Wind Effects on Sprinkler Irrigation Performance

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Abstract. *Sprinkler efficiency, and implications on water waste, is often considered in terms of a single variable, such as minimum distribution uniformity* ***or*** *maximum precipitation rate. However, single variable metrics can be misleading. In addition, metrics, such as distribution uniformity, are measured in zero-wind buildings, which can inadvertently hide the extent to which efficiencies might decline when other variables are introduced, such as wind. The overarching objective of this study was to investigate a multi-variable approach to comparative sprinkler efficiency. The first objective of this study was to measure and analyze both distribution uniformity (DU) and application efficiency (AE) - total water caught in target zone divided by total water intended for target zone - versus wind speed across different nozzle designs. The second objective was to measure the distribution of the water droplet sizes for the same nozzles' sprays. Ultimately, the study was intended to determine if measureable trends emerged between the performance of the nozzles, given increasing wind speed, and their respective water droplet size distributions. During the testing, all nozzles' performance metrics declined with increasing wind – some were affected more than others. Compelling relationships emerged, illustrating a link between a sprinkler's water droplet size distribution and performance in terms of distribution uniformity and application efficiency.*

Keywords. sprinkler efficiency, distribution uniformity, DU, application efficiency, AE, wind speed, average water droplet size, water droplet distributions, The University of Arizona, zero-wind buildings, multi-variable sprinkler efficiency

Introduction

Emission device efficiency has been a focal point for legislative and regulatory actions to drive water conserving irrigation practices. From the EPA WaterSense New Homes Specification to California's Model Efficient Landscape Ordinance, similar standards have been adopted for minimum distribution uniformity and maximum allowable precipitation rates. Empirical evidence suggests that these standards have led to more efficient manufacturer solutions and, when used in conjunction with an integrated irrigation management approach, lead to reductions in water consumption.

Manufacturers, in support of these efforts, are striving to ensure their existing and new emission devices meet these tough regulations. Although there are independent agencies that can be used to verify subsets of legislative requirements; in many cases, manufacturers are left to test and self-certify that their sprinklers meet all requirements of a given legislation. However, most, if not all testing performed by manufactures is done indoors – in zero-wind conditions.

Relying on single variables to assess efficiencies – even comparatively between two emission devices –will not adequately indicate which product will perform more efficiently. Distribution uniformity and precipitation rate-only metrics, measured in zero-wind buildings, ignore water loss that will occur when wind pushes the spray pattern out of the target zone. The underlying assumption is that two different nozzles, if comparable at zero wind, will have reduced, but similar, degraded performance at any wind speed. To state it another way, if nozzle A's distribution uniformity and/or application efficiency is higher than nozzle B at a wind speed of zero, then at any wind speed, nozzle A's distribution uniformity and/or application efficiency will continue to be higher than nozzle B. The rationale is that both nozzles' performance will be reduced similarly.

Relying on single variables to assess efficiencies – even comparatively between two emission devices – often overstates that variable's effect on efficiency. As an example, Dukes et al. (2006) found that, "Although catch can measurements have been used for many years to quantify sprinkler irrigation application uniformity, it is clear that this method neglects the important process of water redistribution through the plant canopy, on the soil surface, and beneath the soil surface." The research concludes that the use of lower quarter distribution uniformity overstates the amount of water that needs to be applied to turf. This research points out that lower half, not lower quarter, is a closer approximate to soil moisture distribution uniformity. The research also illustrates a point in which an increase in catch can distribution uniformity does not translate into increased soil distribution uniformity, because the soil will distribute the water more evenly than a nozzle, sans sandy conditions. The authors also note that similar results have been reported by Mateos et al. (1997) and Stern and Bresler (1983) and Mecham (2001) on turfgrass. This indicates that there is too much emphasis on distribution uniformity scores, if distribution uniformity is used as a lone metric to indicate efficiency.

Given the objective of analyzing single efficiency metrics as wind was introduced, to determine the effects of varying wind speed on those metrics; our hypothesis was that all nozzles' efficiencies would decrease as wind speed increased, but the rate of decrease in performance would not be consistent across different nozzle designs. Further, we hypothesized that a relationship exists between the rate of decreased performance and average water droplet size, more specifically, the distribution of water droplet sizes making up a nozzle's spray pattern.

Methods

Efficiency Metrics vs. Wind Speed in Plot Testing

The following is excerpted from the final project report submitted by Karsten Turf Research Facility, The University of Arizona:

