect on the modeling outcome than others. According to the Technical Reference Guide [15], there are multiple equations, which govern modeling sprinklers in FDS. First is equation 8.7.

$$\frac{d_m}{D} \propto \mathrm{We}^{-\frac{1}{3}}$$

This equation states that the median droplet diameter is calculated with the orifice diameter (D), and the Weber Number (We). Below is equation 8.8 from the Tech Guide, the Weber Number.

$$\mathrm{We} = \frac{\rho_d u_d^2 D}{\sigma_d}$$

The Weber Number is a function of droplet density (ρd), discharge velocity (ud), and liquid surface tension (σd, 72.8*10^-3 N/m for water at 20 ^{0}C, default). FDS attempts to track changes in pressure and use these changes to the track droplet boundary conditions. Below are equations 8.9, 8.10, and 8.11 that FDS uses for mass flow, droplet speed, and median diameter.

$$\begin{aligned} \dot{m} &\propto \sqrt{p} \\ u_d &\propto \sqrt{p} \\ d_m &\propto p^{-1/3} \end{aligned}$$

These equations mean that the mass flow, discharge velocity and median diameter are proportional to functions of pressure.

6.1.1 Number of Particles

The FDS 6 user guide states that a sprinkler creates more droplets in a second than what FDS can replicate (User Guide, section 14.5.2) [16]. As a result, FDS 6 uses one particle to track the movement of a group of particles. To specify the number of particles that is introduced per second, the PROP line is used:

PARTICLES_PER_SECOND (Default is 5000)

A large number of particles can cause the model to be unstable. However, larger number of droplets can yield more accurate mass flux distributions. Therefore a sensitivity analysis needs to be conducted for particles per second when modeling sprinklers.

6.1.2 Particle Size Distribution

Another parameter to input into FDS is DROPLET DIAMETER. FDS then uses this value to distribute droplet size in one of three different ways. These distributions are listed below:

ROSIN-RAMMLER-LOGNORMAL

The Rosin-Rammler-Lognormal is the default distribution used in FDS 6. Research at FM has suggested that the Cumulative Volume Fraction (CVF) can be represented by using a combination of log-normal and Rosin-Rammler distributions. These relationships can be seen below:

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{[\ln(d'/d_m)]^2}{2\sigma^2}} \, \mathrm{d}d' & (d \le d_m) \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & (d_m < d) \end{cases}$$

In the equation, dm is the mean droplet diameter. Then σ and γ are empirical constants, which are 0.6 and 2.4 by default. When the droplet diameter is less than or equal to the mean droplet diameter, the lognormal distribution is used. When the droplet diameter is greater than the mean diameter, the Rosin-Rammler distribution is used. In FDS 6, the Lognormal and Rosin-Rammler distributions can be used independently to predict the CVF as well.

LOGNORMAL

$$\frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{[\ln(d'/d_m)]^2}{2\sigma^2}} .$$

ROSIN-RAMMLER

$$1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} .$$

6.2 Limitations

One of the known limitations of FDS is the cell size. When setting up an FDS simulation, one needs to keep in mind how many cells to create and the size of each cell. The more cells added, the longer the simulation will take to run. However, more cells do not necessarily mean greater accuracy. When setting up an FDS file, different number of cells needs to be tested. However, when trying to set up precise experiments in FDS, rounding will need to take place. For example, an order of millimeters might not be possible in FDS; therefore the experiment will need to be measured to the nearest centimeter.

Another limitation in FDS is the effect of the deflector. Deflectors vary between different types of sprinklers. An extended coverage sprinkler will have a different deflector than a residential sprinkler. To account for this limitation, FDS sprinkler modeling tries to characterize the spray after it hits the deflector and the spray is formed. FDS sprinkler modeling ignores the beginning stages of the atomization process.

6.3 List of Relevant Inputs and Defaults

There are numerous inputs for sprinklers within FDS. A sprinkler is a device and its properties can be inputted on the &PROP line. A list of the inputs can be found in section 17.20 of the User Guide. More detail on these inputs can be found in section 15.3.1 of the User Guide.

Property/ FDS Function Name	Explanation	Unit used in FDS	Default Value
FLOW_RATE	This can be calculated if K_FACTOR and OPERATING_PRESSURE are provided instead. FLOW_RATE is to be used for liquid droplets. MASS_FLOW_RATE is for solid particle use.	L/min	0
OFFSET	Radius of a sphere surrounding the sprinkler where the water droplets are initially placed in the simulation. Beyond the offset droplets are assumed to be completely broken up.	m	0.05
PARTICLE_VELOCITY	Initial particle velocity	m/s	0
ORIFICE_DIAMETER	Diameter of the nozzle orifice. This parameter coupled with FLOW_RATE can be used to calculate the droplet velocity by taking their product. However, PARTICLE_VELOCITY must be fined tuned to reproduce a particle spray profile. This parameter is NOT used if PARTICLE_VELOCITY or SPRAY_PATTERN_TABLE is specified.	m	0
SPRAY_ANGLE	A pair of angles that outline the conical spray pattern. 0 degrees is the direction of sprinkler orientation. If the sprinkler is on the ceiling shooting down. Zero degrees is then facing down.	Degrees	60,75
DIAMETER	The mean diameter of the spray distribution	µm	500
K_FACTOR	The K Factor of the experimental sprinkler	L/min/bar^.5	1
OPERATING_PRESSURE	The pressure used in the experiment	Bar	1

Table 3: FDS Inputs

7.0 Characterization of Upright Extended Coverage k-25.2 Fire Sprinkler

7.1 Manufacturer's Data

Manufacturer Data	Value	Units
K-Factor	25.2	Gpm/psi^.5
Orientation	Upright	
Orifice Diameter	.027	meters

Table 4: k-25.2 Manufacturer's Data

7.2 Underwriter's Laboratories Experiments

The initial phase of data collection was conducted the week of January 28, 2013 at Underwriter Laboratories in Northbrook, IL. A single k-25.2 extended coverage upright sprinkler was studied. All data obtained relating to the sprinkler was from the manufacturers specification sheet. The three days in the lab included calibration and use of the DIPA technology as well as PIV analysis. Prior to running the DIPA tests, measurements of the room and the sprinkler location were documented. These measurements were taken by a tape measure and recorded into datasheets.

7.2.1 Sprinkler Setup

The sprinkler used was a k-25.2 extended coverage upright sprinkler. The sprinkler deflector to the ceiling distance was 3 inches. The floor to the deflector ceiling was 10 feet. The sprinkler was mounted on a 2.5 inch branch line. The ceiling was 97 inches by 97 inches and rotates with the sprinkler. The setup rotates on a circular traverse while the camera and laser states stationary. The setup is not fixed and was observed to be swaying. For the sprinkler tested, a flow rate of 87 gpm was used.

7.2.2 PIV Setup

Prior to the group's arrival to Underwriters Laboratories, the PIV testing for the k-25.2 sprinkler was completed. The experiment was conducted in UL's sprinkler research lab using their circular traverse setup. Measurements were taken from angle 5 degrees to 87.5 degrees at every 2.5 degrees totaling in measurements at 34 different angles. Measurements could not be made at 0 degrees because the rotating pipe assembly blocks the camera. Measurements at 90 degrees could also not be taken because the rotating pipe assembly blocks the laser sheet. For each angle 150 image pairs were taken. The camera took each image 150 µs apart. The images were calibrated at 5 degrees, 15 degrees, 30 degrees, 45 degrees, 60 degrees, and 75 degrees. Then using the Insight 3g software, all 150 image pairs were analyzed to produce a velocity vector map and an excel output file. Each vector was outputted with x,y coordinates and velocity in x and y direction.

7.2.3 DIPA Setup

The group was able to observe and conduct the DIPA experiment during their trip. The experiment was completed in UL's sprinkler research lab using their circular traverse setup. Measurements were taken from angle 5 degrees to 87.5 degrees at every 2.5 degrees totaling in 34 angles. Measurements could not be made at 0 degrees because the rotating pipe assembly blocks the camera. Measurements at 90 degrees could also not be taken because the rotating pipe assembly blocks the laser sheet. For each angle 150 image pairs were taken. The camera takes each image 150 µs apart. The images were calibrated at 5 degrees, 15 degrees, 30 degrees, 45 degrees, 60 degrees, and 75 degrees. 4 different image sets were taken. There was one with an origin at 0, 0 (at the sprinkler), 8, 0(8 inches to the right of the sprinkler), 0, 8(8 inches below the sprinkler) and 8, 8(8 inches below and 8 inches to the right of the sprinkler). During the group's time, only data for (8, 0) was analyzed at 15 degrees. Using the insight 3g software, all 150 image pairs were analyzed to measured droplet size data.

7.3 Measured Model Inputs

7.3.1 Spray Angle

There are two different spray angles that are needed in FDS 6. There is an outside spray angle and an inside spray angle. To find the outer spray angle eight pictures were taken using a Sony DSC-WX80 16.2mp digital camera. Four images were taken at an azuthumal angle of 0 and the other four at 90. The viewpoint that the camera is focused at will be from the ceiling including the sprinkler down to the middle of the spray. Then by analyzing the picture, the spray angle was measured by drawing two tangential lines to the initial spray shape as seen in figure 14 below. A protractor was then used to calculate the angle. The second set of images were the images taken using the PIV. Since these images are only the right side of the spray, the angle is measured slightly different. The angle is measure between directly under the sprinkler up to the line drawn tangential to the spray. This angle is then doubled since the spray is assumed to be symmetrical. The outer spray angle was confirmed by comparing the digital images to the PIV laser images.

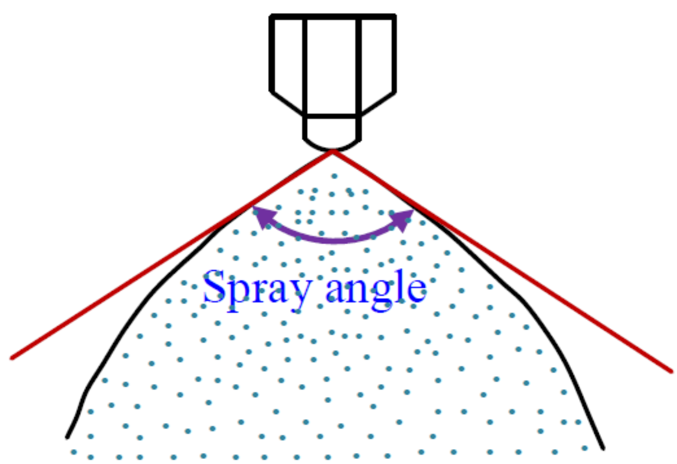


Figure 14: Outside Spray Angle [3]

Once the 8 images were analyzed, the 8 spray angles were averaged to find the final average outer spray angle. The inside spray angle was measured by analyzing the PIV laser images. At each calibrated angle, the PIV laser image was analyzed to measure the inner spray angle. If there is an inside spray angle visible in the image, it will be measured using protractor, but if there is no visible inside spray angle, the inside spray angle is assumed to be zero.

The average spray angle found from the digital camera images was 150.11 degrees. The PIV laser images were analyzed and an average angle of 147.14 degrees was measured. This resulted in a 2% difference between the digital camera and the PIV images. This small difference means expensive technology is not needed to measure spray angle. All that is needed is a sprinkler set up and a digital camera.

7.3.2 Droplet Size

In FDS 6, particle sizes follow one out of three selected distributions:

- Rosin-Rammler-Lognormal Distribution
- Rosin-Rammler Distribution
- Lognormal Distribution

The default distribution is the Rosin-Rammler-Lognormal distribution. This combination uses two distributions by utilizing the Rosin-Rammler method up until the median volumetric diameter (DV50) where it then switches to the Lognormal distribution when droplets are greater than the median. For FDS to utilize these distributions, the DV50 number needs to be specified. Analysis was conducted with the DIPA data at 15 degrees. Due to time constraints, only a single angle of 15 degrees was analyzed. Since such a small sample size was analyzed and the DIPA technology has not been validated, historical droplet sizes were researched. A former UL test on a similar k-25.2 upright sprinkler found that the mean volumetric diameter was 1161 microns.

Dave Sheppard's dissertation (figure 15) was also consulted where with similar experimental parameters and average of 1126.3 microns was found. Therefore, the 1161 microns found by a UL test was confirmed by the findings of Dave Sheppard.

Sprinkler	Pressure (kPa)	Elevation (degrees)	d_1 (μm)	DV50 (μm)	d_{32} (μm)
P25A	138	0	323	910	2272
P25A	138	10	254	865	1852
P25A	138	30	257	961	1958
P25A	138	60	361	1197	2276
U16B	163	30	322	850	689
U16B	163	60	400	817	694
U16B	163	90	511	751	698
U16B	198	30	313	814	662
U16B	198	60	370	726	624
U16B	198	90	494	696	647
U16B	232	30	300	744	622
U16B	232	60	358	697	598
U16B	232	90	483	699	654
U25A	89	30	355	1057	853
U25A	89	60	475	1155	938
U25A	89	90	795	1167	1055
U25A	123	30	331	950	767
U25A	123	60	388	1056	822
U25A	123	90	727	1117	1018
U25A	158	30	280	829	659
U25A	158	60	337	975	750
U25A	158	90	652	1000	918

Figure 15 - Dave Sheppard's Droplet Size Analysis

7.3.3 Spray Offset

In FDS 6, droplets start at a defined distance away from the sprinkler. This is to prevent all of the droplets from coming out of the same computational cell. This offset is measured where the atomization process enters its final stage, droplet formation. From Dave Sheppard's research, he found that a spray offset of 0.2m was a reasonable assumption for the atomized region. Confirmation of this 0.2m offset was completed by analyzing the PIV laser images at the calibrated angles. This analysis was conducted by drawing a 0.2m radius around the sprinkler to see if the atomization process was complete at the offset. 0.2 meters was drawn on the PIV images to see if it is a reasonable assumption to use. To draw 0.2 meters on the images, a μm/pixel conversion was used. For example at angle 0500, there are 417.83 μm/pixel. Therefore at 0.2 meters, there are 478 pixels. A radius was drawn 478 pixels away from the sprinkler.

After analyzing the PIV images with the 0.2 radius lines drawn on them, it was determined that 0.2 m was a reasonable assumption for the spray offset. By looking at the drawn radius, it was confirmed that this was the same distance where ligaments turned into droplets.

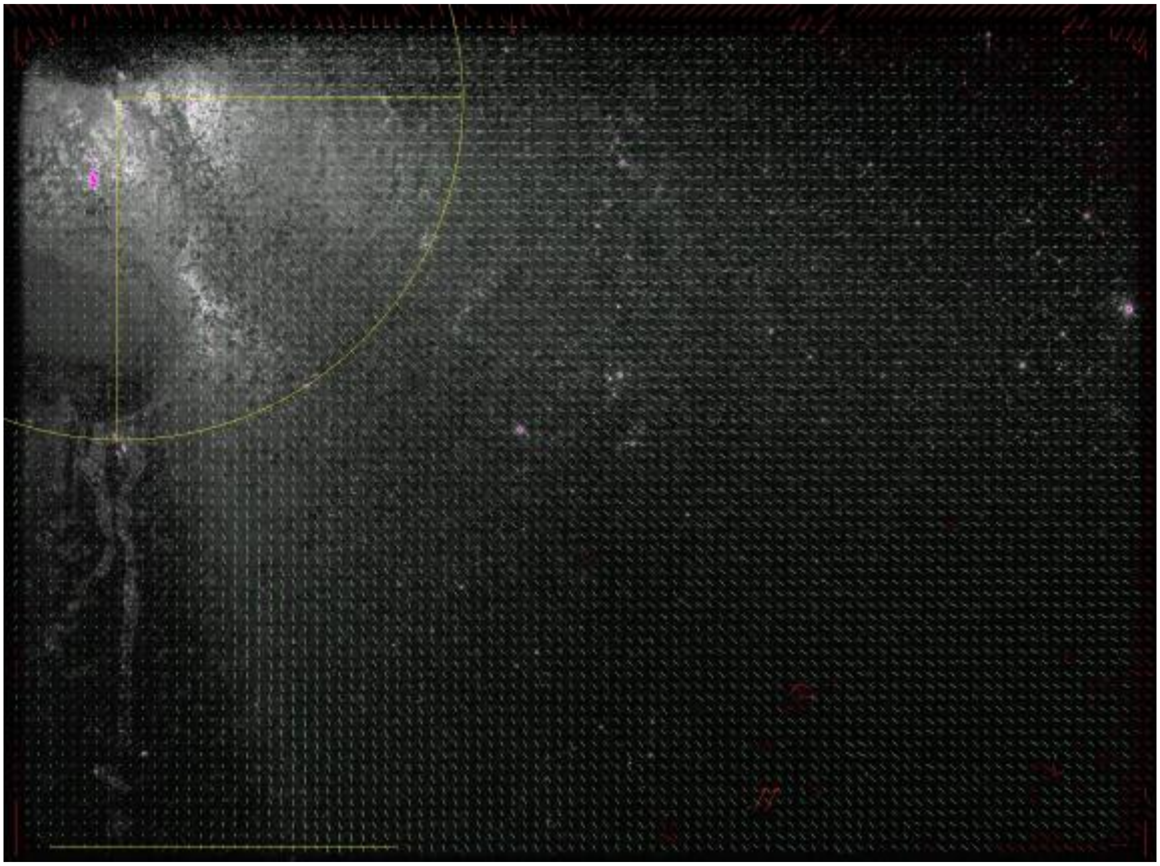


Figure 16: Spray Offset at 15 Degrees

7.3.4 Initial Velocity

It is an assumption when running FDS to use the velocity of the water exiting the orifice for the initial droplet velocity at the offset distance. It is not known if this is accurate or not. However, there is an option in FDS to define this value at the spray offset. Therefore, the PIV was used to measure the droplet velocity at the offset distance. Analysis of the PIV results was conducted at the calibrated angles. To conduct this analysis, velocities at ± 10% of the spray offset were observed.

The droplet velocity at the offset was calculated at distances ranging from .18m to .22m or plus or minus 10% of the measured .2m offset (0.2m ± 10%). These calculated velocities were then analyzed using a radial scatter plot (figure 17). Due to interference from the branch line velocities from 0 degrees to 20 degrees were not included in the calculation of the average velocity. By averaging the velocities from 20 degrees to 90 degrees an average droplet velocity at the 0.2m offset was determined to be 8.65 m/s.

