This is not a peer-reviewed article.
5th National Decennial Irrigation CD-ROM Proceedings
Phoenix Convention Center, 5 - 8 December 2010, Phoenix, AZ USA
M. Dukes ed. St Joseph Mich: ASABE
ASABE Publication Number 711P0810cd

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An ASABE Conference Presentation

Paper Number: IRR10-8726

Droplet Kinetic Energy from Center-Pivot Sprinklers

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Written for presentation at the
5th National Decennial Irrigation Conference
Sponsored jointly by ASABE and the Irrigation Association
Phoenix Convention Center
Phoenix, Arizona
December 5 - 8, 2010

Abstract. *The kinetic energy of discrete water drops impacting a bare soil surface generally leads to a drastic reduction in water infiltration rate due to formation of a seal on the soil surface. Under center-pivot sprinkler irrigation, kinetic energy transferred to the soil prior to crop canopy development can have a substantial effect on seasonal runoff and soil erosion, especially when the soil is not protected by crop residue cover. In the design of center-pivot irrigation systems, selection of sprinklers with minimum applied kinetic energy may minimize these problems. Size and drop velocity from common rotating spray-plate center-pivot sprinklers with flow rates of approximately 40 and 20 L min^{-1} were measured indoors using a laser. Two approaches to characterize the kinetic energy transferred to the soil by rotating spray-plate sprinklers were evaluated. Specific power* *represents the rate at which kinetic energy per unit area is transferred to the soil as a function of distance from a sprinkler and is analogous the radial water application rate distribution from a single sprinkler. Specific power was used to estimate the amount of kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers spaced 3 m along a center-pivot lateral. Kinetic energy of irrigation sprinklers has traditionally been characterized using area-weighted kinetic energy per unit drop volume. This method heavily weights the effects of the largest drops, which travel the farthest and have the largest kinetic energy, but does not account for the volume applied by each drop size. The traditional method of characterizing sprinkler kinetic energy was not well correlated to amount of kinetic energy transferred to the soil.*

Keywords. Sprinkler, Center pivot, Infiltration, Kinetic energy, Runoff, Sprinkler irrigation.

Introduction

When discrete water drops impact a bare soil surface, a drastic reduction in water infiltration rate is generally observed due to soil surface seal formation. The physical processes involved in formation of a surface seal include compaction, aggregate destruction, soil particle detachment, dispersion, and deposition of fine particles in surface pores. These physical processes reduce surface soil porosity and mean pore size to create a disturbed layer with reduced hydraulic conductivity that expands in size and depth with time (Assouline and Mualem, 1997). The effect that soil surface seal formation has on water infiltration rate has been studied by Agassi et al. (1985, 1994), Thompson and James (1985), Mohammed and Kohl (1987), Ben-Hur et al. (1987), and Assouline and Maulem, (1997). These studies have shown that the kinetic energy of discrete drops impacting a bare soil surface is a primary factor in determining the reduction in water infiltration rate due to soil surface sealing. Much of the research on soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; DeBoer and Chu, 2001; Silva, 2006). Soil surface seal formation in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard.

Soil erosion involves the processes of detachment of soil particles from the soil surface and transport of the soil particles. In interrill erosion, soil particle detachment is caused by drop impact and soil transport is caused by drop splash and runoff sheet flow (Watson and Laflen, 1986). Soil particle detachment was found to be related to drop kinetic energy by Ekern (1954), Wischmeier and Smith (1958), Moldenhauer and Long (1964), Bubenzer and Jones (1971), Quansah (1981), Gilley and Finkner (1985), Agassi et al. (1994), and Ben Hur and Lado (2008). Soil detachment is one of the processes contributing to soil surface seal formation. Reduction of infiltration rate due to soil surface seal formation increases runoff sheet flow and the capacity to transport detached soil particles.