> The study was conducted at the University of Arizona Karsten Turf Research Facility located in Tucson, AZ. The Karsten Facility is located in the alluvial valley of the Rillito River at an elevation of 2440' above sea level. The specific experimental site consisted of eight 12'x12' blocks (plots) of Midiron Bermuda grass turf. Each plot has its own irrigation system complete with separate control valve and meter. Sprinklers are installed at the corners of each plot in a square spacing arrangement with adjacent heads separated by a distance of 12'. A total of 32 casings were installed in each plot to hold irrigation catch cups. All casings were installed to allow catch cups to be placed at turf level. Sixteen round casings constructed of 4” diameter PVC pipe were installed in a centered and evenly spaced square grid within the plot area. The separation distance between adjacent round casings was 3'. Sixteen rectangular casings constructed of short lengths of vinyl gutter were installed along the perimeter of the plot to facilitate collection of water applied to the edge of each plot. Catch cups were inserted into the casings prior to each irrigation run. The circular cups were the funnel-shaped cups manufactured by the CalPoly Irrigation Training and Research Center. Rectangular food storage containers (6”x 4.5”; Up and Up Brand) served as the perimeter catch cups.
>
> The meters for each plot were calibrated at the beginning of the study and each time a different set of sprinklers were compared. The calibration procedure involved attaching a hose to one of the 2 irrigation risers while capping the remaining risers. The system was then operated for a set period of time with the water passing through the system collected in a large plastic carboy. The weight increase in the filled carboy was converted to volume units and then compared to the difference in meter readings obtained before and after each run. Meter adjustment factors were derived by dividing the volume collected during a run by the volume indicated by the meter.
>
> Each set of sprinkler heads was compared on a minimum of ten mornings during the summer of 2012 and winter of 2013. All sprinklers were installed in 4" Rain Bird Model 1800 SAMPRS bodies. Preliminary tests were conducted for each set of sprinklers to determine the precipitation rate. Run times were then set such that each set of heads applied approximately 0.50" of water. For a given comparison event, irrigation of all plots (both sprinklers) was initiated at the same time. The termination time of irrigation varied due to the differences in precipitation rate of the opposing sprinklers. At the completion of each run, the volume of water in each cup was determined by transferring the water collected into a graduated cylinder and recording the resulting volume. Catch

cup volumes were then converted to depth by dividing by the surface area of the cup. All comparisons were run during the morning hours in the summer of 2012. Some afternoon comparisons were included in the winter of 2013 to avoid subfreezing conditions and to better assess the performance of the sprinklers during periods with higher wind speeds.

Sprinkler performance was evaluated by measuring distribution uniformity (DU) and application efficiency (AE). Distribution uniformity was computed using the 16 circular catch cups located within each plot. Specific DU computations included the low quarter distribution uniformity (LQDU) and low half distribution uniformity (LHDU). The LQDU is determined by computing the average of the lowest 25% of catch volumes (depths) then dividing this value by the average volume (depth) of all cups. The LHDU is determined by computing the average of the lowest 50% of catch volumes (depths) then dividing this value by the average volume (depth) of all cups. The scheduling coefficient (SC) was also computed for each comparison using the 16 circular catch cups. The SC was computed by dividing the average depth of water collected in the 16 catch cups by the smallest depth of water collected in a single cup (of 16 catch cups).

Application efficiency was determined using two difference computation procedures. The first procedure (AE16) involved taking the average depth of the 16 circular catch cups and dividing by the equivalent depth of water that passed through the water meter (meter volume converted to depth based on plot area of 144 sq. ft.). The second computation procedure (AE32) used all 32 catch cups to estimate the depth of water reaching the turf surface. In this procedure the total area of the plot was divided into 21 rectangular areas with catch cups located at the four corners of each area (Fig. 2). The average depth of water applied to each rectangle was computed by taking the average of the four corner catch cups. The four small corner areas of the plot had just three catch cups since the sprinkler head was located on the fourth corner (Fig. 2). For these corners, the depth of water collected at the head was estimated by averaging the catch values of the two closest cups. This estimated value was then averaged with the three cup values to estimate the depth of water received in the small corners. Depth estimates for the 25 rectangles were then multiplied by their respective areas (9, 4.5 or 2.25 sq. ft.), summed and divided by the total plot area (144 sq. ft.) to obtain the average amount of water reaching the plot surface. This value was then divided by the actual depth of water applied (as determined from the meter) to determine AE32.

Experimental design was randomized complete block with two treatments (irrigation heads) and four reps. All data were analyzed using the appropriate statistical procedure as provided by SAS (SAS Institute, Cary, NC).

A weather station was installed upwind of the plots to provide data on temperature, humidity, wind speed and wind direction during each evaluation period. Temperature and humidity were monitored at 5' (1.5 m) above ground level (agl) with a Vaisala Model HMP45C combination temperature and relative humidity sensor. Wind speed and direction were monitored at 6.6' (2.0 m) agl using a RM Young Model 03002Wind Sentry Set. All sensors were connected to a Campbell Scientific Inc. 4 Model 10X datalogger programmed to scan sensors at 0.2 Hz and output parameter means every 15 sec. The meteorological data were downloaded to a portable computer then imported into spreadsheet software where the data were summarized over the specific run times of each evaluation.

Nozzle's Water Droplet Distribution Testing

The following is excerpted from the final project report submitted by Spraying Systems Company, Spray Analysis and Research Services group:

> The Sympatec HELOS Particle Analyzer was used to acquire drop size measurements for this test. The Sympatec is a laser diffraction instrument that measures drop size based on the energy of the diffracted light caused by drops passing through the analyzer's sampling area. The Sympatec uses a 632.8nm HeNe-laser with a long resonator. The scattered light intensity distribution is measured using a multi-element semicircular photo-detector housed in the receiver unit. Testing was performed using a R6 and R7 lens setup. These lens configurations allow a measurement range of 9.0 μm to 1750 μm and 18.0 μm to 3500 μm respectively.
>
> The spray head and nozzles were attached to the platform of a lift truck, which allowed for the entire spray plume to be passed through the measurement zone [vertically] at a specified [1 foot, 3 feet, 6 feet] horizontal distance. The water pressure [30 psi, 50 psi, 70 psi] was controlled by an adjustable needle valve and monitored using an analog Bourdon Tube pressure gauge. A cylinder with approximately a two inch wide cut along its length was lined with a mist eliminating pad, which was used to block most of the stream and only allow a narrow section to pass through the measurement zone of the analyzer. The mist eliminating pad prevented splashing of the spray inside the cylinder from interfering with the testing portion of the spray pattern.
>
> Drop size distribution is expressed by the particle size versus the cumulative volume percent, as all drops within a given spray plume are not the same size. Smaller droplets possess greater drift potential. These drops have less momentum than larger droplets and are more likely to drift off or evaporate as they move further away from the nozzle orifice. As the MVD (DV0.5) is the average volume of all the droplets present in the sample, the presence of larger droplets significantly influences the resultant MVD value.