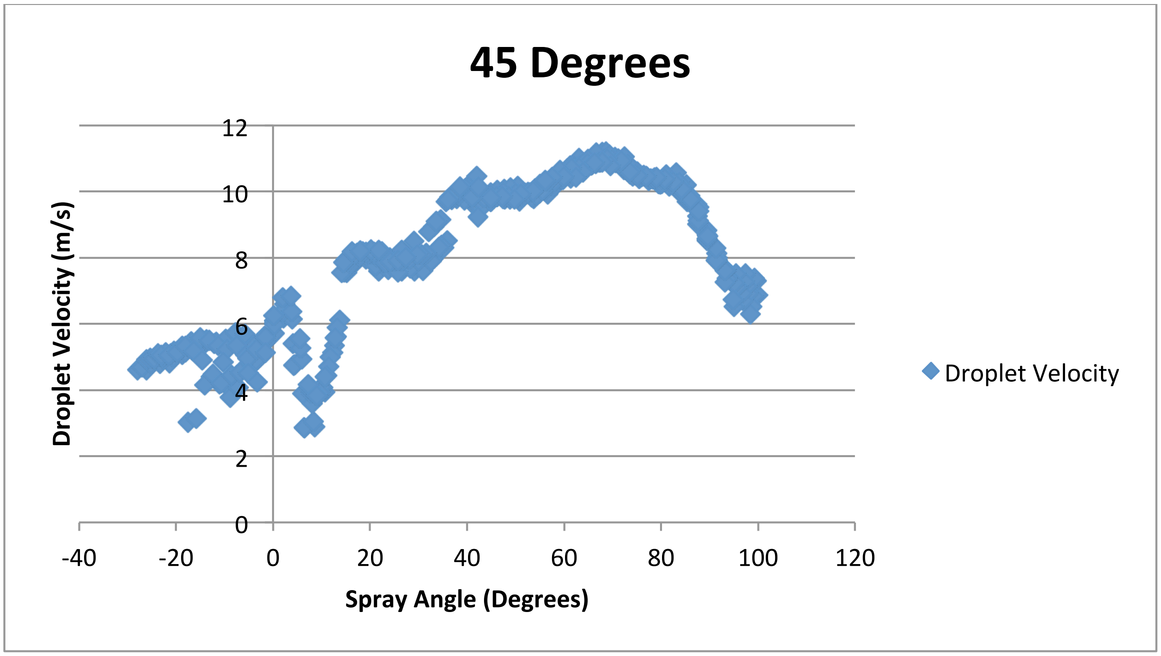


Figure 17: Velocity Radial Scatter Plot

8.0 Characterization of Pendant k5.6 Sprinkler

Manufacturer Data	Value	Units
K-Factor	5.6	Gpm/psi^.5
Orientation	Pendant	
Orifice Diameter	.0127	meters

Table 5: k-5.6 Manufacturer's Data

8.1 Measured Model Inputs

8.1.1 Spray Angle

Spray angle was measured the same for the k5.6 sprinkler as it was in for the k25.2 sprinkler by using a protractor on digital images. To find the outer spray angle, images were taken using a Sony DSC-WX80 16.2mp digital camera during bucket tests conducted at Tyco.

Three angles were found from three images and were averaged. The resulting outer spray angle was 145.25 degrees. To find the inner spray angle, more images were analyzed. The average of three angles resulted in an inner spray angle of 46 degrees.

8.1.2 Droplet Size

Since no tests could be conducted to measure droplet size for the k-5.6 sprinkler, historical data was used. Dave Sheppard measured a k5.6 sprinkler at a pressure of 57kPa (16.1 GPM) for four tests. The average of these four tests results in a DV50 number of 1121 micrometers.

Sprinkler	Pressure (kPa)	Elevation (degrees)	d_1 (µm)	DV50 (µm)	d_{32} (µm)
P10B	130	0	187	252	318
P10B	130	10	198	286	389
P10B	130	30	190	337	565
P10B	130	60	162	439	1250
P10B	196	0	189	255	316
P10B	196	10	202	279	358
P10B	196	30	175	262	365
P10B	196	60	162	350	899
P10B	306	0	192	256	319
P10B	306	10	210	279	338
P10B	306	30	181	254	341
P10B	306	60	177	322	635
P13B	37	0	205	791	1608
P13B	37	10	212	895	2017
P13B	37	30	406	1485	2856
P13B	37	60	721	3393	1915
P13B	57	0	196	733	1570
P13B	57	10	206	1142	5693
P13B	57	30	305	1159	2534
P13B	57	60	573	1450	2888
P13B	88	0	194	688	1561
P13B	88	10	187	613	1431
P13B	88	30	264	1003	2576
P13B	88	60	469	1251	2767

Figure 18: Dave Sheppard's Droplet Size Analysis

8.1.3 Spray Offset

Once again, since offset could not be measured for the k5.6 sprinkler, historical data was used. Sheppard states in his dissertation that of 0.2m was a reasonable assumption for the atomized region. Therefore 0.2 meters was used as the offset distance for the k5.6 sprinkler. There were no PIV data for this sprinkler; therefore the group was no able to check the offset distance.

8.1.4 Initial Velocity

Since no PIV tests were run on the k5.6 sprinkler, velocity could not be measured at the offset. Velocity was then calculated at the orifice using the equation.

$$V = \frac{4Q}{\pi d^2}$$

Where v is velocity, Q is flow rate, and d is orifice diameter. The orifice diameter for the sprinkler was .0127 meters, the flow rate was 15 gallons per minute and the resulting velocity at the orifice was 7.4 meters per second

9.0 Prediction of Actual Delivered Density (ADD) with FDS and Comparison to Measured ADD for K25.2 Sprinkler

9.1 Tyco Experiments

Water flux rather than an input or initial characteristic, is an output in FDS. To validate the experiment and verify the four main inputs, water flux distribution in FDS was used. To measure the flux distribution, a bucket test was used. On February 21, 2013, the project group went to Cranston, Rhode Island to conduct bucket tests of the k-25.2 upright sprinkler at Tyco's Sprinkler Research Lab. The bucket test conducted at Tyco was setup to the dimensions of the ADD test in UL Standard 1767. There were 16 buckets set up below the sprinkler. Each bucket was .5 meters by .5 meters. The buckets were setup up in 4 squares each one meter by one meter.

Each square has a six inch flue space in between. The distance from the top of the buckets to the deflector was three feet. The deflector of the sprinkler was mounted six inches below the ceiling.

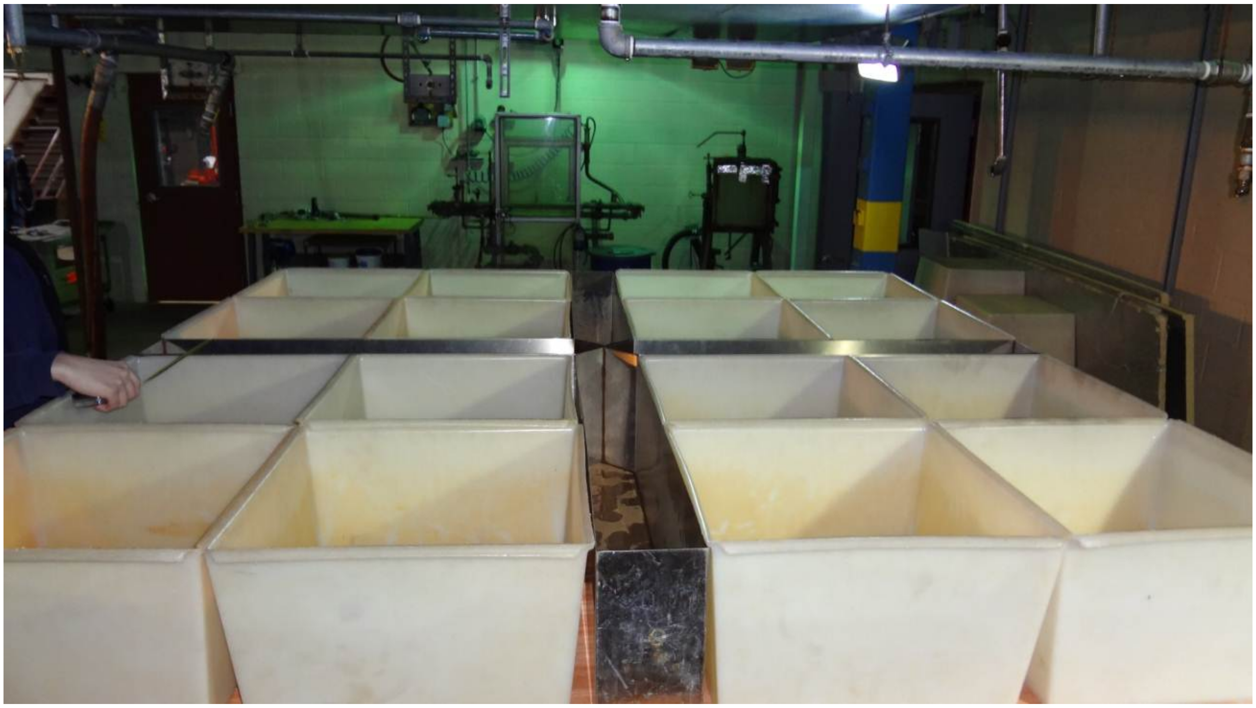


Figure 19: Tyco Bucket Test Setup

9.2 Tyco Bucket Test Collection Data Collection

The group observed and measured the testing setup to confirm the dimensions were the same as UL 1767. Once the dimensions were confirmed, the testing began. Three separate bucket tests were run. The first test was run for 3 minutes 48 seconds. The flow was stopped because the water in the center buckets was about to overflow. The buckets were then measured using a calibrated dipstick and a ruler. The calibrated dipstick was accurate to 2.5 lbs. and the ruler was accurate to .125 inches. The buckets in the center had too much water to be measured by the calibrated dipstick. Therefore water was poured into another bucket and the weights were added. Once the measurements were complete and recorded, the water was dumped into the grated floor, and the buckets were once again setup. For the second test the group decided to aim for 3 minutes of flow to avoid having to pour water out from the center buckets. The second test ran for exactly 3 minutes and the measuring process was conducted again. The third test ran for 3 minutes 1 second.

After conducting the tests, the group was left with two sets of data. There was one set of three tests with the calibrated dipstick and one set of three tests with the ruler. The data from the calibrated dipstick was easier to work with because it was already in pounds. The ruler data needed to be converted from inches into pounds. This was difficult because the buckets were trapezoids. From tape measure measurements it was known that the top of the bucket was 19 inches and the bottom of the bucket was 17 inches. Also, the depth of the bucket was 12.5 inches. From this data, simple geometry was performed to find at a measured depth, what the width of the bucket was. Now that the width and depth were known, the volume could be found. The calculated volume was multiplied by a density of 62.3lb/ft3 to find the weight of the water. The weight was then divided by the amount of time the test was run for to find a flow rate. The units of the flow rate was in lb/s, but since FDS outputs flow rate in kg/s, the group decided to convert to kg/s. The two measurement methods were within 4 % of each other for all of the buckets. The group decided to use the calibrated dipstick results. There was less uncertainty in this measurement method. It was possible to average the three bucket tests since the results of each were similar.

Pan Test Averages from Tyco Trip (kg/s)				
Pan1 0.124	Pan 2 0.142		Pan 3 0.135	Pan 4 0.126
Pan 5 0.084	Pan 6 0.266		Pan 7 0.251	Pan 8 0.085
		Sprinkler		
Pan 9 0.084	Pan 10 0.260		Pan 11 0.238	Pan 12 0.080
Pan 13 0.119	Pan 14 0.139		Pan 15 0.146	Pan 16 0.105

Table 6: Tyco Bucket Test Results

9.3 Sources of Error

The determination of uncertainty was necessary to see how accurate the bucket test measurements were. There are four different sources of error. The first error was due to the ramp up of the flow. The second error was the uncertainty of the dipstick and ruler. The Third error is the fluctuation of flow rate. The last error is droplets on the ceiling. The following is the explanation of the calculations.

9.3.1 Ramp-up time

The ramp-up time it took to get the sprinkler up to the anticipated flow rate (87 gpm), took approximately 22 seconds between the three tests. The flow rate quickly reached a flow rate of above 80 gpm within 2 seconds of startup and took the remaining 20 seconds to slowly reach the 87 gpm. The average time each sprinkler was running for was 196 seconds.

0-2 seconds: 0 gpm -80 gpm (assumed average of 40 gpm over time: 0 -2 seconds)

3-22 seconds: 80 gpm – 87 gpm (assumed average of 83.5 gpm over time: 3 -22 seconds)

(2/24seconds)* (40gpm) + (22/24 seconds) * (83.5gpm) = 79.875 gpm

Therefore the average flow rate during the "ramp-up" process was 79.875 gpm.

Ramp-up: 0 – 22 seconds: 79.875 gpm

Steady-state: 23- 196 seconds: 87 gpm (ideal)

Uncertainty:

$$\frac{\text{Ramp-up time}}{\text{Total time}} * \frac{(\text{Steady-state (gpm)} - \text{Ramp-up (gpm)})}{\text{Steady-state (gpm)}}$$

= (22/196 seconds) * (87 – 79.875)/ 87

= 0.91%

±0.91 %

9.3.2 Measurement techniques

The calibrated dipstick provided by Tyco was made up of 2.5 lb increments spanning from 5lbs to 120lbs. To calculate the uncertainty of measurement errors, an average of 75lbs was used as the base value to cover the majority of the magnitude of measurements captured at Tyco.

$$= \frac{\text{Uncertainty in measurement}}{\text{Base Value}}$$

= 1.25lbs / 75lbs = 1.67%

±1.67 %

9.3.3 Fluctuating flow rate

The flow rate, after reaching steady state at 87 gpm, still continued to fluctuate from measurements of 86.6 gpm to a maximum of 87.5 gpm. A range of 0.9 gpm was seen with the sprinkler at the desired 87 gpm.

Uncertainty:

$$= \frac{\text{Uncertainty in measurement}}{\text{Base Value}}$$

= 0.5gpm / 87gpm = 0.57 %

±0.57%

9.3.4 Ceiling effects

The uncertainty of the ceiling playing a role in affecting the water distribution into the buckets is unknown, so a large percent error was used to account for this factor:

±5%

9.3.5 Total Uncertainty:

= Ramp-up time + measurement techniques + fluctuating flow rate + ceiling effects

= (±0.91%) + (±1.67%) + (±0.57%) + (±5%)

Total Uncertainty:

= ±8.15 %

10.0 Prediction of Actual Delivered Density (ADD) with FDS and Comparison to Measured ADD for k5.6 Sprinkler

10.1 Tyco Experiments

A second water flux distribution comparison was completed to see if a different sprinkler would increase or decrease the predictive capability. To validate the experiment and verify the four main inputs, water flux distribution in FDS was used. To measure the flux distribution, a bucket test was used. On April 12, 2013, the project group went to Cranston, Rhode Island to conduct bucket tests of the k-5.6 pendent sprinkler at Tyco's Sprinkler Research Lab. A similar bucket test setup was used as the k-25.2 sprinkler. There were 16 buckets set up below the sprinkler. Each bucket was .5 meters by .5 meters. The buckets were setup up in 4 squares each one meter by one meter. Each square has a six inch flue space in between. The distance from the top of the buckets to the deflector was three feet. The deflector of the sprinkler was mounted six inches below the ceiling.

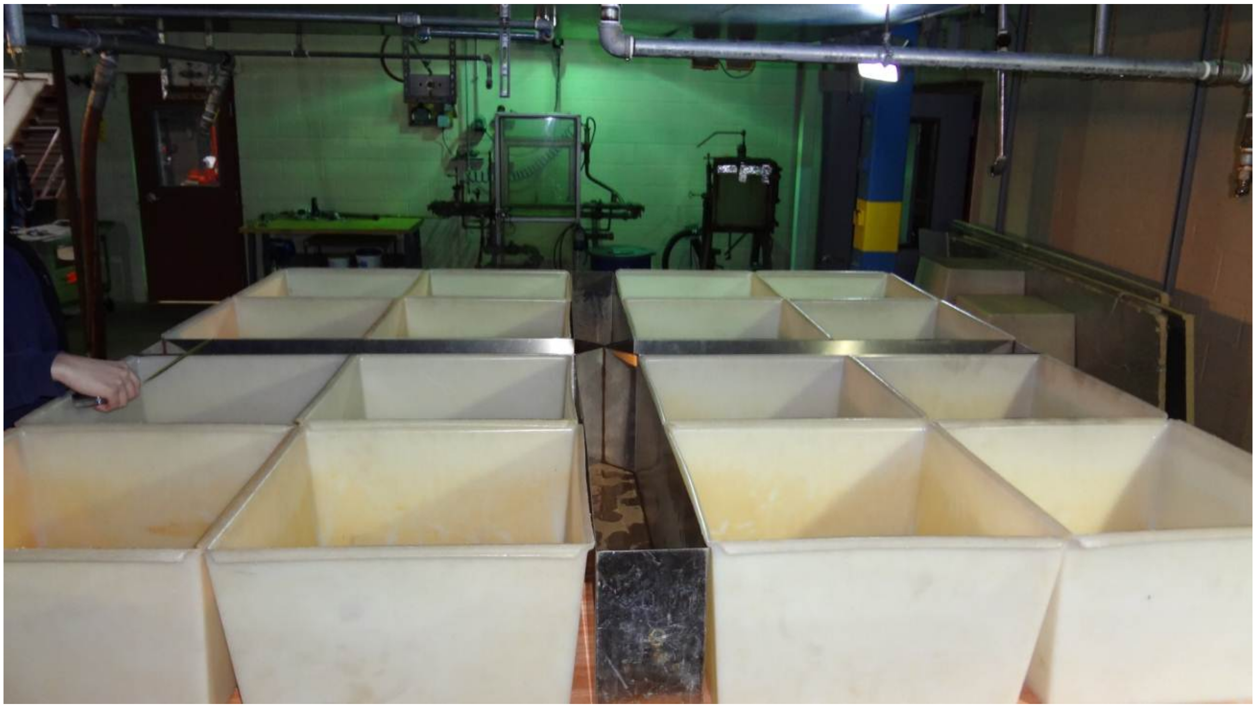


Figure 20: Tyco Bucket Test Setup

10.2 Tyco Bucket Test Collection Data Collection

Once the dimensions were confirmed, the testing began. Three separate bucket tests were run. All three tests were run for 5 minutes and 30 seconds. Measurement techniques were performed to determine the amount of water in each individual bucket. The same measurement tools and techniques were used as the previous k-25.2 sprinkler.

It was possible to average the three bucket tests since the results of each were similar. After putting the data in workable form by calculating the flow rate of each bucket in kg/s, it was then possible to compare this data with the FDS water flux outputs.

Pan Test Averages from Tyco Trip (kg/s); k-5.6				
Pan1 0.014	Pan 2 0.076		Pan 3 0.068	Pan 4 0.041
Pan 5 0.034	Pan 6 0.045		Pan 7 0.052	Pan 8 0.045
		Sprinkler		
Pan 9 0.014	Pan 10 0.070		Pan 11 0.038	Pan 12 0.016
Pan 13 0.033	Pan 14 0.072		Pan 15 0.079	Pan 16 0.024

Table 7: Tyco Bucket Test Results

10.3 Sources of Error

The determination of uncertainty was necessary to see how accurate the bucket test measurements were. Just like the bucket testing previously completed, there are four different sources of error. The first error was due to the ramp up of the flow. The second error was the uncertainty of the dipstick and ruler. The Third error is the fluctuation of flow rate. The last error is droplets on the ceiling. The following is the explanation of the calculations.

10.3.1 Ramp-up time

The ramp-up time it took to get the sprinkler up to the desired flow rate (21 gpm), took approximately 13 seconds between all three tests.

0-13 seconds: 0 gpm -21 gpm (assumed average of 10.5 gpm over time: 0 -13 seconds)

Therefore the average flow rate during the “ramp-up” process was 10.5 gpm.

