DROPLET CHARACTERIZATION USING DIRECT IMAGING TECHNIQUES

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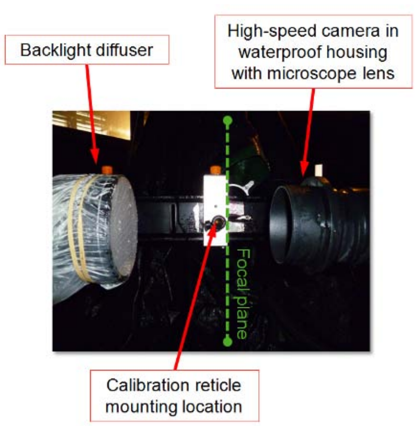
Introduction

The ability to accurately measure sprinkler spray characteristics is necessary to validate predictive modeling tools such as Fire Dynamic Simulator (FDS), in turn leading to better predictions of the spray's impact on the fire environment. Better predictions of sprinklered fires in FDS coupled with a better understanding of the impact of deflector changes will also eventually help to streamline the development of new fire suppression products. The pertinent spray characteristics include droplet size, droplet velocity, ligament breakup distance and flux distribution. Of these, droplet size is a particularly important variable for both modeling accuracy and fire suppression capabilities of the spray.

Droplet size was measured using a laser and a high resolution CCD camera through a technique known as high-magnification shadow imaging (shadowgraphy). A variety of parameters were varied to better understand their effect on droplet size, including spray angle, K-factor, pressure, radial distance from the nozzle and location in the spray. All tests were done using commercially available variations of the Tyco D3 directional spray nozzle.

Setup

A sophisticated setup was used to obtain accurate measurements of droplet size in precise locations within the sprinkler spray. In the shadowgraphy setup, a laser was used with an incandescent light diffuser to provide an evenly lit background synchronized to, and opposite from, the high speed CCD camera. A microscope lens was mounted to the camera and focused to take images in a space approximately 15mm (0.6in) wide by 12mm (0.5in) high at a point midway between it and the light source. The images were calibrated using a glass calibration reticle, with measurements etched covering a 5mm distance centered in the image. A close up view of the camera and backlight assembly is shown in the leftmost picture below.

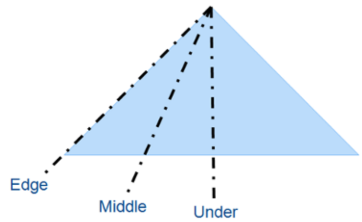


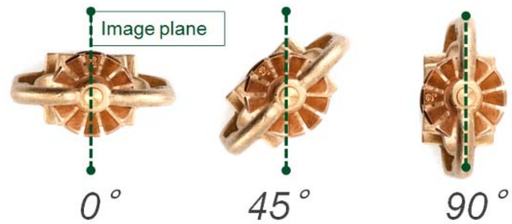
The camera and backlight assembly was mounted on a 3-axis linear translation stage, which allowed movement of the imaging setup in 1mm (0.04in) increments within a 1m^3 (35ft^3) space (center image above). The nozzle was mounted on a rotation system which allowed automated rotation of the nozzle in 1° increments (rightmost image above). The combination of the translation stage and the nozzle rotation system allowed for easy, accurate and repeatable movement of the measurement location within the spray.

Test matrix

The Tyco D3 nozzle is available in a variety of spray angles and K-factors, which made it an ideal choice for the initial research with the shadowgraphy setup. Six different parameters were chosen, as shown in the table and figures below.