> All drop size measurements were taken at the same distances for nozzles of the same type […]. The spray plume was scanned a minimum of three times, […], and straight averaged to obtain the final cumulative drop size values and cumulative distribution graphs.

Attention should be brought to this last point. A minimum of three scans were taken for each pressure and distance point. In cases where the first three scans did not show consistency in measurements, additional scans were obtained to ensure consistent results. Inconsistent results were often the result of water droplets getting onto the measuring device's lens, which would create results that were easily distinguishable as an invalid scan.

Results and Discussion

Efficiency Metrics vs. Wind Speed in Plot Testing

Table 1 shows a summary of results obtained during both summer and winter trials of Nozzle B versus Nozzle C. A range of significantly different values were obtained as measured by the catch can method. It is apparent that wind speed during individual comparison events greatly impacted the comparative results in all four measurements. Nozzle B produced significantly higher values in all four metrics, as compared to Nozzle C, regardless of the season.

Table 1 Average of Metrics (B versus C)

Summer Trials				
Wind Speed Range	0 – 9.2 mph			
Wind Speed Average	3.6 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle B	52%	72%	81%	78%
Nozzle C	40%	64%	62%	60%
Stat Sig ($p<0.05$)	Yes	Yes	Yes	Yes
Winter Trials				
Wind Speed Range	1.1 – 5.1 mph			
Wind Speed Average	3.1 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle B	75%	85%	77%	79%
Nozzle C	65%	80%	75%	72%
Stat Sig ($p<0.05$)	Yes	Yes	Yes	Yes

The researchers noted in their report that Nozzle C appeared to produce smaller droplet sizes in comparison to Nozzle B and was more vulnerable to drift under moderate to high wind conditions – which is confirmed in the data. The lower values of AE(16) and AE(32) for Nozzle C provide clear evidence that a significant amount of water simply drifted out of the target zones.

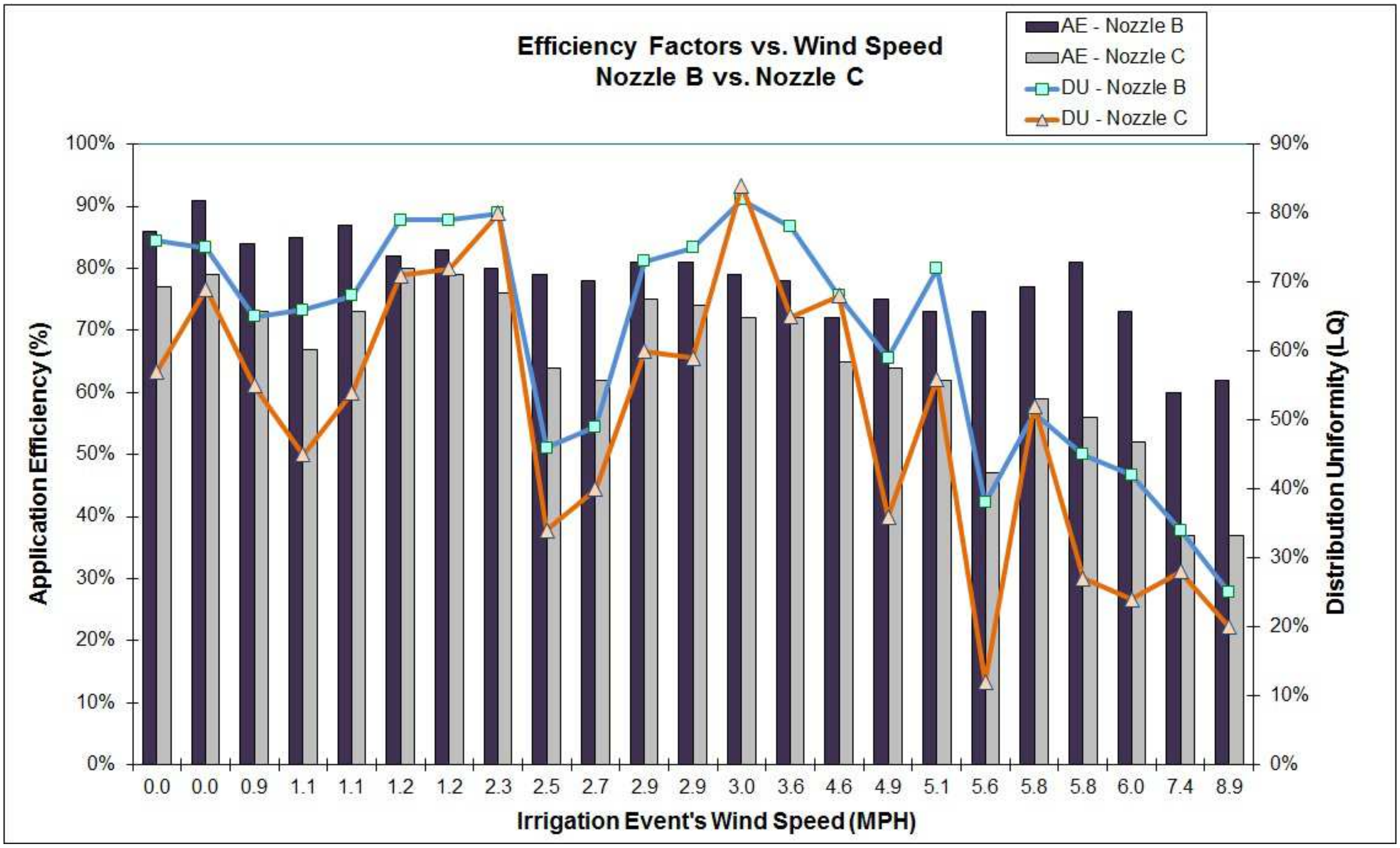
The researchers also noted that the depth of water collected was significantly lower in plots irrigated with Nozzle C – even though all plots received 0.50 inch of water.