Ramp-up: 0 – 13 seconds: 10.5 gpm

Steady-state: 14- 330 seconds: 21 gpm (ideal)

Uncertainty:

$$\frac{\text{Ramp-up time}}{\text{Total time}} * \frac{(\text{Steady-state (gpm)} - \text{Ramp-up (gpm)})}{\text{Steady-state (gpm)}}$$

= (13/330 seconds) * (21 – 10.5)/ 21

= 1.97%

±1.97 %

10.3.2 Measurement techniques

The calibrated dipstick provided by Tyco was made up of 2.5 lb increments spanning from 5lbs to 120lbs. To calculate the uncertainty of measurement errors, an average of 33lbs was used as the base value to cover the majority of the magnitude of measurements captured at Tyco.

$$= \frac{\text{Uncertainty in measurement}}{\text{Base Value}}$$

= 1.25lbs / 33lbs = 3.79%

±3.79 %

10.3.3 Fluctuating flow rate

The flow rate, after reaching steady state at 21 gpm, still continued to fluctuate ranging from ±0.5 gpm.

Uncertainty:

$$= \frac{\text{Uncertainty in measurement}}{\text{Base Value}}$$

= 0.5gpm / 21gpm = 2.38 %

±2.38%

10.3.4 Ceiling effects

The uncertainty of the ceiling playing a role in affecting the water distribution into the buckets is unknown, so a large percent error was used to account for this factor:

±5%

10.3.5 Total Uncertainty:

= Ramp-up time + measurement techniques + fluctuating flow rate + ceiling effects

= (±1.97%) + (±3.79%) + (±2.38%) + (±5%)

Total Uncertainty:

= ±13.14 %

11.0 FDS Testing

Once all the inputs were found for the FDS 6 simulation, the bucket test was replicated for the k25.2 sprinkler and the k5.6 sprinkler. The FDS 6 input values used for the k25.2 sprinkler were:

Input	Value	Units
K-Factor	360	L/min/bar^.5
Spray Angle	73.57	Degrees
Offset	0.2	Meters
Droplet Velocity	8.65	m/s
Droplet Diameter	1161	Micro meters
Particle Number	5000	Particles per second
Flow Rate	329.295	L/min

Table 8: FDS inputs for K25.2 sprinkler

The FDS results are summarized in table 9.

FDS 6 Simulation kg/s				
Pan1 0.02	Pan 2 0.07		Pan 3 0.06	Pan 4 0.02
Pan 5 0.07	Pan 6 0.59		Pan 7 0.59	Pan 8 0.06
		Sprinkler		
Pan 9 0.07	Pan 10 0.59		Pan 11 0.60	Pan 12 0.07
Pan 13 0.02	Pan 14 0.07		Pan 15 0.07	Pan 16 0.02

Table 9: FDS results for K25.2 Sprinkler

After running the FDS 6 simulation, the results were analyzed and put into the bucket setup to match the bucket test results. By observing this chart, it can be seen that FDS 6 predicts symmetry in the buckets. The four inner pans, (6, 7, 10, 11) range from .59 kg/s to .60 kg/s, a 2% difference. The eight outer pans, (2, 3, 8, 12, 15, 14, 9, 5) range from .06 to .07 kg/s, a 14% difference. With symmetry, these pans should all be the same. Lastly, the four outer diagonal pans (1, 4, 13, 16) are all .02 kg/s. Within all the groups the maximum difference between buckets is 1 kg/s. This means the simulation is relatively uniform.

Tyco-FDS Percent Difference **±8.15 %**				
Pan1 85%	Pan 2 45%		Pan 3 53%	Pan 4 85%
Pan 5 20%	Pan 6 -123%		Pan 7 -135%	Pan 8 24%
		Sprinkler		
Pan 9 17%	Pan 10 -126%		Pan 11 -151%	Pan 12 17%
Pan 13 86%	Pan 14 51%		Pan 15 52%	Pan 16 83%

Table 10: Percent difference of bucket test data and FDS results

Once the FDS 6 results were analyzed, the results were compared to the measured bucket test using percent difference. As can be observed in the resulting chart, the percent difference varies depending on the section of buckets. The inner pans' (6, 7, 10, 11) percent difference varies from -123% to -151%. This means in FDS 6, there is more water in the 4 inner buckets than in the measured bucket test. For the group of 4 pans (2, 3, 14, 15) the percent difference ranges from 45% to 52%. This means that in these buckets, FDS 6 is only predicting half the amount of water of the experimental test. For the 4 pans (5, 9, 8, 12) the percent difference ranges from 17% to 24%. This is the most accurate section of the FDS prediction, being within 25% of the actual test. For the 4 pans (1, 4, 13, 16) the percent difference ranges from 83% to 85%. Since the percent difference is so large due to an unsymmetrical water distribution, a sensitivity analysis was not conducted for this sprinkler. The outputs of the sensitivity analysis would not be beneficial if the percent difference is consistently large.

The inputs for the K5.6 sprinkler were then put into FDS to replicate the bucket test at Tyco.

Input	Value	Units
K-Factor	80.7	L/min/bar^.5
Spray Angle	72.625	Degrees
Offset	0.2	Meters
Droplet Velocity	7.4698	m/s
Droplet Diameter	1121	Micro meters
Particle Number	5000	Particles per second
Flow Rate	56.775	L/min

Table 11: FDS inputs for K5.6 sprinkler

The FDS results are summarized in table 12 below.

FDS Results for a k-5.6 (kg/s)				
Pan1 0.02	Pan 2 0.04		Pan 3 0.05	Pan 4 0.02
Pan 5 0.04	Pan 6 0.07		Pan 7 0.07	Pan 8 0.05
		X		
Pan 9 0.05	Pan 10 0.07		Pan 11 0.07	Pan 12 0.05
Pan 13 0.02	Pan 14 0.05		Pan 15 0.04	Pan 16 0.02

Table 12: FDS results for K5.6 sprinkler

Once again, FDS 6 replicates a uniform distribution. The four inner buckets, (6, 7, 10, 11) are all .07 kg/s. The eight outer pans, (2, 3, 8, 12, 15, 14, 9, 5) range from .04 to .05 kg/s, a 20% difference. With symmetry, these pans should all be the same. Lastly, the four outer diagonal pans (1, 4, 13, 16) are all .02 kg/s. Within all the groups the maximum difference between buckets is 1 kg/s. This means the simulation is uniform.

Percent Difference for a k5.6 **±13.14 %**				
Pan1 -36%	Pan 2 41%		Pan 3 -32%	Pan 4 59%
Pan 5 35%	Pan 6 -69%		Pan 7 -33%	Pan 8 -2%
		X		
Pan 9 -229%	Pan 10 -2%		Pan 11 -113%	Pan 12 36%
Pan 13 48%	Pan 14 -187%		Pan 15 43%	Pan 16 19%

Table 13: Percent difference between bucket test and FDS test for K5.6 sprinkler

As can be seen in table 13, the percent difference between the bucket test and FDS test is not low. The distribution of the water in the experimental bucket test was not uniform, resulting in a non-uniform percent difference. The inner pans' (6, 7, 10, 11) percent difference varies from -2% to -113%. This means in FDS 6, there is more water in the 4 inner buckets than in the measured bucket test. For the group of 4 pans (2, 3, 14, 15) the percent difference ranges from -187% to 43%. For the 4 pans (5, 9, 8, 12) the percent difference ranges from -229% to 36%. For the 4 pans (1, 4, 13, 16) the percent difference ranges from -36% to 48%. Since the percent difference is so large due to the unsymmetrical water distribution, a sensitivity analysis was not conducted for this setup of this sprinkler. The outputs of the sensitivity analysis would not be beneficial if the percent difference is consistently large. Therefore, bucket test data where 4 sprinkler were running was analyzed using the same inputs for the k5.6 sprinkler

Therefore, bucket test data where 4 sprinklers were running was analyzed using the same FDS inputs as the one sprinkler test.

X	4 Sprinkler Bucket Test Results for a k-5.6 (kg/s)				X
	Pan1 0.011	Pan 2 0.010	Pan 3 0.010	Pan 4 0.011	
	Pan 5 0.010	Pan 6 0.009	Pan 7 0.009	Pan 8 0.010	
	Pan 9 0.010	Pan 10 0.009	Pan 11 0.009	Pan 12 0.010	
X	Pan 13 0.011	Pan 14 0.010	Pan 15 0.010	Pan 16 0.010	X

Table 14: FDS results for K5.6 sprinkler simulation with 4 sprinkler setup

Once again, FDS 6 is simulating a uniform distribution. All four inner pans (6, 7, 10, 11) are .009 kg/s. The eight outer pans (2, 3, 8, 12, 15, 14, 9, 5) are all .01 kg/s. The four pans (1, 4, 16, 13), range from .01 to .011, a 10% difference. All of the groups of pans are within 1 kg/s of each other, representing a uniform distribution.

X	Percent Difference for a k-5.6				X
	Pan1 8%	Pan 2 17%	Pan 3 17%	Pan 4 9%	
	Pan 5 26%	Pan 6 28%	Pan 7 27%	Pan 8 27%	
	Pan 9 31%	Pan 10 33%	Pan 11 40%	Pan 12 21%	
X	Pan 13 6%	Pan 14 21%	Pan 15 13%	Pan 16 -5%	X

Table 15: Percent difference between bucket test results and FDS simulation for 4 sprinkler setup

The four sprinkler bucket test data was moderately uniform, giving better FDS results. The four inner pans (6, 7, 10, 11), range from 28% to 40% different. The 4 pans (2, 3, 14, 15), range from 13% to 21 %. The four pans (5, 8, 9, 12), range from 21% to 31%. The four pans (1, 4, 16, 13), range from -5% to 9 percent. All of the pans are within 40 percent of the actual bucket test, much closer than the previous two simulations. The average percent of all the buckets was 19.8 percent. With this setup, FDS 6 is reasonably close considering the potential uncertainty of the measurements and bucket test. A sensitivity analysis can be conducted on this setup since the percent difference is low.

12.0 Results of Sensitivity Analysis

A sensitivity analysis was completed to determine the relative importance of each FDS input. It was possible to discover which default values were reasonable to use and which inputs needed to be measured for higher accuracy. The parameters included in the sensitivity analysis were those not included in the manufacturer's specification. These parameters were:

- Spray Offset
- Spray Angle
- Droplet Size
- Droplet Velocity
- Particles Per Second

To conduct the sensitivity analysis, deterministic and parametric approaches were used. Deterministic analysis evaluates each parameter individually while all other parameters are held constant [17]. Parametric analysis is moving one or a few inputs across reasonably selected ranges, such as low to high in order to examine the shape of the response. As part of the sensitivity analysis a base case of the best measured FDS inputs was conducted. Then using a deterministic approach, all inputs were kept constant while changing a single input. The three outputs for each of the sensitivity tests were average percent difference, absolute average percent difference, and maximum absolute percent difference.

The average percent difference was calculated using a multi-step process. First, the percent difference between the measured bucket test and the FDS simulation for all 16 buckets was found. The percent differences for these 16 buckets were averaged to find the "average percent difference." This gives an indication of how well the FDS prediction was at replicating a bucket test. In this calculation a negative percent difference would cancel out a positive, therefore not necessarily being the best representation.   An absolute average percent difference was used to account for the negative and positive relationship. To find the “absolute average percent difference,” the absolute value of all 16 buckets’ percent difference was averaged. This value gave a better understanding on how close the FDS prediction actually was. The maximum absolute percent difference was found by locating the highest magnitude of the percent error in all 16 buckets.

12.1 Base Case and Results

The base case test was run with the best measured and available inputs. When inputs could not be measured, historical values were used from prior research using similar sprinklers and flow rates. Velocity was calculated using the built-in equation in FDS:

$$V = \frac{4Q}{\pi d^2}$$

This equation resulted in a velocity of 7.47 m/s. Inner and outer spray angle were measured using a protractor on digital images taken of the spray. Droplet size and spray offset were found from historical data from Dave Sheppard’s research using a k5.6 sprinkler and a flow rate of 16 gpm. Since there was no prior research on particles per second, the default value of 5000 particles per second in FDS was used to complete the base case test.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%

Table 16: Base Case

By running this base case test, it can be observed how close the FDS simulation was to the measured bucket test. The average percent difference between the actual measured bucket test and the simulated FDS test was 19.8%, the average absolute percent difference was 20.5%.

The maximum absolute percent difference was 39.7%. It is shown that using a k5.6 pendant sprinkler tested at 16 gpm, that FDS can show a prediction that is about 20% different than the measured bucket test.

12.2 Offset:

As described in section 4.5, the droplets start as a sheet and breaks up into droplets at some distance away from the sprinkler. This distance is defined as the offset. In FDS 6, the offset has a default value of 0.05m. Dave Sheppard's research found that a spray offset of 0.2m was a reasonable assumption for the atomized region for the 11 sprinklers of various types and orientations [1]. FDS uses 0.05m as the default offset. By running a test with all the best known inputs and the default offset it was found that 0.2m was a better approximation. Running FDS with the default offset of 0.05m decreased the ability to replicate the test by about 10%.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
Default Offset	7.47	23	72.625	1121	0.05	5000	31.1%	31.1%	46.9%

Table 17: Spray Offset

12.3 Spray Angle:

There are two different spray angles that are needed in FDS 6. There is an outside spray angle and an inner spray angle. The outer spray angle is the angle of the outer boundaries of the spray. The inner spray angle is the small angle where no water is being sprayed on the inside of the spray. A high and a low case were run for each of the spray angles with the higher test being 10% above the measured spray angle, and the lower test being 10% below the measured spray angle. By lowering the inner spray angle, the average absolute percent difference improved by about 5% when compared to the base case. Whereas a higher inner spray angle resulted in about a 7% larger percent difference than the base case.

Similar results were seen when the outer spray angle was lowered. The average absolute percent difference improved by 10%. When the outer spray angle was increased the absolute percent difference was 10% larger.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
Lower Inner Spray Angle	7.47	20.7	72.625	1121	0.2	5000	14.3%	15.1%	33.4%
Higher Inner Spray Angle	7.47	25.3	72.625	1121	0.2	5000	27.7%	27.9%	47.1%
Lower Outer Spray Angle	7.47	23	65.53	1121	0.2	5000	7.1%	10.2%	25.0%
Higher Outer Spray Angle	7.47	23	80.09	1121	0.2	5000	31.9%	31.9%	49.2%

Table 18: Spray Angle

12.4 Droplet Size:

Droplet size is the diameter of the water droplets formed by the sprinkler typically measured in microns. A DV50 number is the mean droplet diameter, and the droplet size that characterizes the sprinkler. The FDS uses a default value of 500 microns for the mean droplet diameter (DV50). Running FDS with the default mean droplet diameter decreased the ability to replicate the test by about 60%.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
Default Droplet Size	7.47	23	72.625	500	0.2	5000	78.6%	78.6%	94.4%

Table 19: Droplet Size

12.5 Velocity:

In FDS there are two ways of defining the droplet velocity. The first method is by inputting the spray velocity at the offset distance. The second method is allowing FDS to calculate the velocity at the orifice using a given flow rate and orifice diameter. From prior testing on the k25.2 sprinkler it was found that the two methods were approximately 10% different. Therefore a sensitivity analysis was conducted ±10% the prediction decreased by about 12% For the higher velocity, the test was about 5% closer to the measured bucket test. This test was done to observe how close the FDS simulation with higher and lower velocity values was to the measured bucket test.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
Lower Velocity	6.72	23	72.625	1121	0.2	5000	32.4%	32.4%	52.2%
Higher Velocity	8.22	23	72.625	1121	0.2	5000	13.5%	15.0%	30.6%

Table 20: Spray Velocity

12.6 Particles per second:

The FDS 6 user guide states that a sprinkler creates more droplets in a second than what FDS can replicate [16]. As a result, FDS 6 uses one particle to track the movement of a group of particles. A large number of particles can cause the model to be unstable. However, larger number of droplets can yield more accurate mass flux distributions. Therefore a sensitivity analysis needs to be conducted for particles per second when modeling sprinklers. The first test increased the particles per second by 2000 particles for a total of 7000 particles per second. The percent difference was about the same compared to the base case. The second test then increased the particles per second to 10000. Once again the percent difference was about the same, only being .1% higher than the base case. Therefore, it was found that running FDS with more particles per second does not improve the bucket test prediction for a k5.6 sprinkler.

	Velocity (m/s)	Inner Spray Angle (degrees)	Outer Spray Angle (degrees)	DV50 Droplet Size (microns)	Offset (m)	Particles Per Second	Average Percent Difference	Average Absolute Percent Difference	Maximum Absolute Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
Particles Per Second (Test 1)	7.47	23	72.625	1121	0.2	7000	20.4%	20.6%	37.5%
Particles Per Second (Test 2)	7.47	23	72.625	1121	0.2	10000	19.9%	20.2%	37.7%

Table 21: Particles per Second

12.7 Default Values:

Lastly a test was run with all of the default values. This test was done to observe how close the FDS simulation with default values was to the measured bucket test. The percent difference between the actual measured bucket test to the simulation was almost 100% off.

	Velocity (m/s)	Inner Spray	Outer Spray	DV50 Droplet	Offset (m)	Particles Per	Average Percent	Average Absolute	Maximum Absolute

		Angle (degrees)	Angle (degrees)	Size (microns)		Second	Difference	Percent Difference	Percent Difference
Base Case	7.47	23	72.625	1121	0.2	5000	19.8%	20.5%	39.7%
All Default Values	7.47	60	75	500	0.05	5000	91.8%	91.8%	94.4%

Table 22: Default Values

13.0 Conclusions and Recommendations

Through the research conducted in this project and the sensitivity analysis, a number of conclusions and recommendations were made. After running FDS with the default offset value (0.05m) and with the offset recommended by Dave Sheppard (0.2), the suggested 0.2m for the spray offset is a better approximation than the FDS default of 0.05m. Therefore it is recommended to increase the default offset distance in FDS. Further testing should be done to verify this distance. Droplet size needs to be approximated using historical data or needs to be experimentally measured, since the 500 micron FDS default simulation was about 70% worse than the base case. Since a DIPA or PDA test is not practical without expensive equipment, other measurement methods should be researched. By increasing the particles per second input to 7,000 and 10,000, there was no measurable increase in the percent differences. The simulation time was slightly longer, but did not produce better results. 5,000 particles per second is a valid default input for FDS sprinkler testing.

The sensitivity analysis for spray angle was done by varying the inner and outer angles by ±10%. It was found for both the inner and outer angles, a spray angle of -10% was more comparable to the measured bucket test than the base case. Further testing needs to be completed to determine if this trend stays consistent.

As stated previously, in FDS there are two ways of defining the droplet velocity. The first method is by inputting the spray velocity at the offset distance. The second method is allowing FDS to calculate the velocity at the orifice using a given flow rate and orifice diameter. When the droplet velocity was increased, a closer prediction was observed. However, from section 4.2 it was found that for most droplet sizes, the maximum droplet velocity is at the orifice due to air resistance. Further testing of other sprinkler types is recommended to see if a higher velocity than the one at the orifice continues to produce a closer FDS prediction.