Spray Angle °	K-Factor $gpm/psi^{0.5}$ ($lpm/bar^{0.5}$)	Distance ft (m)	Location	Pressure psi (bar)	Rotation Angle °
65 180	1.2 (17.3) 3.0 (43.2)	1 (0.3) 3 (0.9)	Under Middle Edge	20 (1.4) 100 (6.9)	0 (tine) 45 (slot) 90 (frame)





Every sensible combination of the parameters was studied and repetition at some of the points was used to determine repeatability, for a total of 132 data sets. Some combinations were not necessary; for example, when the measurement was taken under the nozzle only the 0° rotation angle was considered. Note from the right image that 0° represents water flow off of a tine, 45° represents water flow through a slot and 90° represents the frame arm interaction. Measurements were taken at the edge of the spray, under the nozzle and halfway between these points. The edge of the spray was difficult to define, especially at 3ft (0.9m) where the effects of gravity were significantly affecting the spray, and required some subjective consideration of what represented the edge of the spray.

Data Collection and Processing

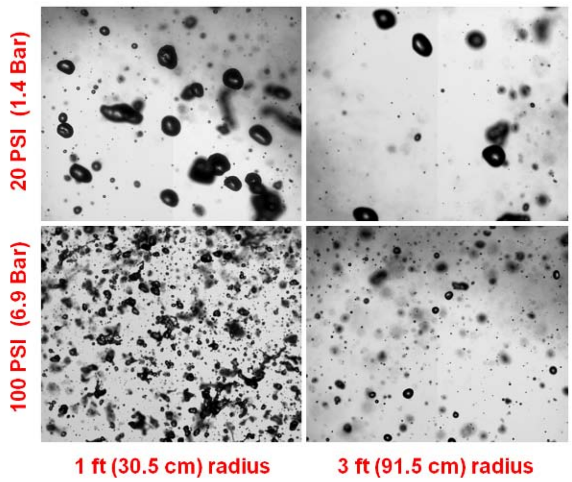
Since water sprays typically consist of droplets of varying diameters, the accuracy of the various droplet size statistics is related to the sample size of droplets utilized in the calculation. Grant et. al. report that 1000-5000 droplets yields an accuracy of 90-95% in the overall statistics obtained from the images.[1] All of the data and statistics presented in the current report are derived from samples containing at least 1000 droplets. To obtain results with an acceptable level of accuracy, a minimum of 100 pictures was collected at each point in the test matrix. Computer software was then used to identify the droplets that are in focus, measure their diameter and calculate the related droplet size statistics for each set of images. Many different statistics are available but the current research focuses on the D32 (the Sauter mean diameter) and DV50 (the volume mean diameter) values, as these are the most commonly utilized when investigating the key evaporative cooling phenomena typically associated with sprinkler sprays.

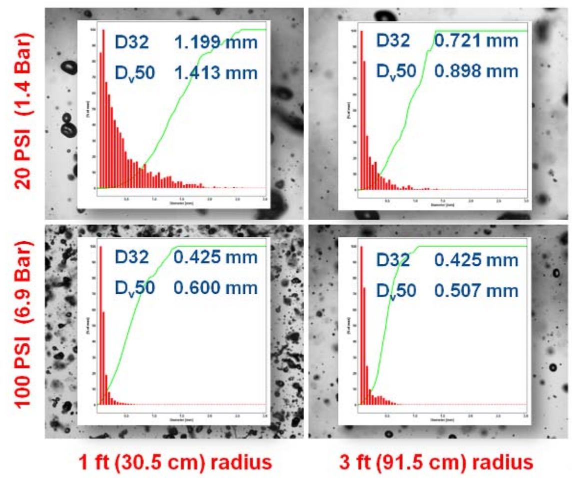
Results and Discussion

A number of interesting trends were observed through data analysis, most of which align with previous research performed by others.[1,2] First of all, if all other factors are held constant and only spray angle is changed, the increase in spray angle from 65° to 180° was observed to cause a decrease in the D32 and DV50 values. Since the directional change in the water jet is most drastic on the 180° deflector (see photographs of nozzles in “test matrix” section above), it is plausible that the resulting water sheet will be thinner and more turbulent than that of the 65° nozzle and cause the observed reduction in droplet size. There were some exceptions to the trend, mostly around the edges of the pattern and at the 90° rotation. On the edges of the pattern, as mentioned above, there was some subjectivity required in the definition of what exactly was the “edge” of the spray. A trial and error approach was used by moving the camera assembly in small increments until it visually appeared to be on the “edge” of the spray. At the 90° rotation, the full effects of the frame arms’ interaction with the water is apparent, which leads to instability and uncertainty in the region. These two exceptions apply to most of the trends seen in the data.