Although separating water loss into drift and evaporation components was not within the scope of this study, the researchers noted in their final report an interesting trend they uncovered in the data and provided a hypothesis for consideration:

> It is interesting to note that the relationship between perimeter catch and wind speed appear to differ from summer to winter as do several other performance parameters. One possible explanation for this difference could rest in the evaporative potential of the atmosphere. Vapor pressure deficit (VPD), a measure of the difference from saturation of the water vapor pressure in the atmosphere, represents the best means of estimating the evaporative power of the air. The VPD during the summer and winter comparisons averaged 2.98 kPa and 0.87 kPa, respectively. One should expect the higher VPDs in summer to produce more spray evaporation during irrigation events with the overall effects greatest in plots irrigated with [Nozzle C] due to the much smaller droplet size. The differing response of [Nozzle C] to wind speed […] support the evaporation hypothesis. It is also interesting to note the improvements in AE16 and AE32 for [Nozzle C] in winter as compared to summer. Considerably more water was reaching the catch cans in winter relative to summer, again suggesting [Nozzle C] is more prone to evaporation due to the smaller droplet size. A similar response was not observed from plots irrigated with [Nozzle B] which produce larger droplets and should be less prone to evaporation.

Graph 1 shows individual irrigation event results for application efficiency and lower quarter distribution uniformity. The data is sorted by wind speed to provide a perspective for the rate of decline of these efficiency metrics as wind speed increases.

Graph 1 Efficiency Factors vs. Wind Speed (B versus C)



The data clearly illustrates that both of these nozzles' performance experienced a decline as wind speed increased, which was expected. Looking at the data in this manner exposes two areas for consideration. First, LQDU values for both nozzles appear to trend together in their decline with increasing wind speed. However, looking at application efficiency, it is clear there is a tipping point for Nozzle C around 4 MPH, where Nozzle C's rate of decline increases as compared to Nozzle B. In this case, given a single view of LQDU, one might conclude the nozzles are comparable, given discussions of data collection and measurement limitations. However, in this case, if one was provided application efficiency versus wind speed, a clear distinction of efficiency becomes apparent, as Nozzle B is clearly able to provide more water into the target zone as wind speed increases.

Table 2 shows a summary of results obtained during both summer and winter trials of Nozzle A versus Nozzle C. A range of significantly different values were obtained, with the exception of LHDU during the summer trials, as measured by the catch can method. This evaluation produced mixed results.

Table 2 Average of Metrics (A versus C)

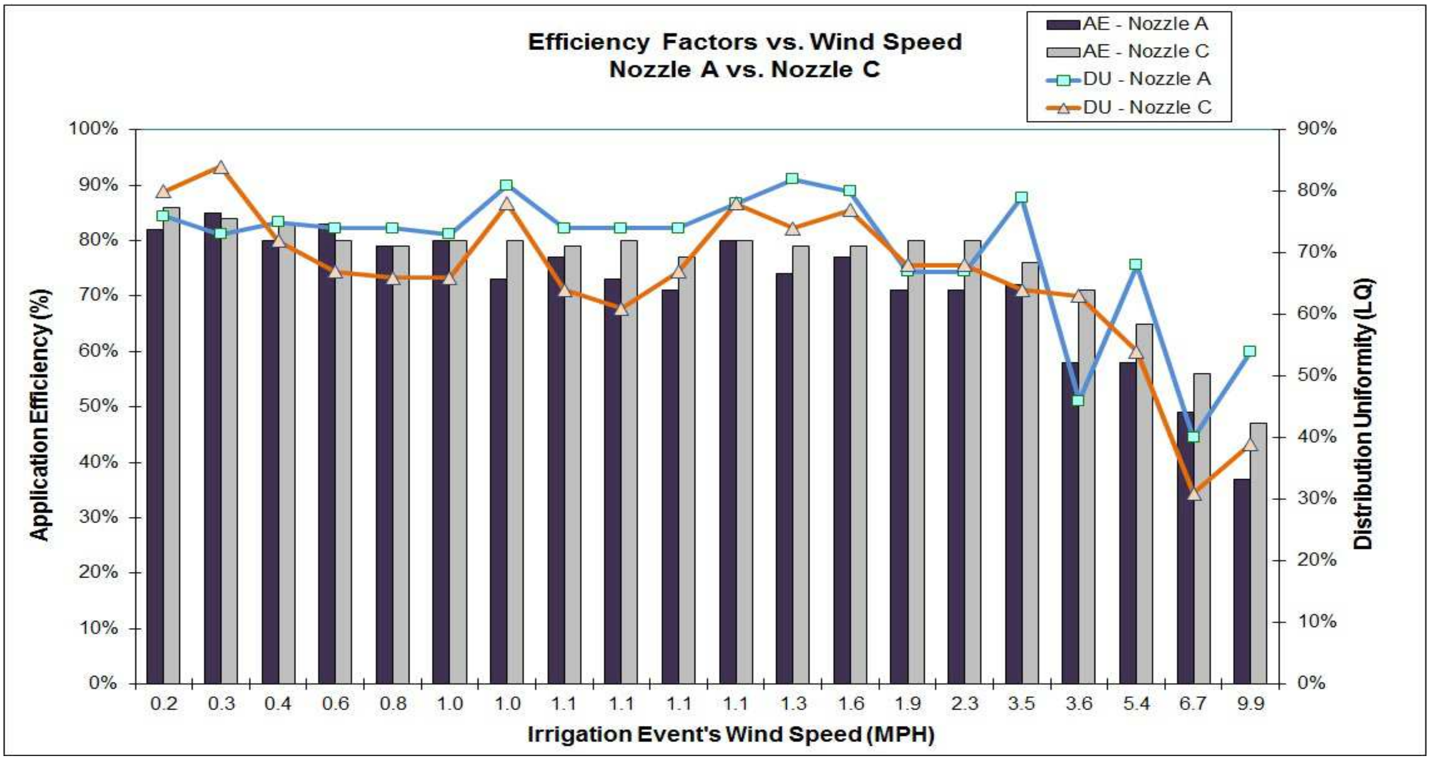
Summer Trials				
Wind Speed Range	0 – 2.5 mph			
Wind Speed Average	1.6 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle A	**75%**	82%	75%	81%
Nozzle C	**70%**	82%	85%	78%
Stat Sig (p<0.05)	Yes	No	Yes	Yes
Winter Trials				
Wind Speed Range	1.1 – 9.8 mph			
Wind Speed Average	3.7 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle A	66%	79%	61%	65%
Nozzle C	62%	77%	74%	71%
Stat Sig (p<0.05)	Yes	Yes	Yes	Yes