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Appendix A: Offset

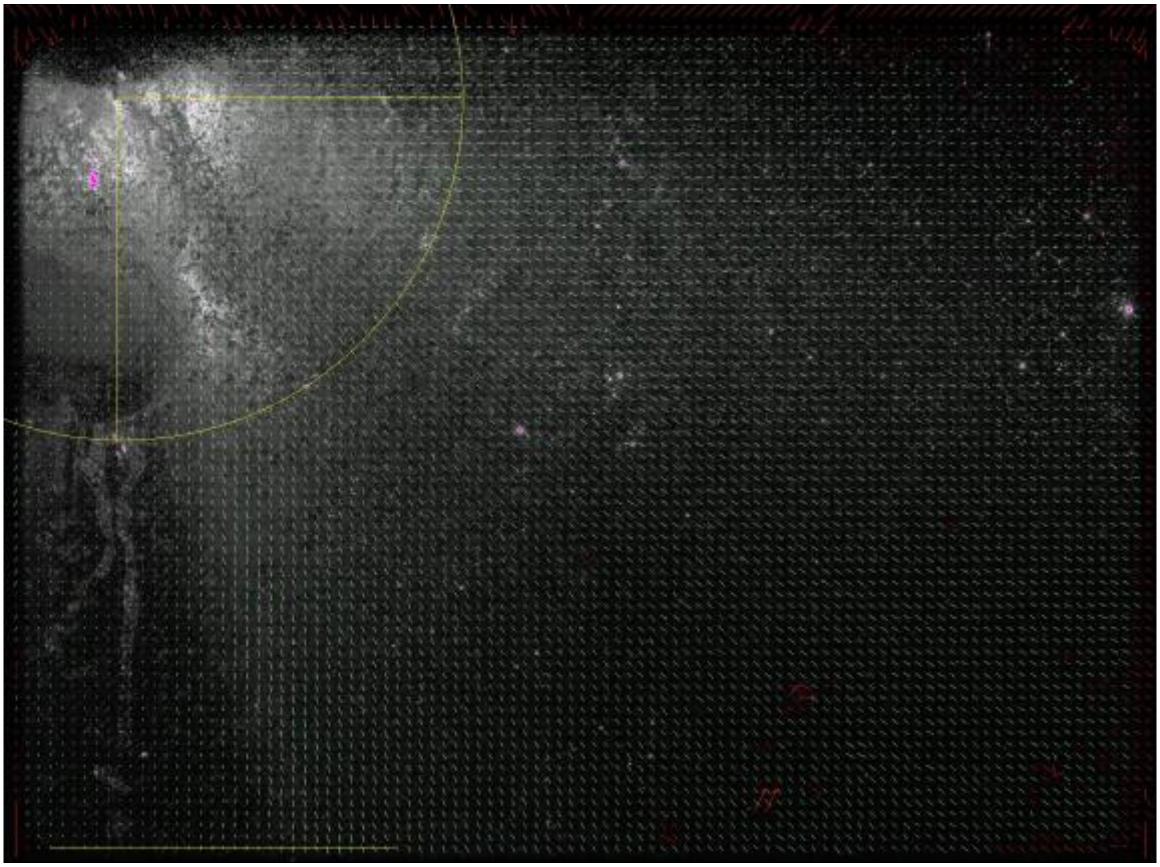


Figure 21 - 0500Deg

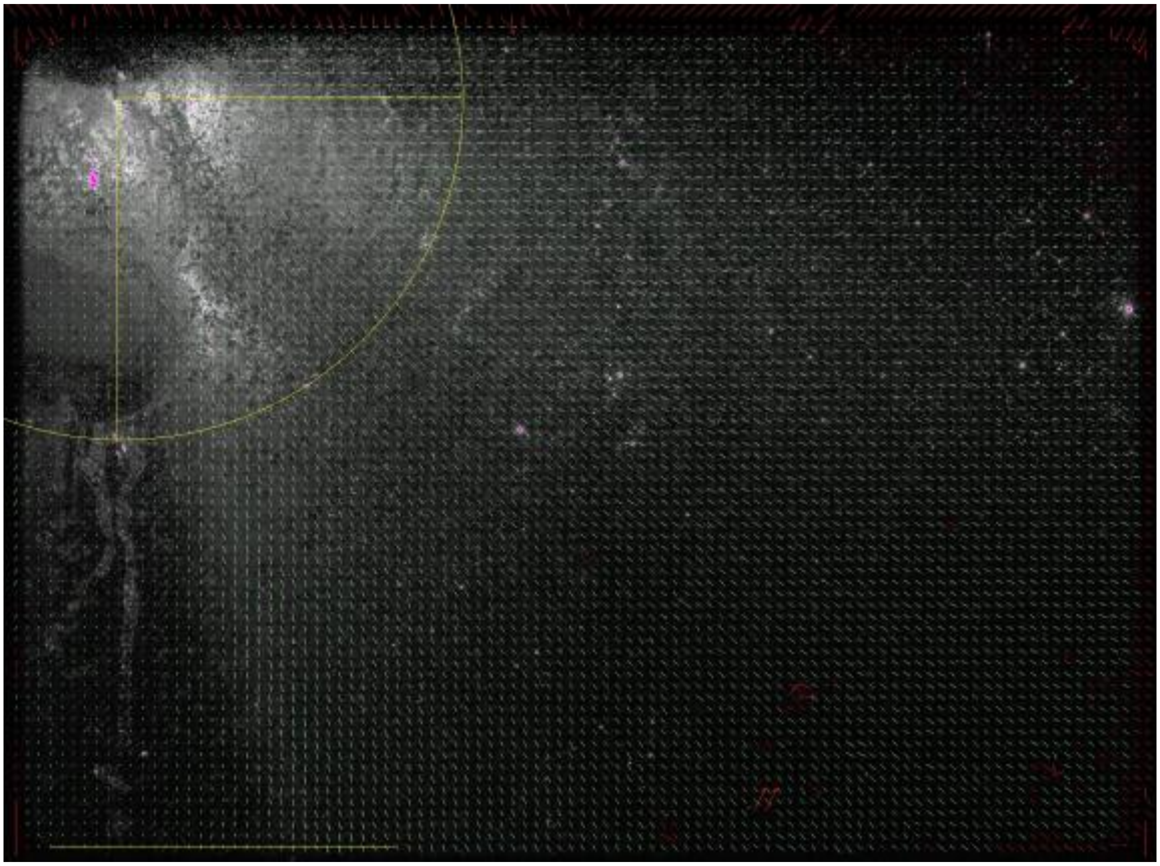


Figure 22 - 1500Deg

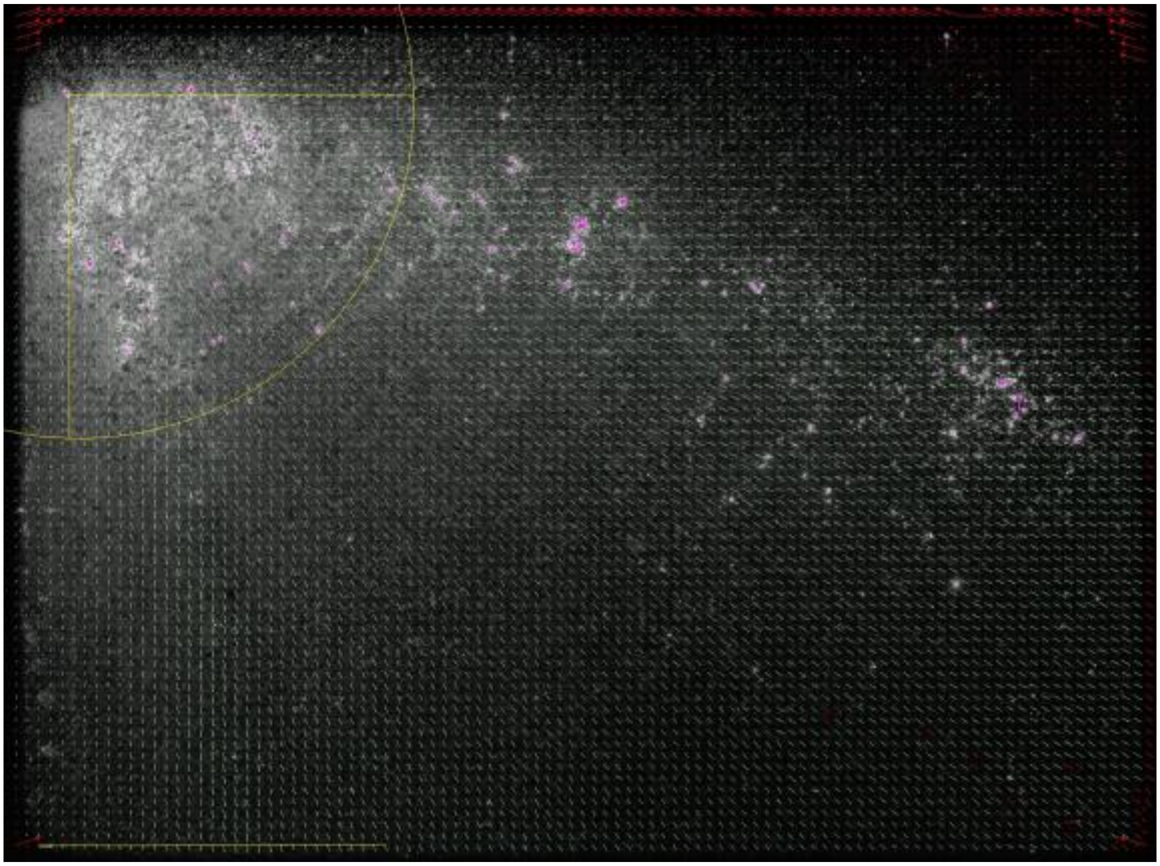


Figure 23 - 3000Deg

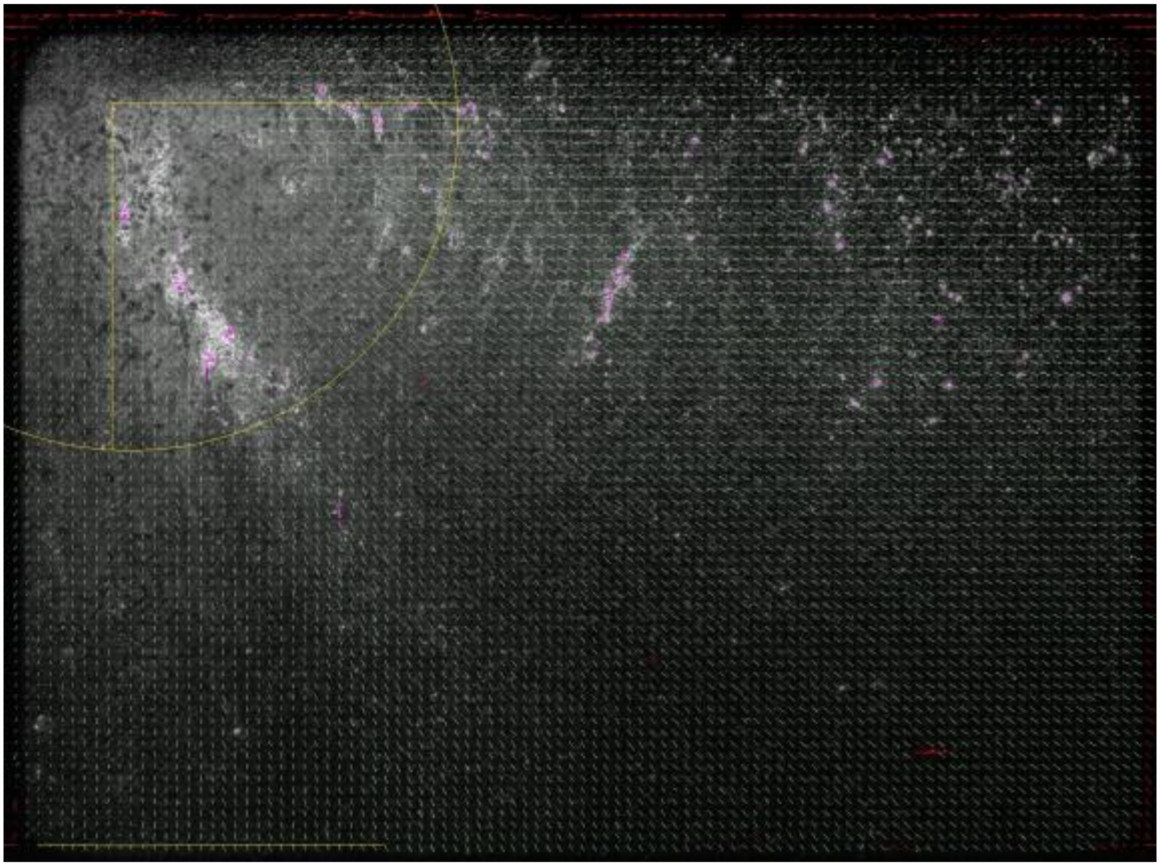


Figure 24 - 4500Deg