There was generally a significant reduction in droplet size observed with an increase in pressure, likely due to the increased momentum and turbulence of the water jet as it interacts with the deflector. The change was most significant in the flow off of the tines. The water flow through the slots showed a similar trend but it was less dramatic, likely due to the minimal change in water sheet geometry generated by the slot. At a higher pressure (assuming all other factors remain the same), the water is hitting the deflector at a higher velocity, further increasing the turbulence and causing the water to shear into smaller droplets than at lower pressures.

Radial distance from the nozzle was chosen as a factor since it is currently unclear exactly where atomization occurs (i.e. when the spray transforms from sheets to ligaments to individual droplets) and due to the potential for air currents affecting the spray farther away from the nozzle. It was found that atomization seemed to occur more rapidly at higher pressures, likely since the droplets have more momentum and turbulence coming off of the deflector. At 20psi (1.4bar), the data points measured at a 1ft (0.3m) radial distance from the nozzle tended to reveal a variety of small droplets and a significant number of larger droplets that skewed the D32 and DV50 values. At 100psi (6.9bar), measurements at 3ft (0.9m) showed results similar to those at 1ft (0.3m), albeit more dispersed. The difference in the two pressures is shown below, which display single pictures from the spray off a tine and the overall statistics for the set of 100 pictures.





If only the K-factor is changed, the increase in K-factor from 1.2K (K17.3) to 3K (K43.2) in general caused an increase in the D32 and DV50 values. For example, as the K-factor increases (and the pressure is held constant), there is more water that must be pushed through the same area resulting in a thicker water sheet and subsequently larger droplets.

Finally, the location in the spray was affected by both the rotation angle of the nozzle (0°, 45°, 90°) and the location (under, middle, edge). Each factor was varied independently but very similar results were seen. In general, it was found that large droplets tend to maintain their initial trajectory while the smaller droplets are more affected by the air currents created by the spray and fill in the void spaces caused by the sprinkler frame (i.e. by the frame arms on the sides and by the sprinkler boss directly under the nozzle). The same trend was generally repeated in the "void" areas in the spray located beneath the deflector tines (i.e. at the 0° rotation in the middle location) and between tines (i.e. at the 45° rotation at the edge location), where smaller droplets were observed. In general, the spray off of the tines (at the 0° rotation in the edge location) was found to have the largest droplets.

Conclusions

As a first step in improved spray characterization, the Tyco D3 nozzle spray was investigated by varying six different parameters. It was found that general trends observed in past research with respect to orifice size, pressure and the differences in spray through a slot versus a tine hold true. In addition, the slots, tines and frame arms create "void" spaces at various locations in the spray that are filled by smaller droplets due to air currents created by the nozzle spray. While generally predictable trends were observed in the sprays generated by the slots and tines, the interaction with the frame arms was unpredictable.

The potential for several problems that may arise when analyzing sprinkler spray droplet size data was realized throughout the project. For example, if there are not at least 1000 droplets in the images that are used to calculate the D32 and DV50 values, the accuracy is not acceptable and the data cannot be trusted. Also, the camera lens must be clear of droplets that would affect the results. These two problems should be considered by anyone analyzing droplet size data.

References

1 Grant G., Brenton, J. and Drysdale, D. "Fire suppression by water sprays." Progress in Energy and Combustion Science 26 (2000): 79-130.

2 Marshall, Andre W. "Unraveling fire suppression sprays." International Association of Fire Safety Science. College Park, MD, 2011.