The impact of wind on sprinkler performance was again evident in this analysis, as can be seen in the decline in metrics from summer to winter trials, which experienced higher winds. Wind negatively impacted both LQDU and LHDU on both nozzles. In some cases, legislation today has us compare LQDU values alone to determine which nozzle is more efficient. Unfortunately, most of the available data to make the comparison has been collected in zero wind conditions. Taking a look at the bolded summer trial's LQDU data – which had very low wind (0 – 2.5 mph) and would closely approximate indoor testing results – one would conclude that Nozzle A is more efficient than Nozzle C.

However, provided more information, as presented in Table 2, one would not be able to conclude determinately which nozzle to be more efficient. One could argue that given this set of data, looking at AE(16) and AE(32) during the winter trials, that Nozzle C is capable of providing more water into the target zone at higher wind speeds. Therefore, selecting Nozzle C will result in higher efficiency due to its ability to provide greater wind protection – delivering more water into the target zone and allowing the soil to provide further distribution of the water in the soil, as supported by Dukes et al. (2006) discussed previously. This supports the concern of overemphasis of any one variable as a determinate of efficiency.

Graph 2 shows the individual irrigation event results for application efficiency and lower quarter distribution uniformity. The data is sorted by wind speed to provide a perspective for the rate of decline of these efficiency metrics as wind speed increases. Looking at the complete set of data in this fashion, as the researchers pointed out, "A clear advantage did not emerge from the evaluations comparing [Nozzle A] to [Nozzle C]." This conclusion was reached because neither nozzle provided a clear advantage in any of the four metrics, when comparing both LQDU and AE.

Graph 2 Efficiency Factors vs. Wind Speed (A versus C)