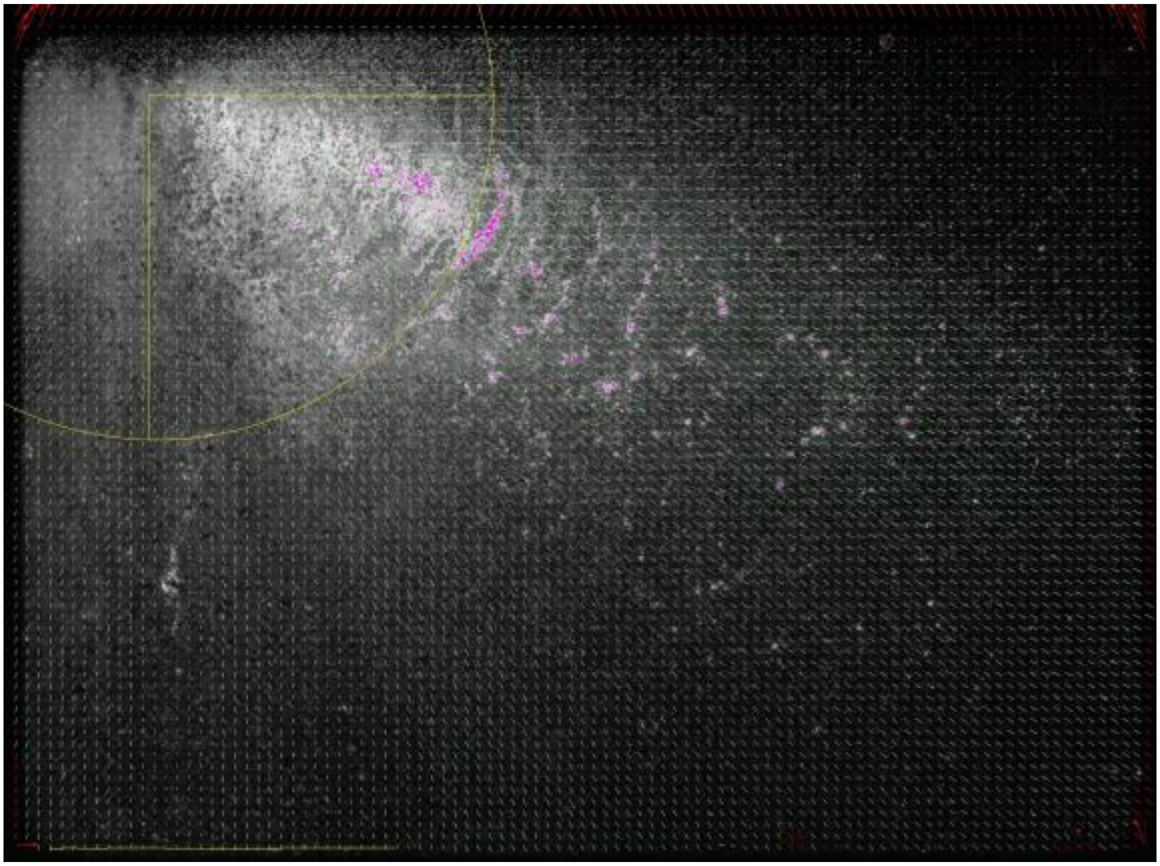


Figure 25 - 6000Deg

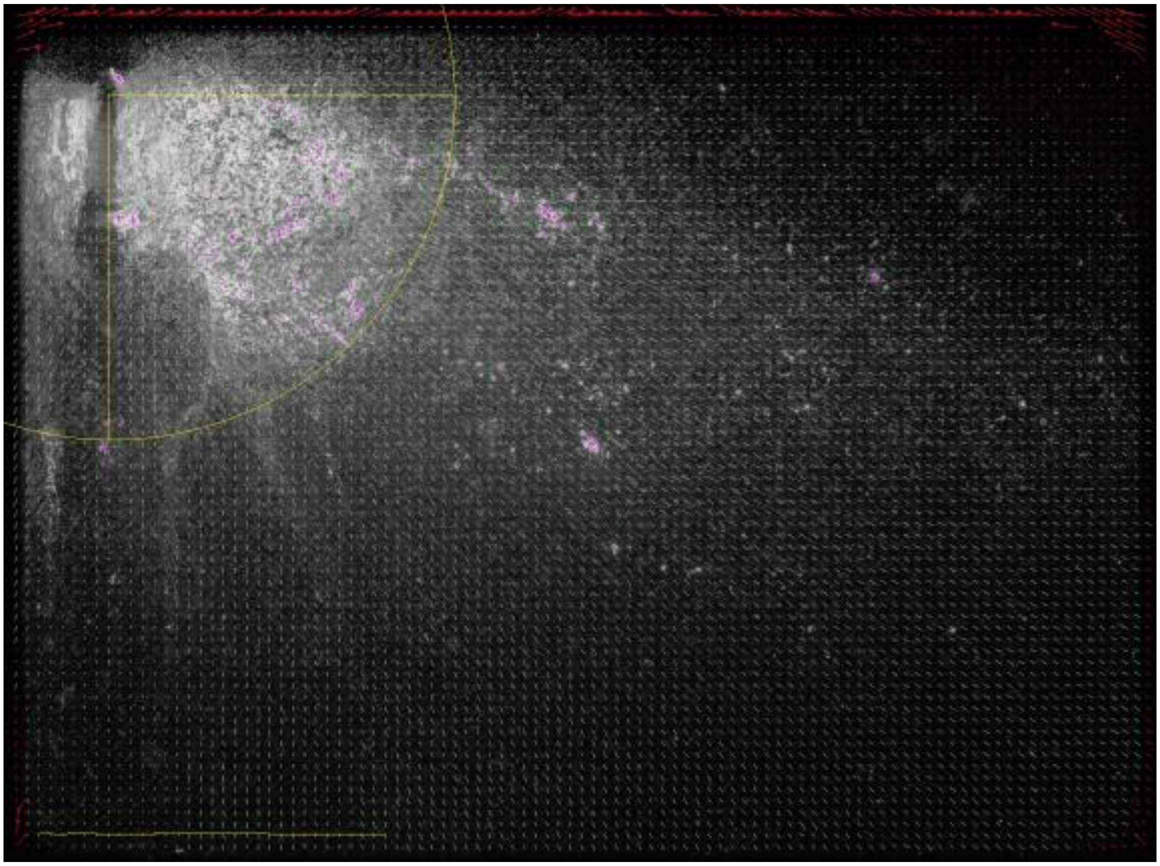


Figure 26 - 7500Deg

Appendix B: Spray Angle from PIV

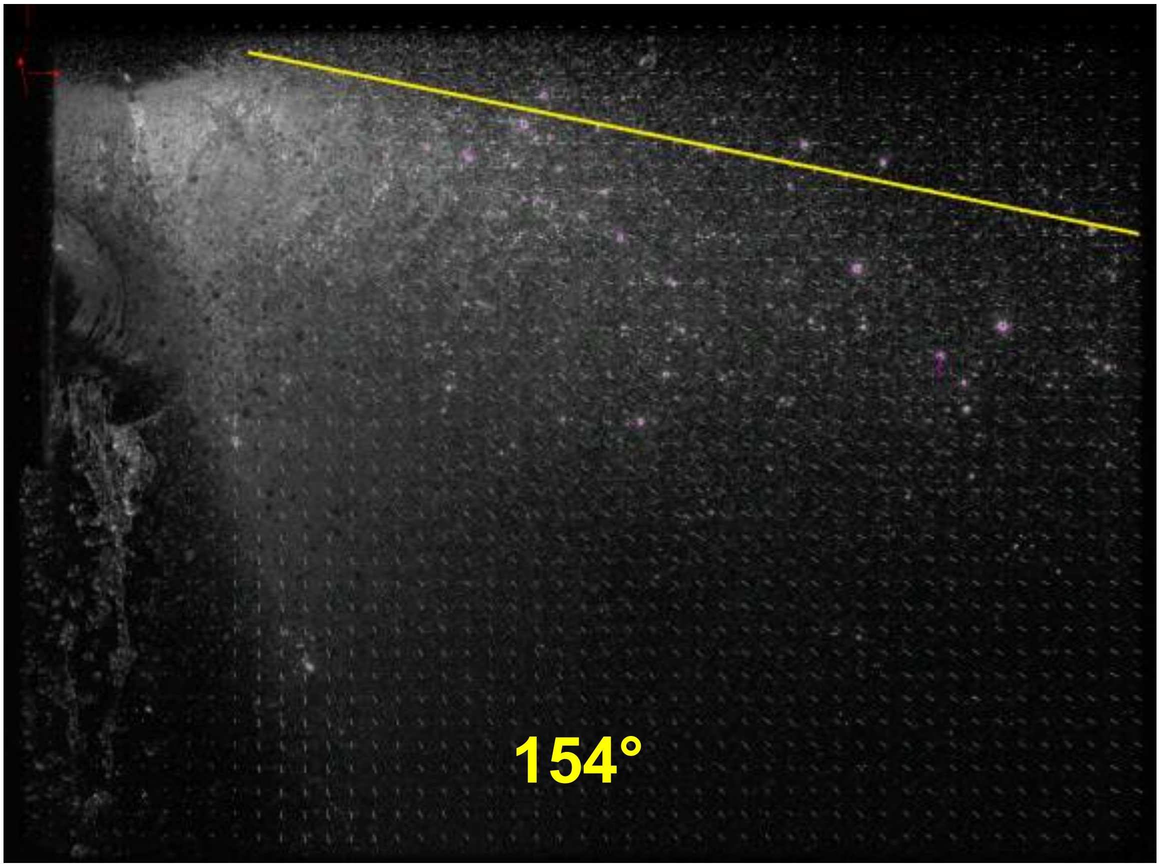


Figure 27:0500Deg

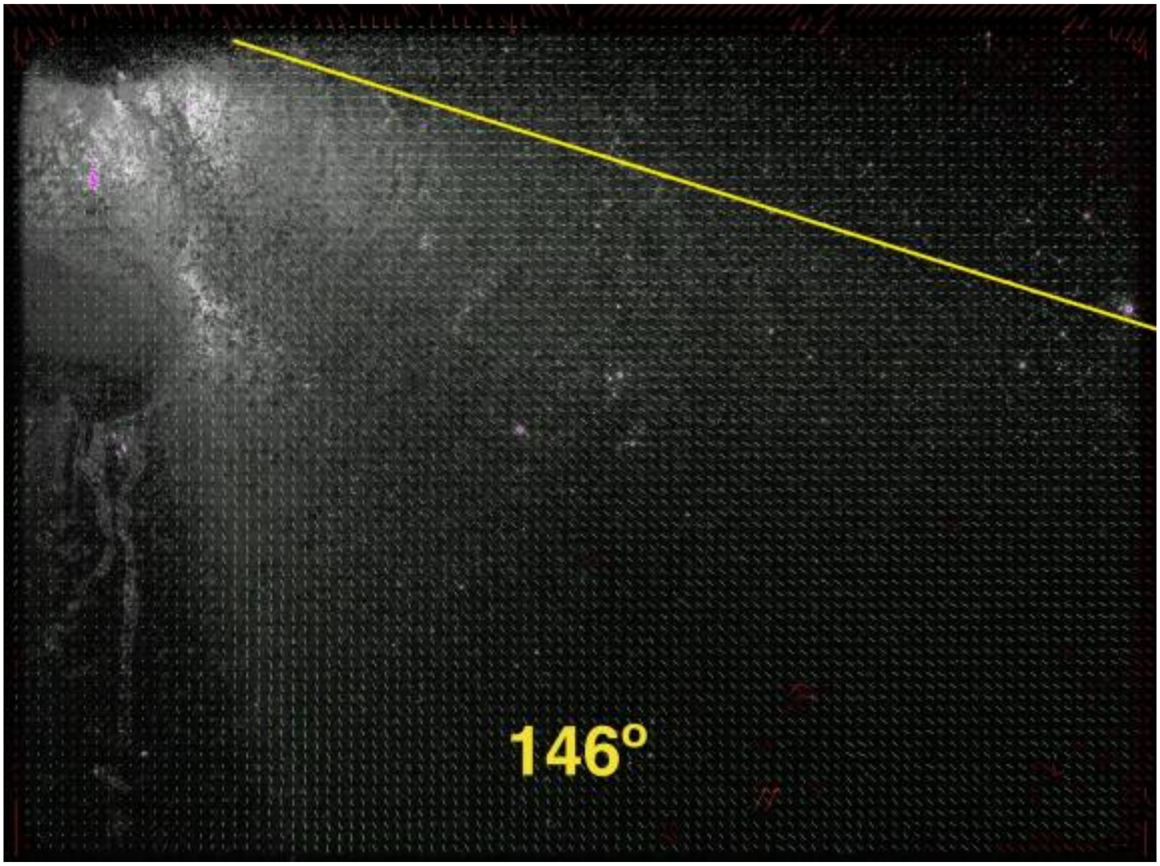


Figure 28 - 1500Deg

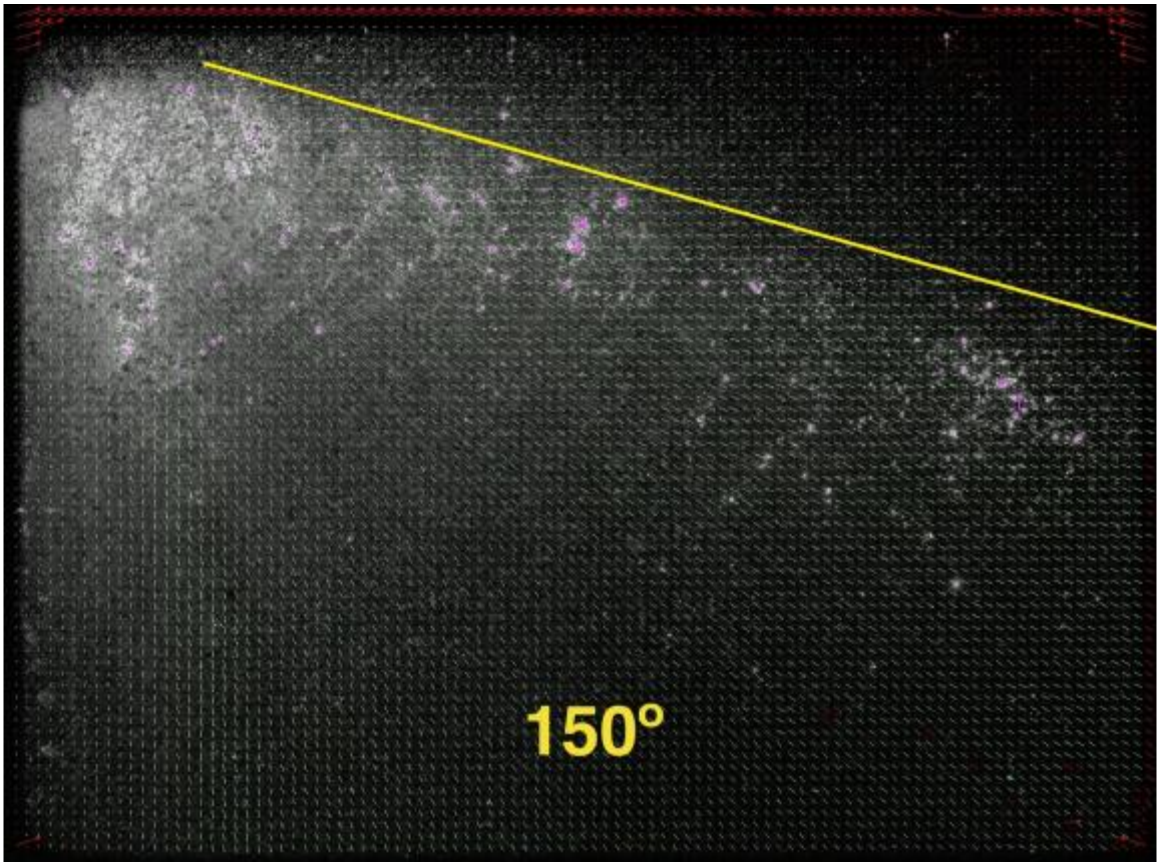


Figure 29 - 3000Deg

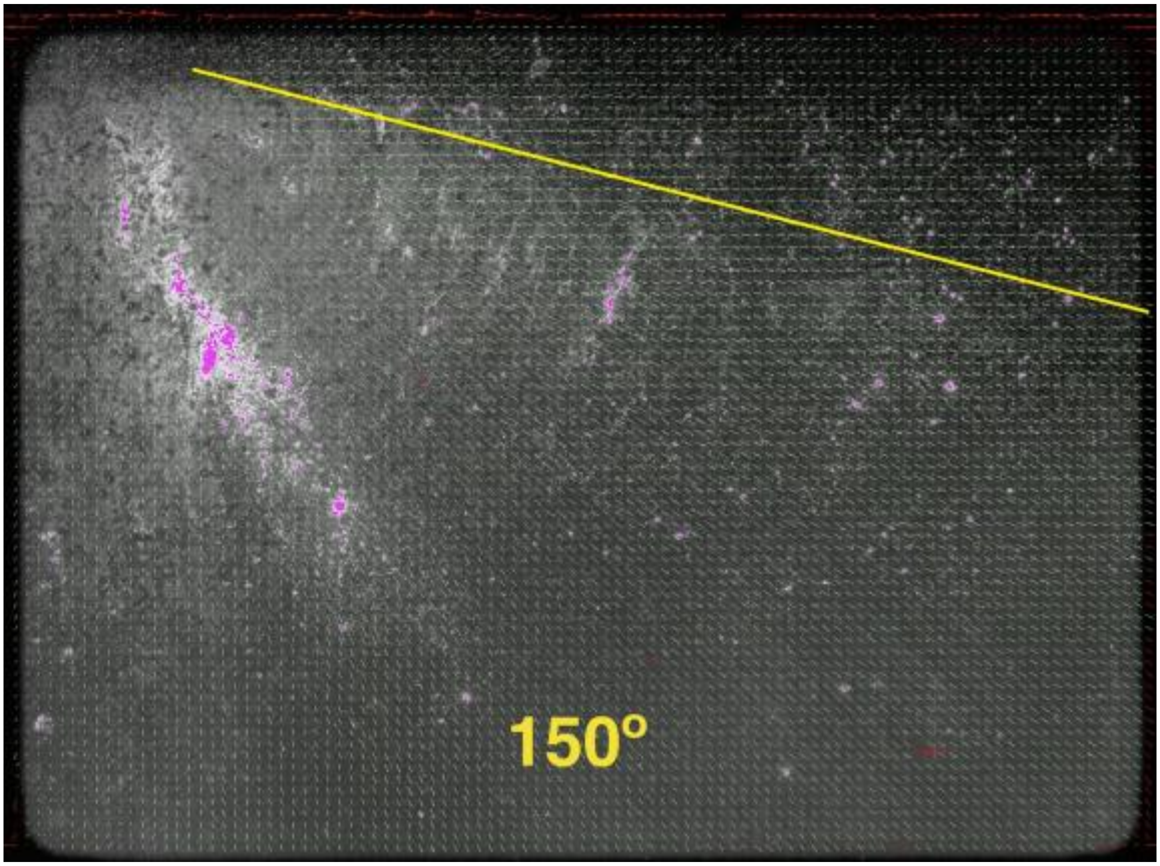


Figure 30 - 4500Deg

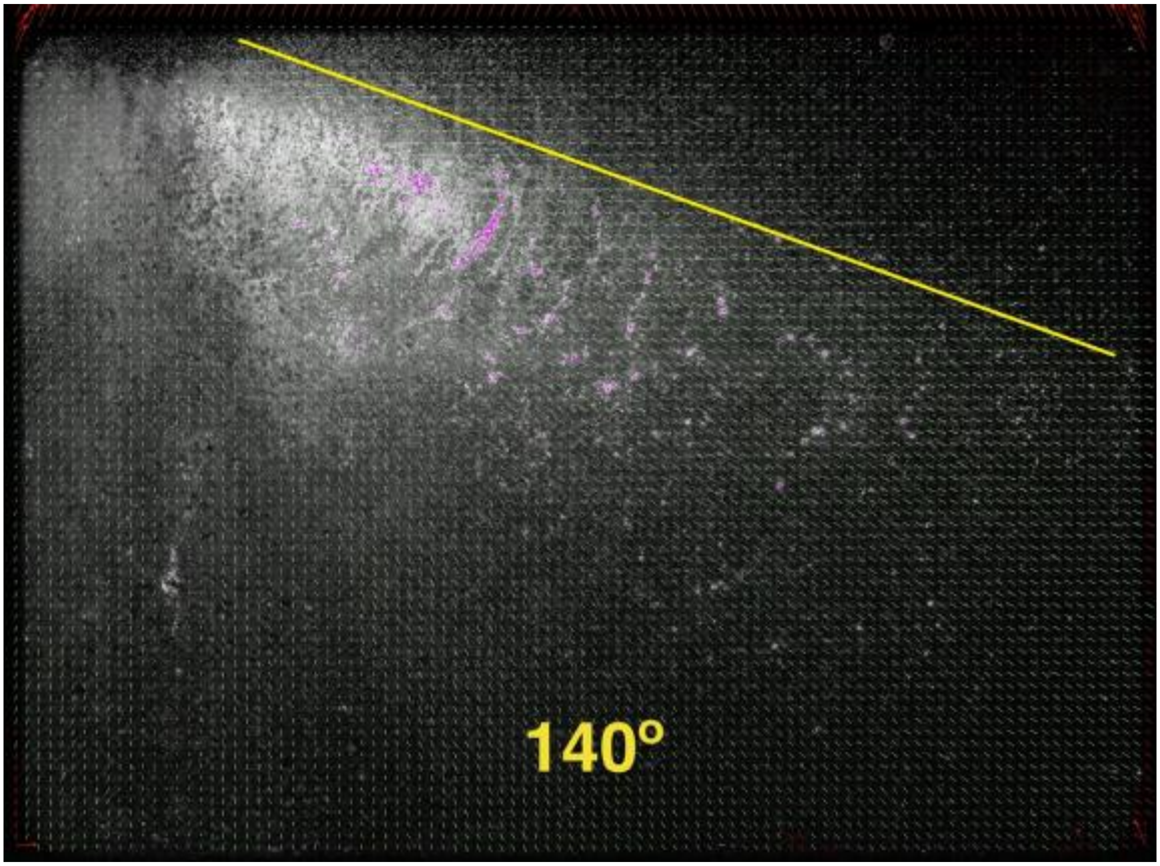


Figure 31 - 6000Deg

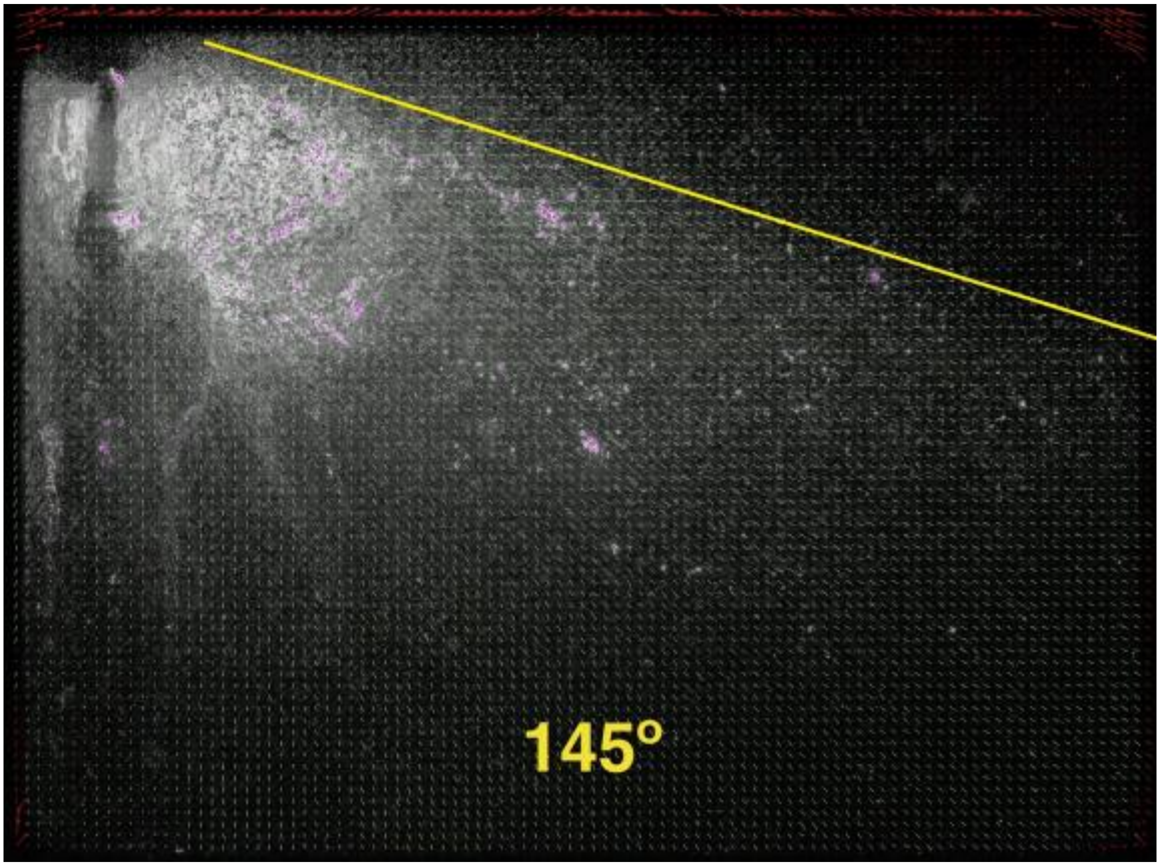


Figure 32 - 7500Deg

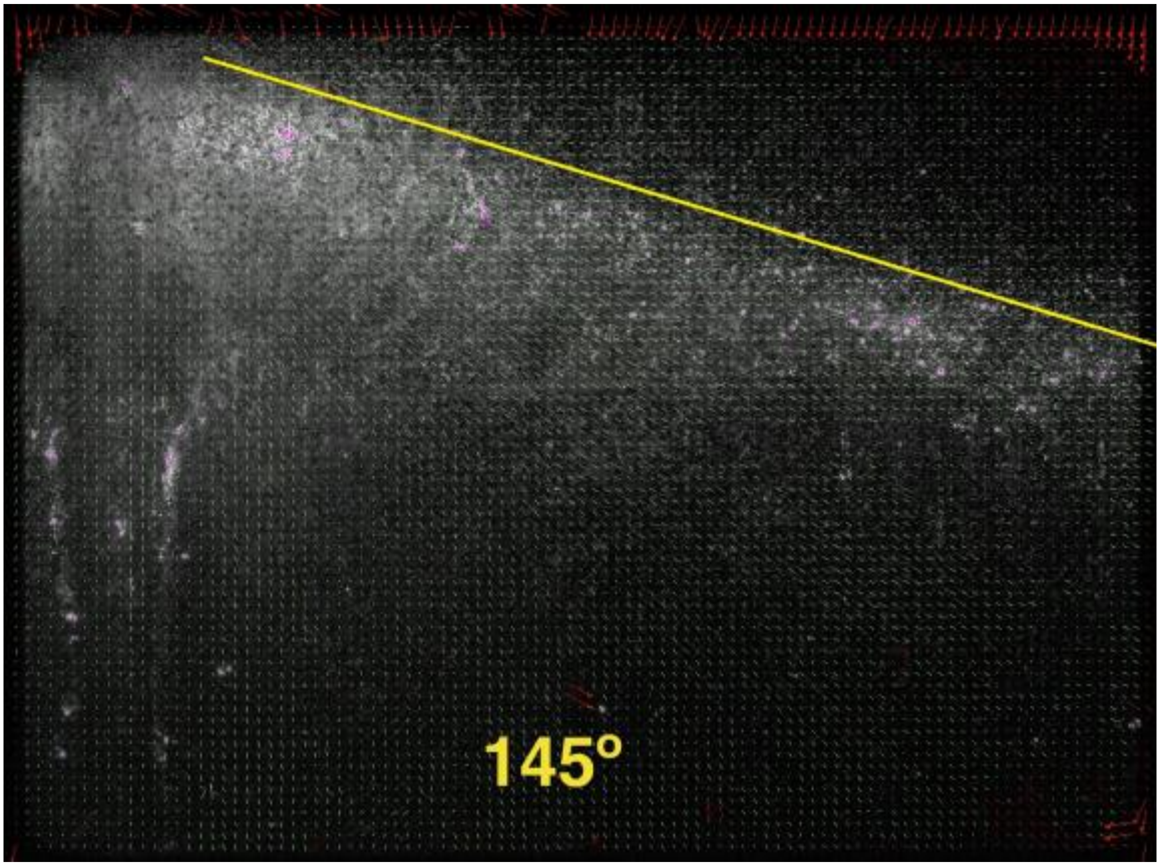
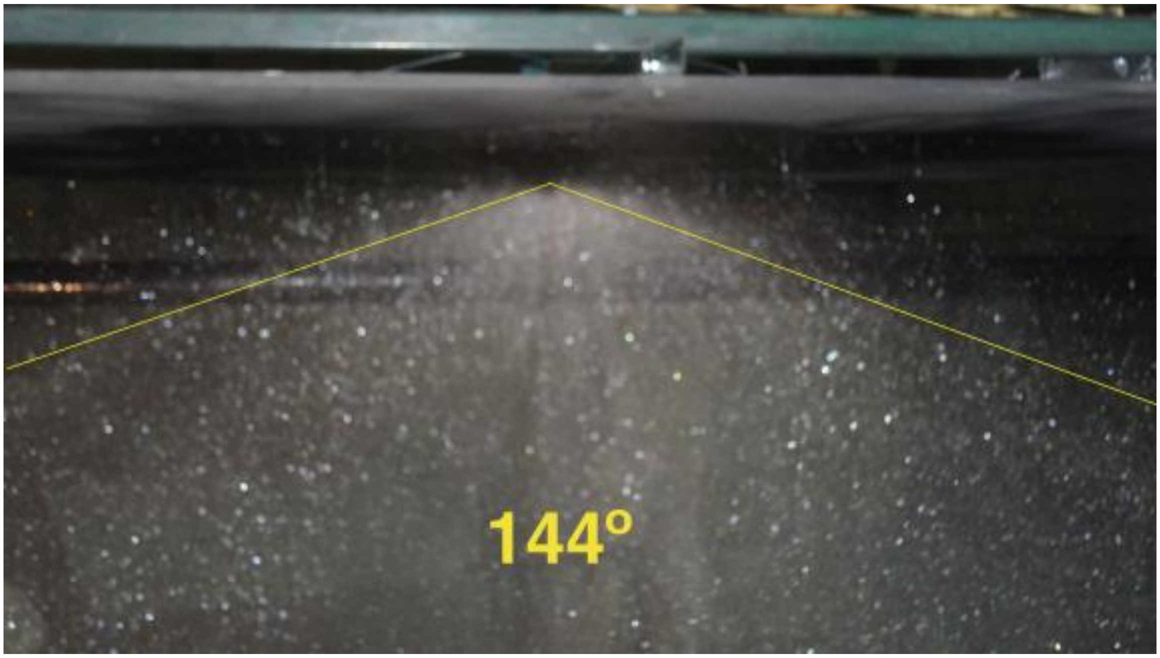
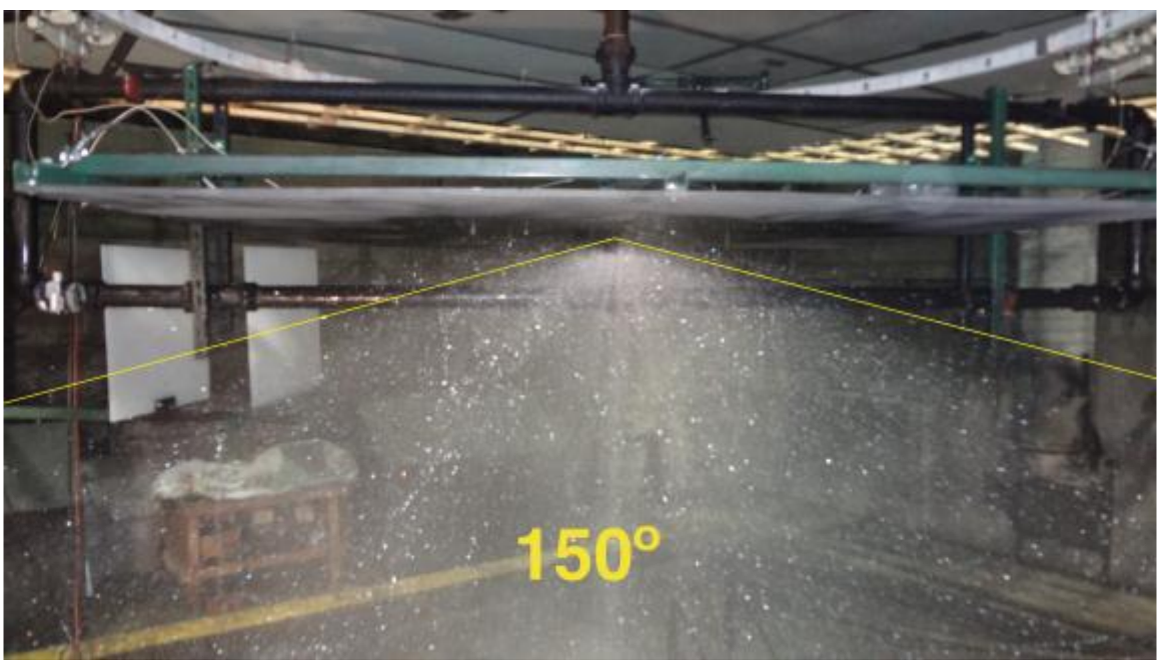
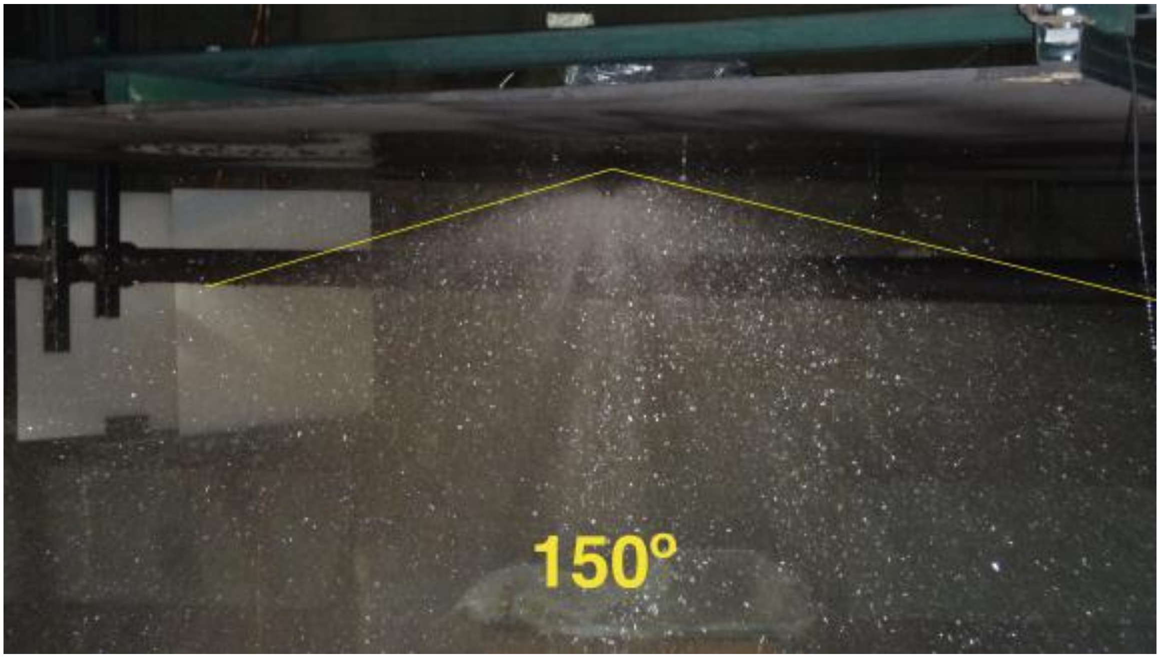