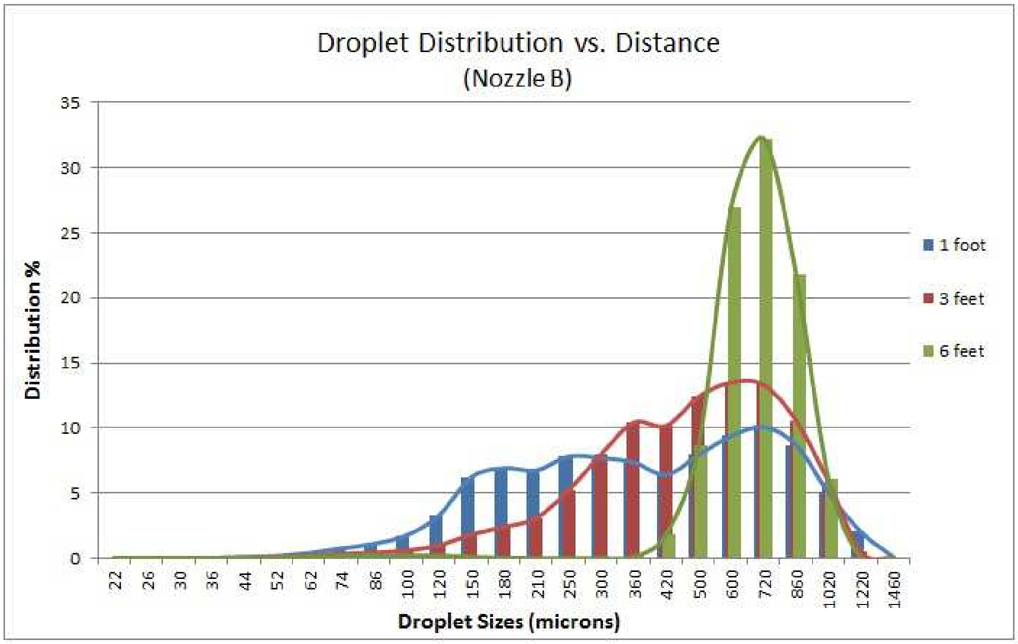


<u>Nozzle's Water Droplet Distribution Testing</u>

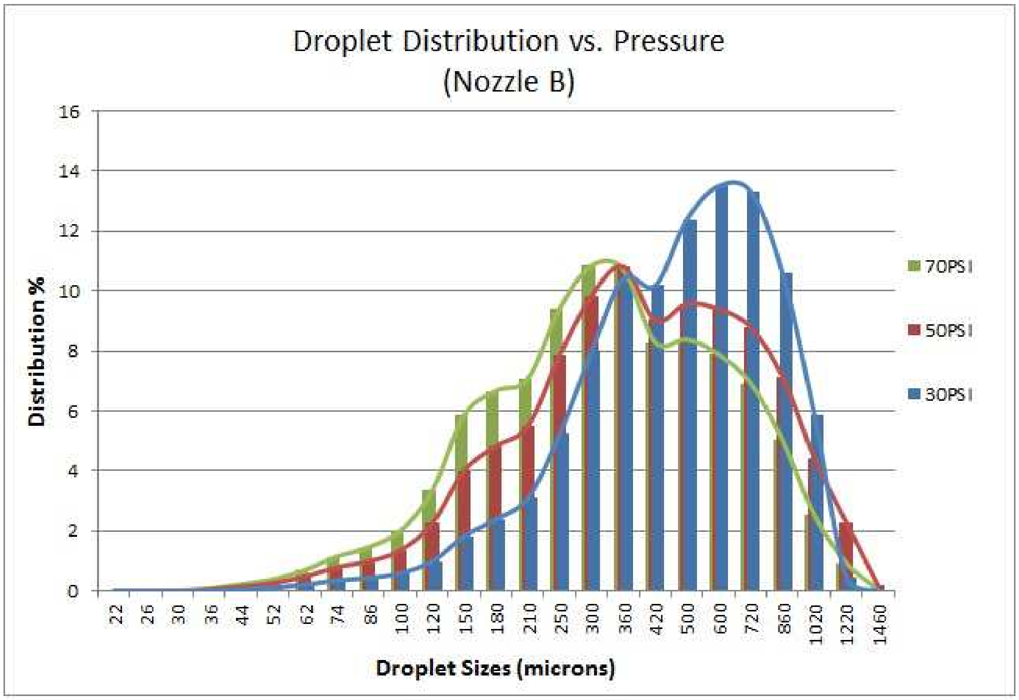
Prior to comparing measured values of each nozzle, it was desirable to ensure expected trends emerged within each nozzle's data. It would be expected that if measurements were made close to the nozzle's orifice and then further away horizontally, closer measurements would contain a higher percentage of smaller water droplet particles. Measurements taken further from the nozzle should contain a higher concentration of larger water droplets because smaller droplets should have drifted (or evaporated) away. Second, it would be expected that significant differences in measurements should be seen as pressure increases. As pressure increases, water should atomize and create a higher concentration of smaller water particles.

It was determined all nozzles would be measured at 1 foot, 3 feet, and 6 feet measurements, horizontally from the nozzle. In addition, at each horizontal location, measurements would be taken at 30 psi, 50 psi, and 70 psi. The expected trends as described are significant in each nozzle's data. Graph 3 and graph 4 are provided to illustrate the existence of the trends captured on Nozzle B. Although pressure regulation was not within the scope of this project, graph 4 provides strong implications regarding the reduction of water lost through evaporation and drift when pressure regulation is installed in high pressure situations. Graph 4 provides strong evidence that high pressure causes smaller water droplets that will increase water loss significantly.