Figure 33 - 8500Deg

Appendix C: Spray Angle from Camera



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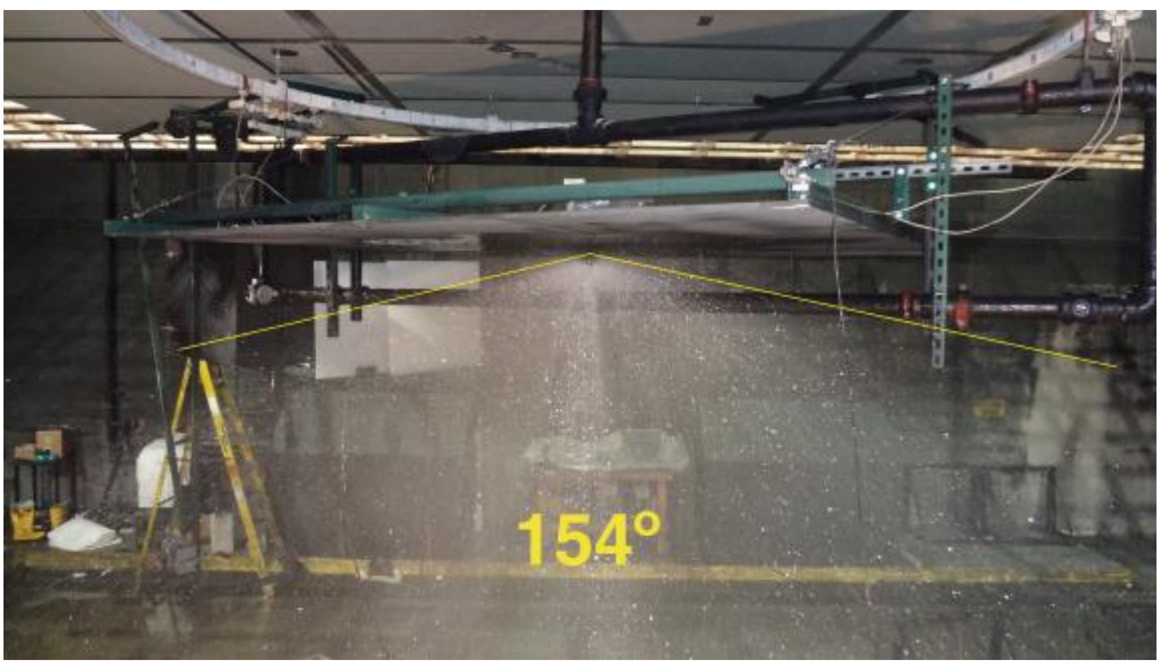
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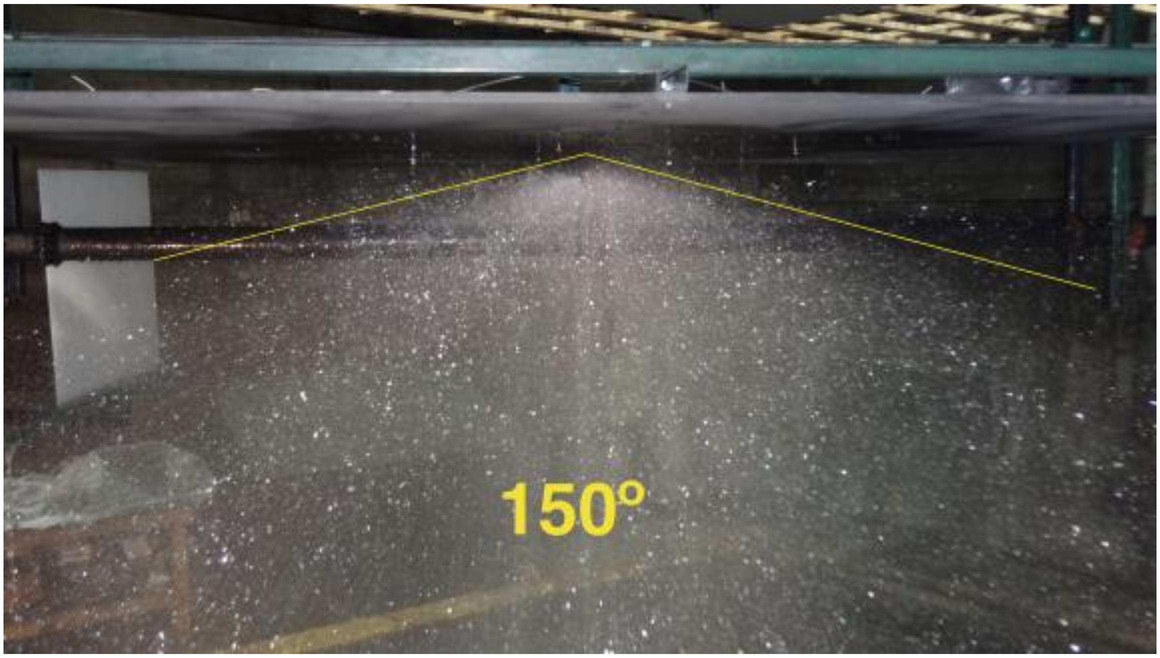
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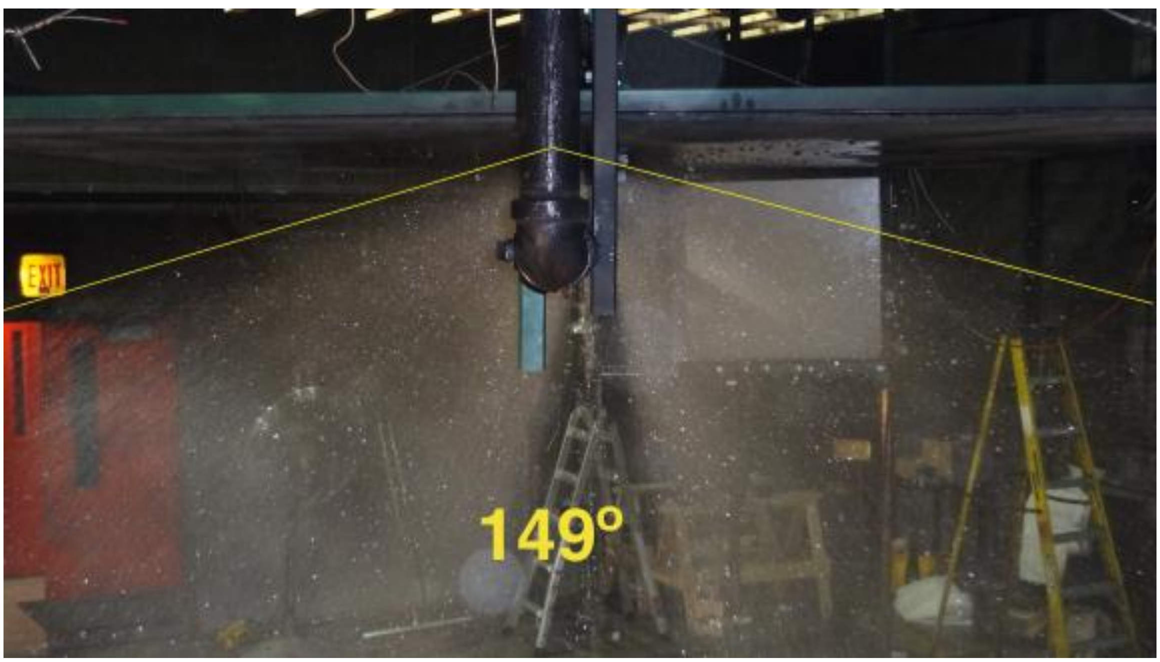
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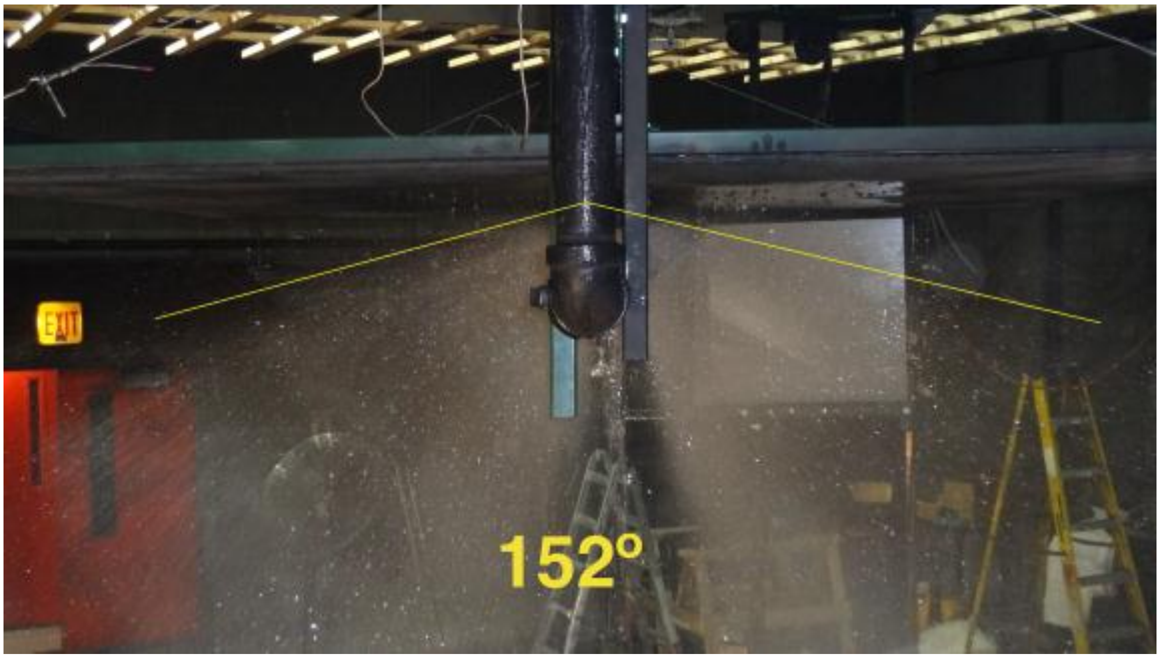
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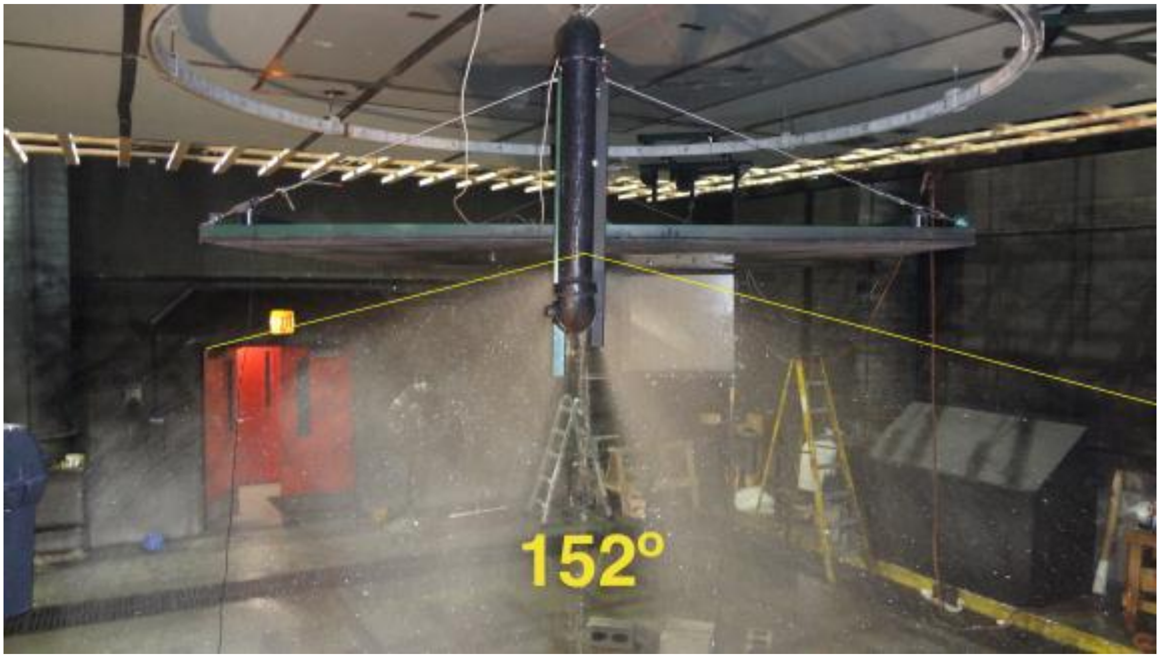
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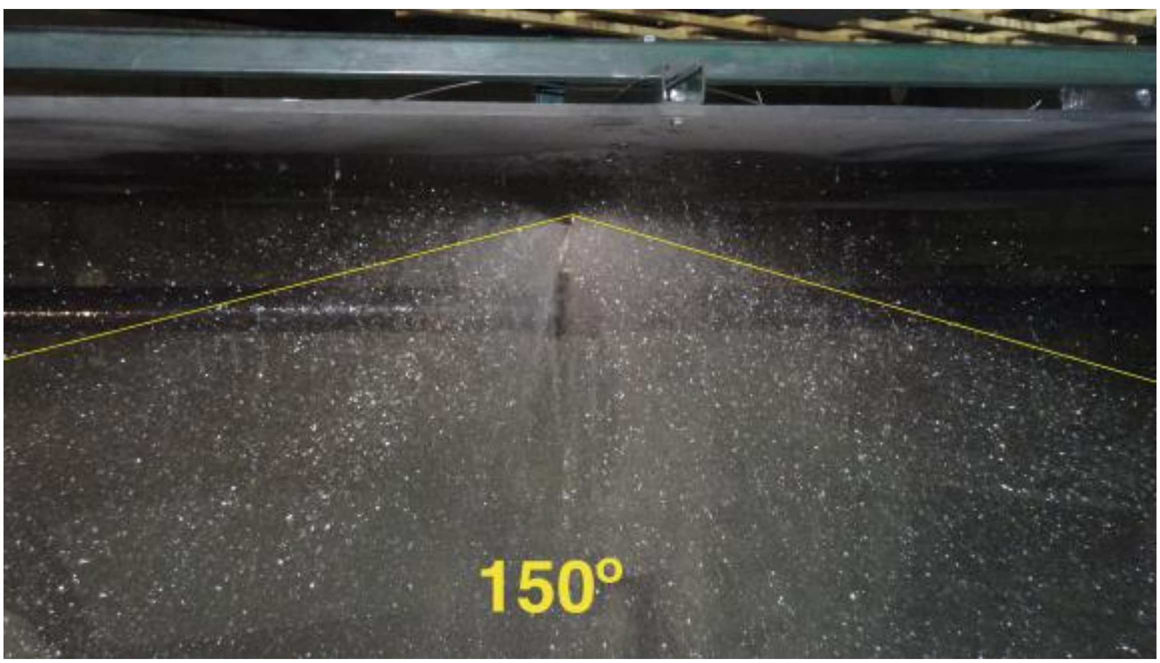
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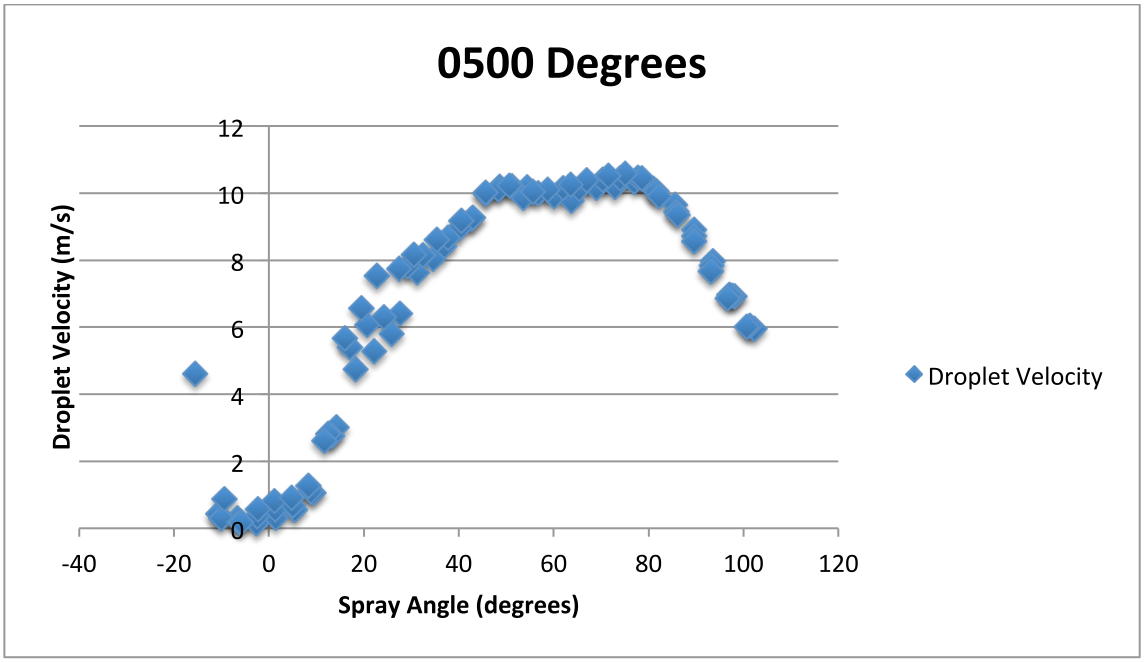
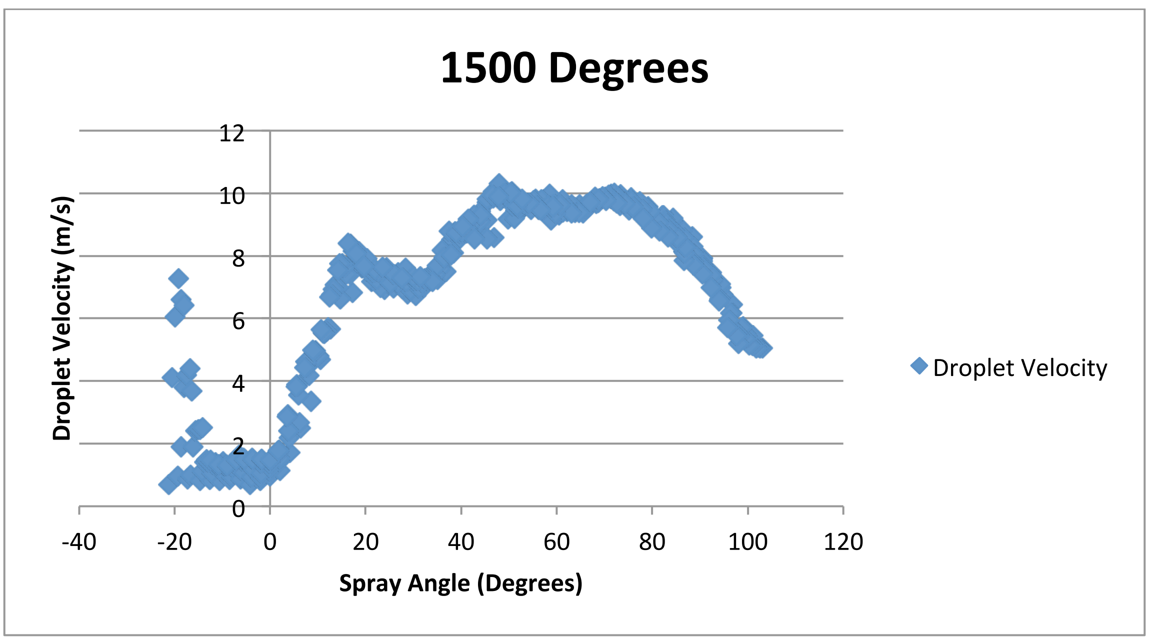
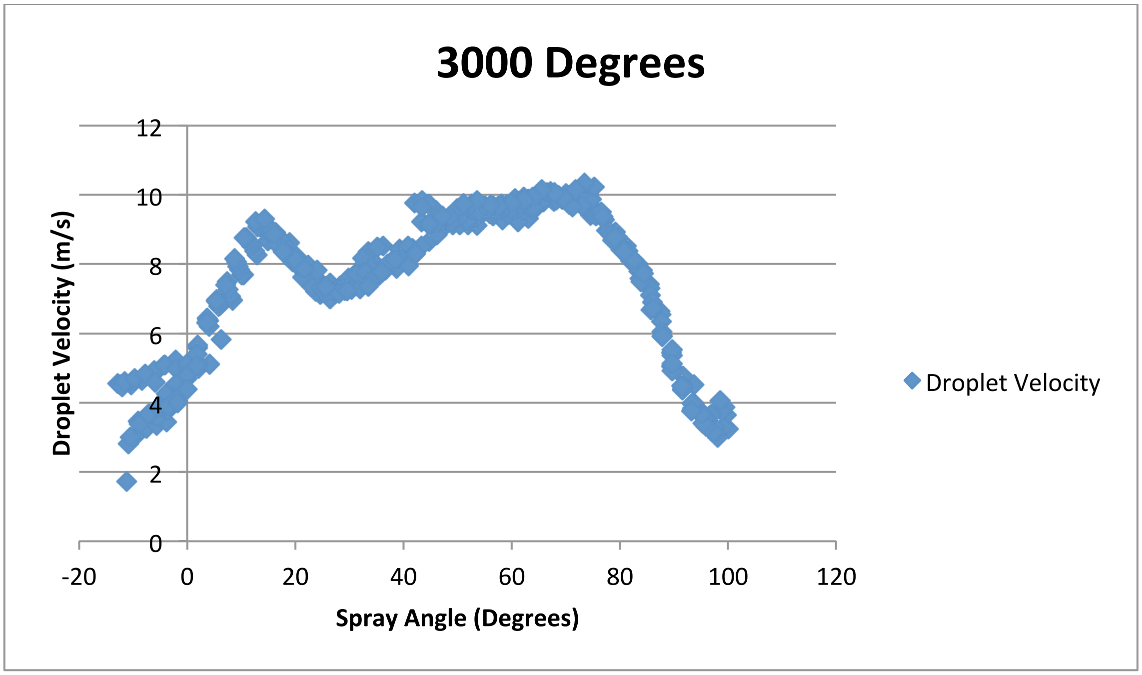
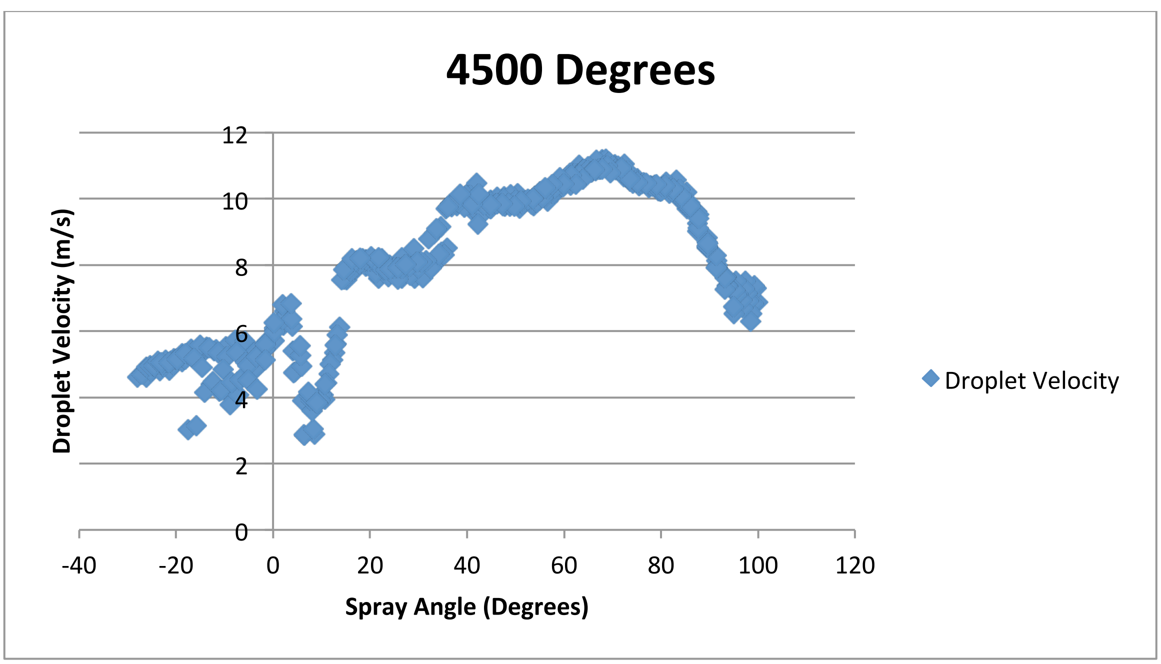
Appendix D: Spray Velocities



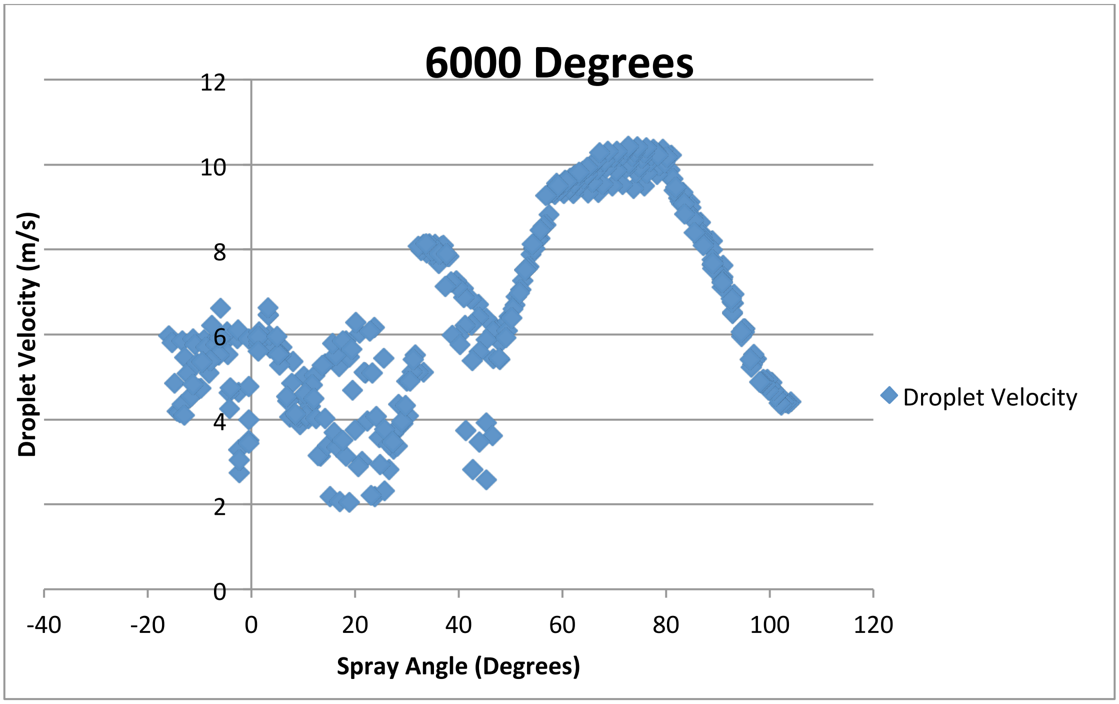


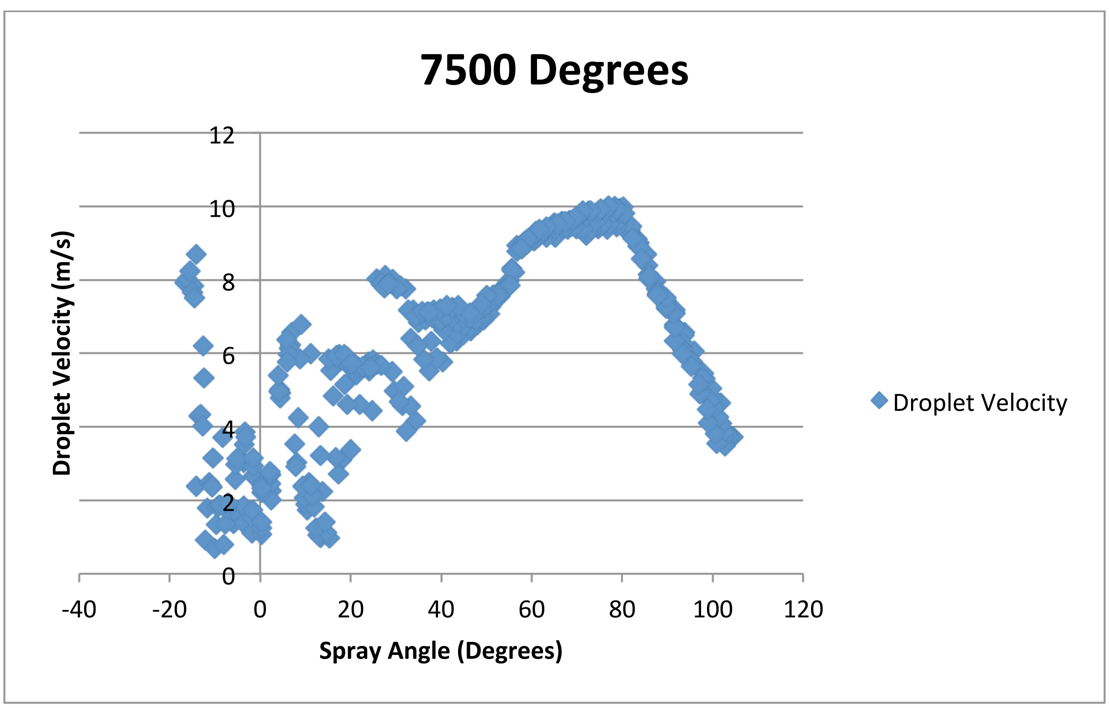


3000 Degrees
Droplet Velocity (m/s)
12
10
8
6
4
2
0
-20
0
20
40
60
80
100
120
Spray Angle (Degrees)
Droplet Velocity



4500 Degrees
Droplet Velocity (m/s)
12
10
8
6
4
2
0
-40
-20
0
20
40
60
80
100
120
Spray Angle (Degrees)
Droplet Velocity


6000 Degrees
Droplet Velocity (m/s)
0
2
4
6
8
10
12
-40
-20
0
20
40
60
80
100
120
Spray Angle (Degrees)
Droplet Velocity


7500 Degrees
Droplet Velocity (m/s)
0
2
4
6
8
10
12
-40
-20
0
20
40
60
80
100
120
Spray Angle (Degrees)
Droplet Velocity

Appendix E: Spray Velocity Contour Maps

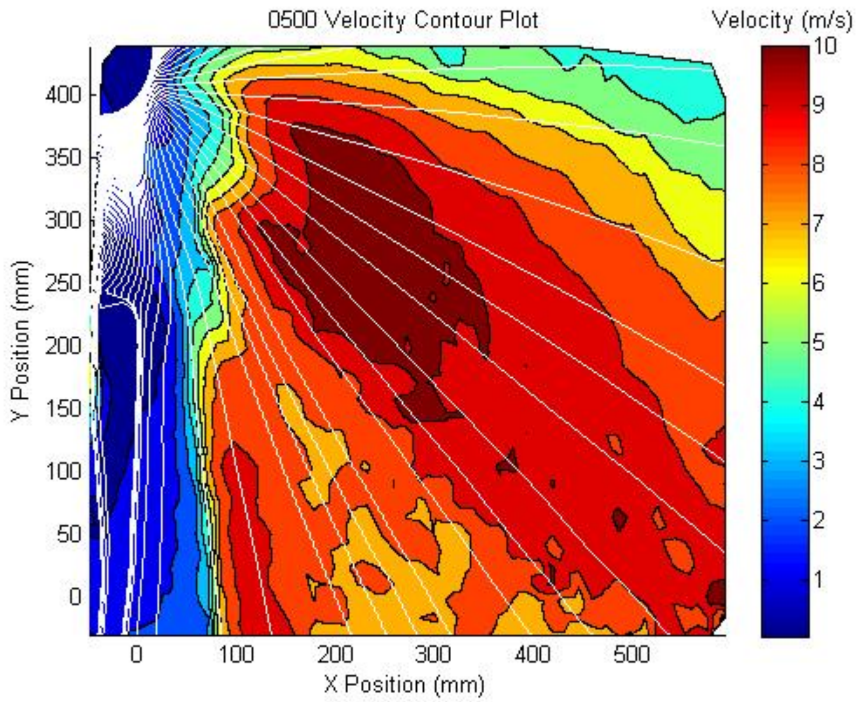


Figure 34 - 0500 Velocity Contour Plot

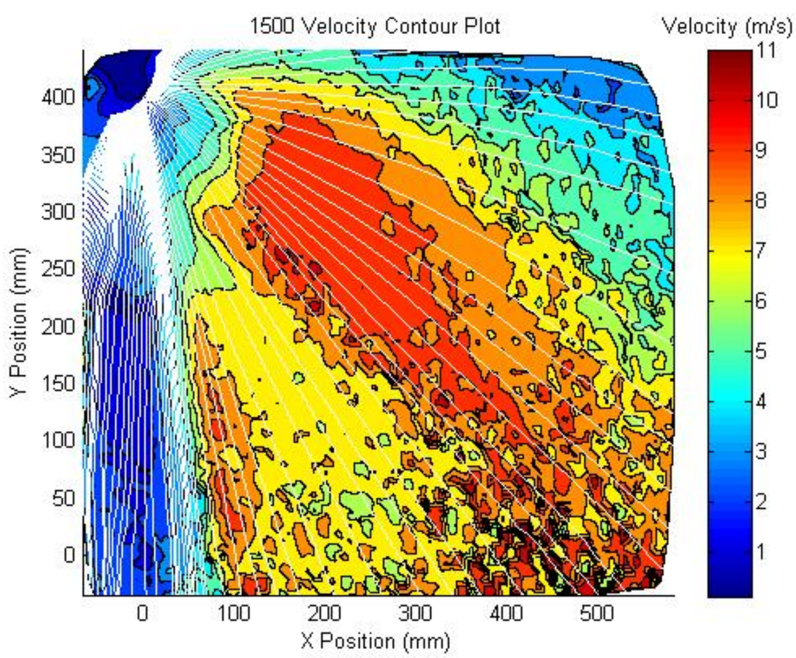


Figure 35 - 1500 Velocity Contour Plot

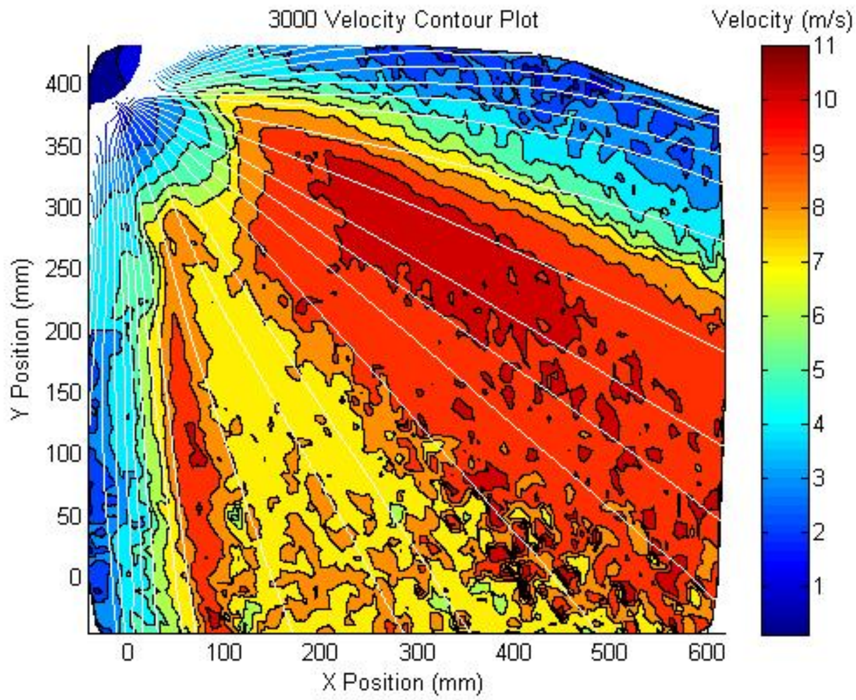


Figure 36 - 3000 Velocity Contour Plot

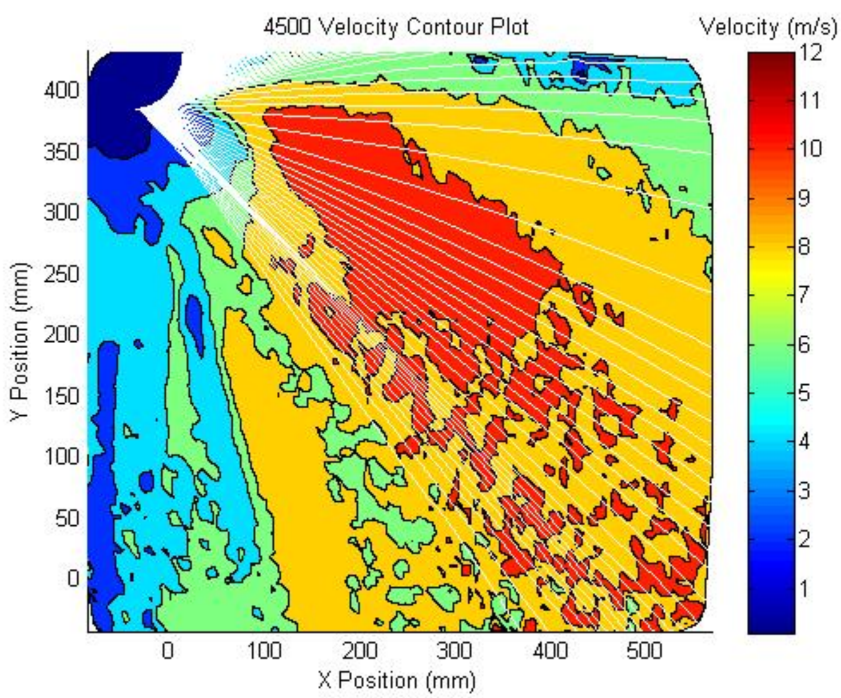


Figure 37 - 4500 Velocity Contour Plot

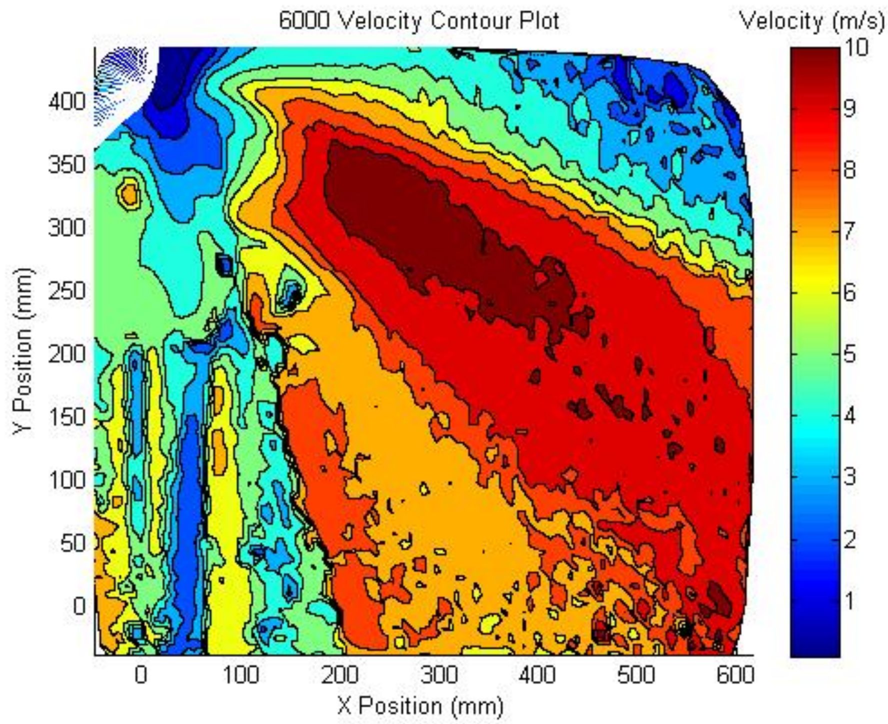


Figure 38 - 6000 Velocity Contour Plot

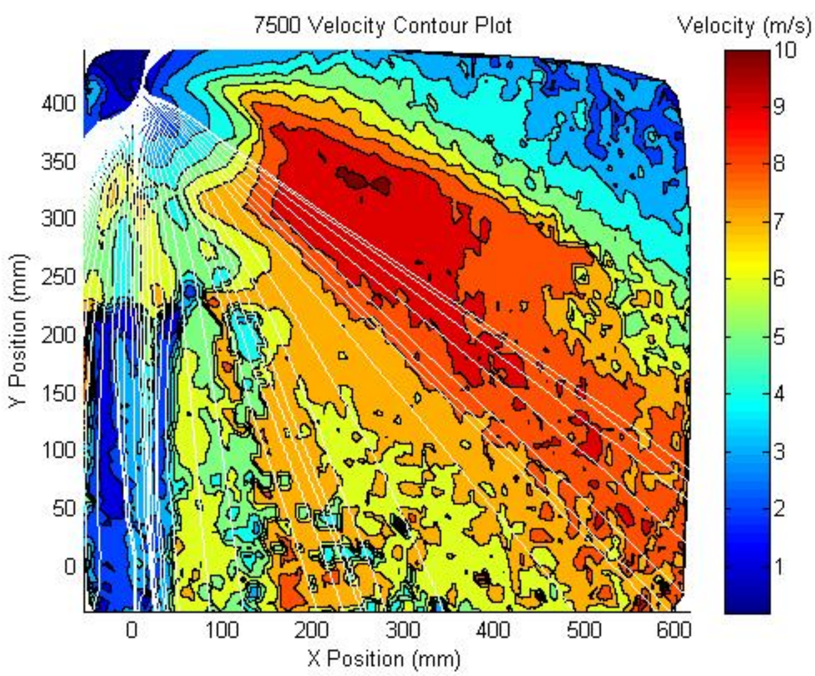


Figure 39 - 7500 Velocity Contour Plot

Appendix F: Pictures from Tyco

Figure 40: Calibrated Dipstick

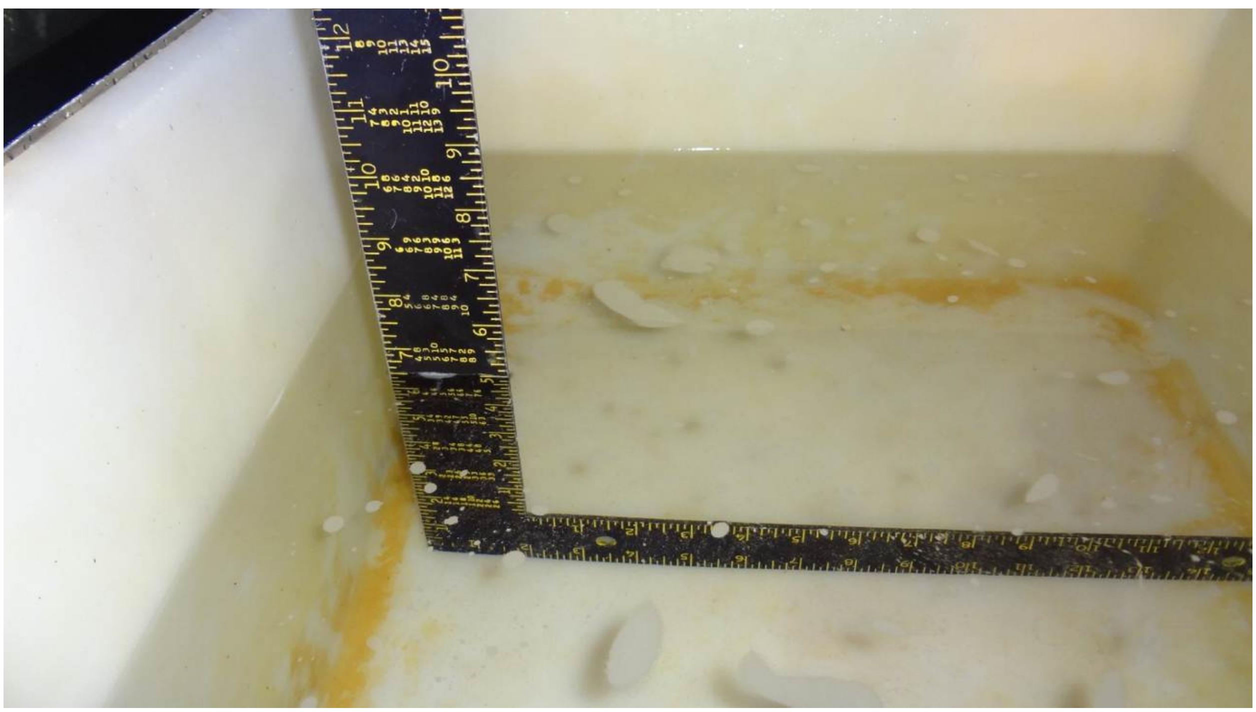


Figure 41: Ruler Measurement

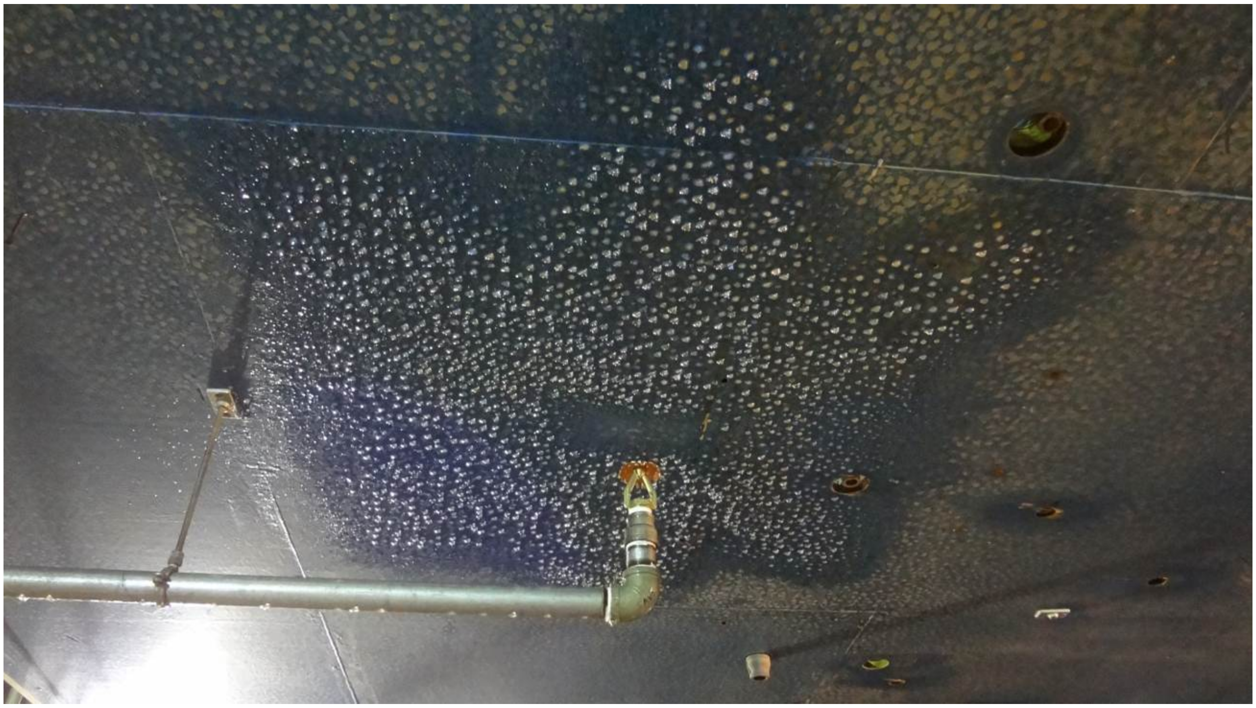


Figure 42: Droplets on Ceiling

Figure 43: Flow Meter Display