Graph 3 Distribution Shift versus Distance from Sprinkler



Graph 4 Distribution Shift versus Operating Pressure

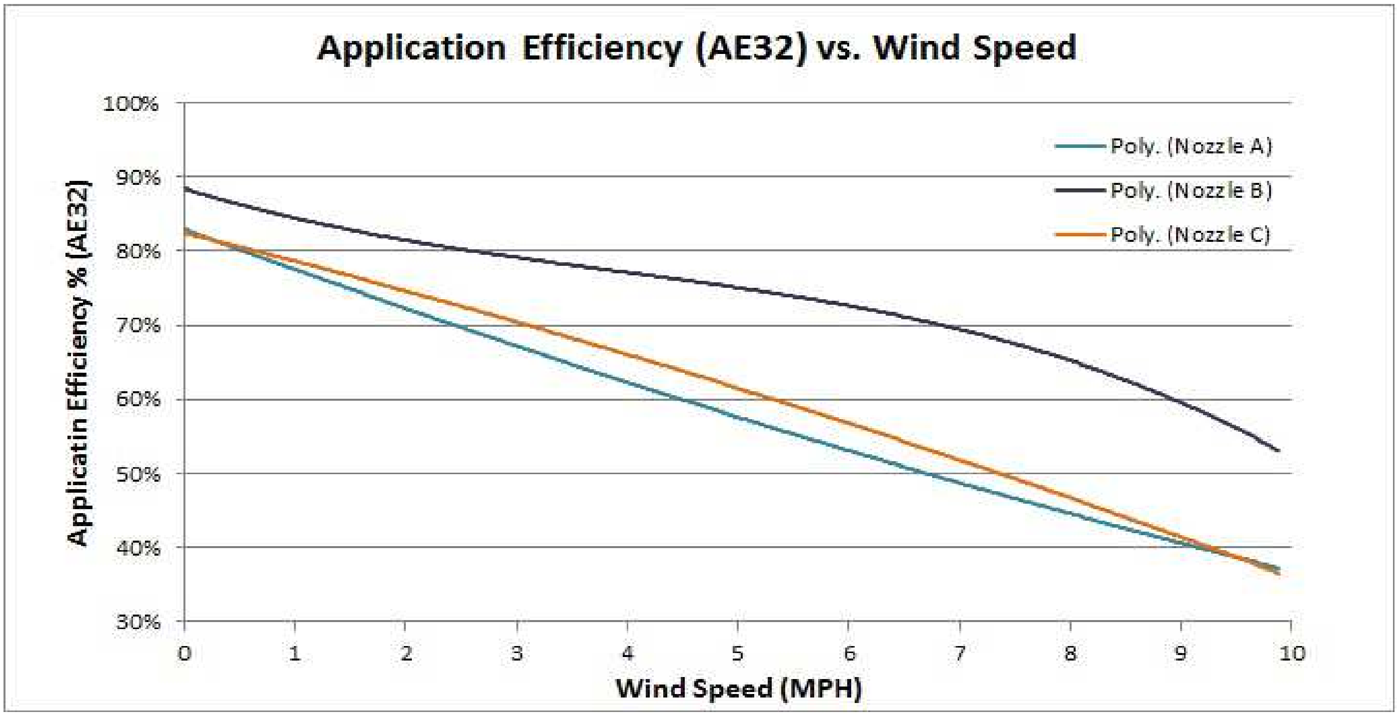


Tying the Research Together

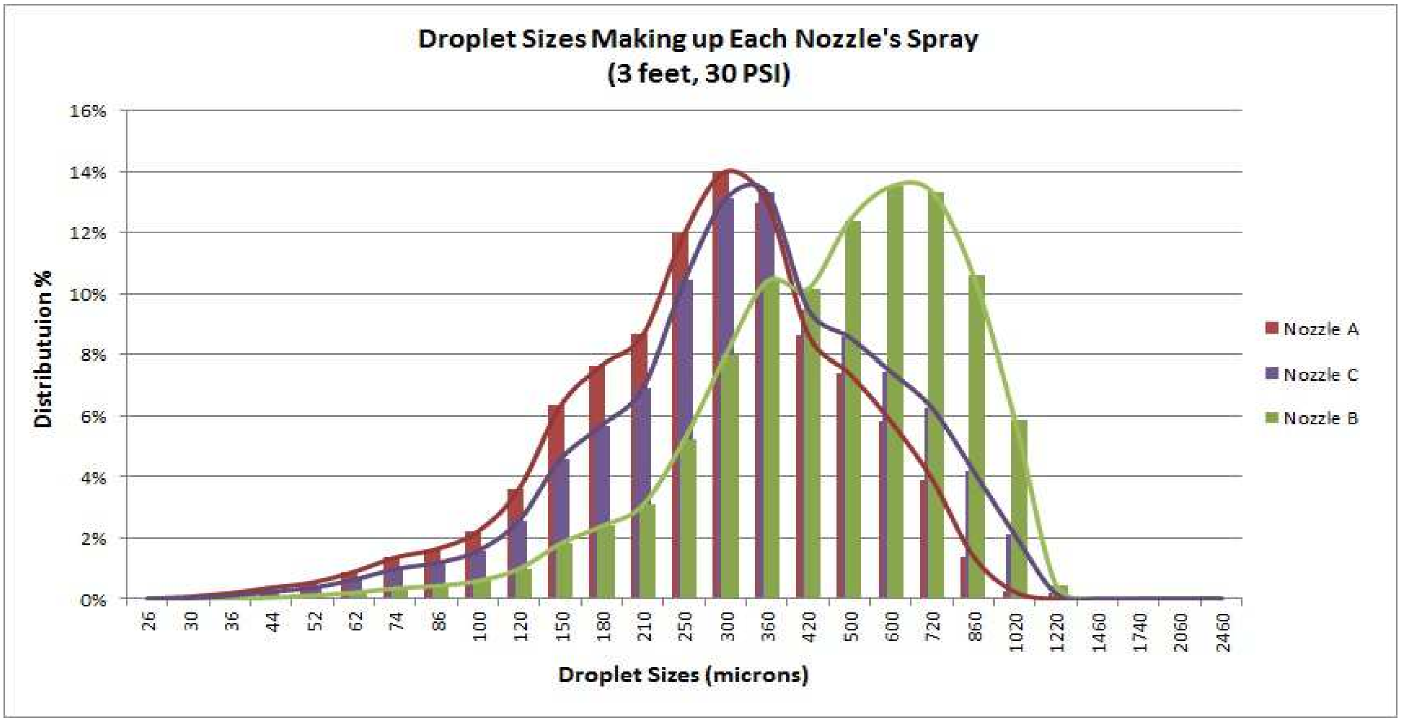
At the outset of this project the primary objective was to determine if efficiency metrics could be plotted against wind. In essence, the objective was to generate more accurate pictures of differing nozzle designs' efficiencies when operated in their actual environments. Over the course of time during the work at The University of Arizona, it became apparent that testing nozzles outdoors for extended periods of time to generate statistically relevant curves is not practical. This led to the second objective, which was to identify a possible solution for overcoming the impractical nature of testing outdoors, yet still being able to generate the data. Hence, the second portion was initiated to take the same nozzles and attempt to measure their water droplet size distribution curves. In this, it was important to ensure the results were repeatable and that the measurements followed trends provided by a general understanding of physics. It has been determined that the results of droplet testing are repeatable. It has been determined that the results of droplet testing follow expectations set forth by a general understanding of physics, regarding distance of measurement and pressure variations. This is all somewhat academic, as other industries have utilized this type of measurement for many years and use the results to develop different nozzle technologies. The American Society for Testing and Materials (ASTM) has well defined standards for measuring particle sizes.

Graph 5 shows the best fit trend lines for each nozzle versus wind speed as determined by The University of Arizona research team. Evident in this graph is that there is something fundamentally different about Nozzle B that allows it to get a higher percentage of water into the target zone as wind speed increases, compared to the other two nozzles. The primary hypothesis is that the attribute is larger average water droplet sizes. Graph 6 confirms the hypothesis.

Graph 5 Trend Lines of Application Efficiency vs. Wind Speed

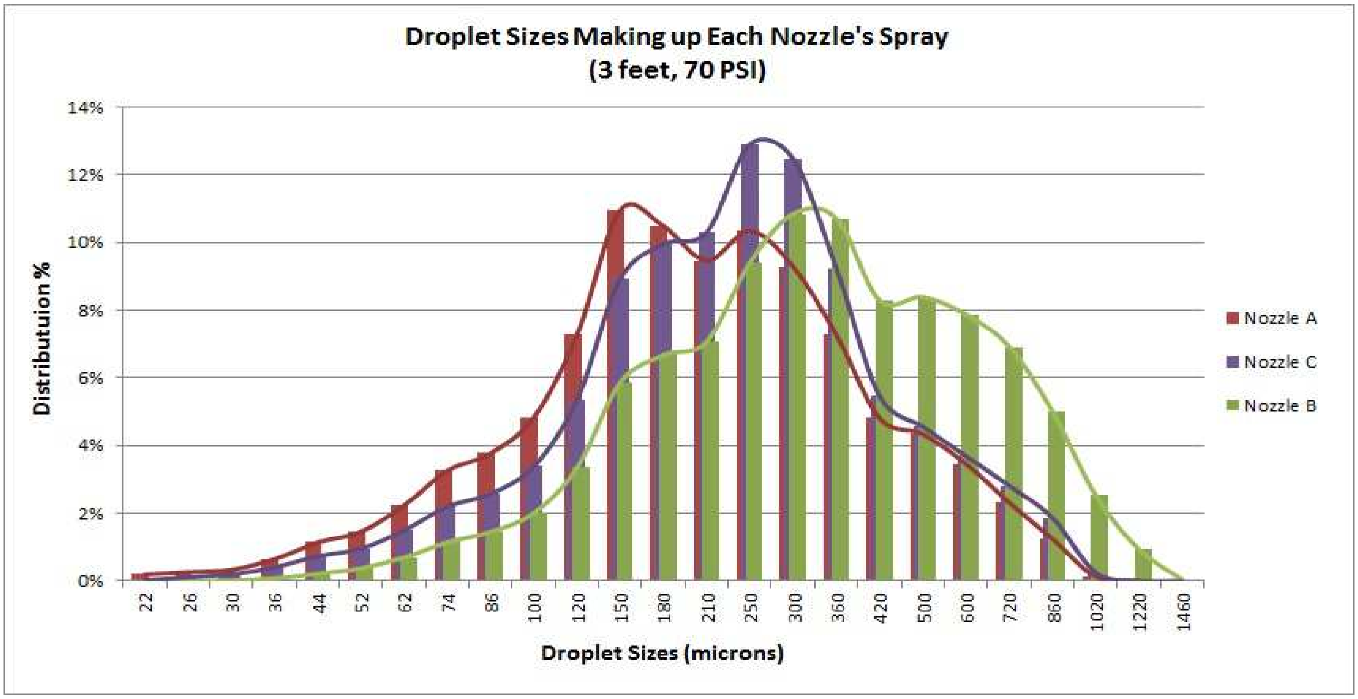


Graph 6 Nozzle Spray Make Up at 3 Feet and 30 PSI



Although not in the original scope of the research, the data that was collected also illustrates that nozzles designed with a spray made up of larger water droplets are able to tolerate higher pressures. This seems logical because it would take higher pressure to atomize larger water droplets.

Graph 7 Nozzle Spray Make Up at 3 Feet and 70 PSI



Conclusions

Although single metrics have been used for years to quantify an emissions device's efficiency factor, it is clear that any single data point metric can be troublesome when relied on solely to compare two devices. A multi-variant approach to quantifying a sprinkler's efficiency, including efficiency metrics versus wind speed, is a step towards a more complete picture of a sprinkler's efficiency.

Despite the testing of only 4 different nozzles, with limited data sets, compelling trends between efficiency factors versus wind speed and water droplet size distribution emerged. This is encouraging and indicates more data should be collected and analyzed to find stronger correlations between wind curves and water droplet size distributions. This could eventually lead to the ability to simply measure a sprinkler's resulting water droplet size distribution and very closely approximate the resulting distribution uniformity and application efficiency as a function of wind speed – removing the need to test product outside for extended periods.

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