The influence that kinetic energy applied by center-pivot sprinklers has on infiltration, runoff, and erosion is well known in the center-pivot sprinkler irrigation industry. Over the past two decades, center-pivot sprinkler manufacturers have continued to develop sprinklers that reduce peak water application rates and droplet kinetic energy to sustain infiltration rates and reduce runoff and erosion. Consequently, there are numerous sprinkler choices available to the center-pivot irrigation system designer and crop producer; however, limited quantitative information is available that relates these choices to performance with regard to infiltration, runoff, and erosion. Kincaid (1996) developed a model to estimate sprinkler kinetic energy per unit discharge volume of common sprinkler types as a function of nozzle size and operating pressure for use as a design aid in selecting center pivot sprinklers. DeBoer (2002) evaluated the kinetic energy per unit discharge of select moving spray plate sprinklers for center-pivot irrigation systems and developed a model of kinetic energy as a function of spray plate type, nozzle size, and operating pressure. Values of kinetic energy per unit discharge are largely dependent on the drop size characteristics of the sprinklers. Sprinklers that produce relatively large drop sizes generate the highest kinetic energy while sprinklers producing relatively small drop sizes yield the lowest kinetic energy. The drop size distribution from a sprinkler has a substantial influence on the wetted diameter and application rate. Sprinklers that create small drop sizes usually produce relatively small wetted diameters and result in higher average application rates. Sprinklers that develop relatively large drop sizes usually generate larger wetted diameters, which reduces average application rate. Runoff and erosion reduction associated with lower applied kinetic energy from smaller size drop distributions can be diminished or eliminated because of the higher application rate. Consequently, kinetic energy per unit discharge has not been helpful in selecting sprinklers and has not proved useful in center-pivot irrigation system design.

King and Bjorneberg (2009) evaluated runoff and erosion from five common center-pivot sprinklers on multiple soils and found significant differences between sprinkler types even though flow rates and wetted diameters were similar. Kinetic energy per unit discharge estimated using the models of Kincaid (1996) and DeBoer (2002) did not correlate with measured runoff or erosion rates. The objective of this study was to determine kinetic energy applied to the soil by sprinkler devices commonly used on center-pivot irrigation systems and compare the results with kinetic energy per unit discharge that has traditionally been used to characterize sprinkler kinetic energy. The results will demonstrate that the latter method does not represent the kinetic energy applied to the soil resulting from center-pivot irrigation.

Methods and Materials

The sprinkler devices used in this study and corresponding operating pressures and nozzle sizes are listed in table 1. The I-Wob[1] and Xi-Wob sprinklers (Senninger Irrigation, Inc., Clermont, Fla.) utilize an oscillating plate with grooves of equal geometry to break up the nozzle jet and create discrete water drops. The R3000 sprinklers (Nelson Irrigation Corp., Walla Walla, Wash.) use rotating plates with grooves to break up the nozzle jet and create discrete streams of water leaving the plate edge. The R3000 sprinkler with the brown plate has ten grooves with multiple trajectories angles and widths. The R3000 sprinkler with the red plate has six grooves of equal trajectory angle (12°) and width. The R3000 sprinklers have plate rotational speeds of 2 to 4 revolutions per minute. The S3000 sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) also uses a rotating plate with grooves to break up the nozzle jet. A purple rotating plate with six grooves of equal width and trajectories from 12 to 20 degrees has a rotational speed of 400 to 500 revolutions per minute. The N3000 sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) utilizes an oscillating plate with grooves of equal geometry to break up the nozzle jet and create discrete water drops. Sprinkler nozzle sizes were selected to provide nearly equal flow rates at the given operating pressures based on manufacturer data.

Drop sizes and velocities were measured using a Thies Clima Laser Precipitation Monitor (TCLPM, Adolf Thies GmbH & Co. KG, Gottingen, Germany) (King et al., 2010). Measurements were conducted indoors with no wind. Measurements were collected at 1-m increments radially outward from the sprinkler. A minimum of 10,000 drops were measured at each location except at the most distal radial location, where a minimum of 4,000 drops were measured to save time. Sprinklers were positioned on the end of a drop tube with nozzle discharge directed vertically downward 0.8 m above the laser beam of the TCLPM. Pressure regulators with nominal pressure ratings for the test condition were used to control pressure at the base of the sprinkler. A pressure gauge located between the pressure regulator and sprinkler base was used to monitor pressure. Pressures were within ±7 kPa of the nominal pressure rating. Specific details of the experimental methods are provided by King et al. (2010).

Radial application rate distributions for the sprinklers were also measured indoors with no wind. Catch cans, 150 mm in diameter and 180 mm tall spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. Sprinkler height was 0.8 m above can opening. The duration of each test was 30 to 60 min. Water collected in each can was

[1] Mention of a trademark, vendor or proprietary product does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable. This type of information is solely provided to assist the reader in better understanding the scope of the research and its results.

Table 1. Sprinkler types, nozzle sizes, pressures and flow rates used in study.

Nozzle Diameter (mm)	Flow Rate (L min^{-1})* 69 kPa	103 kPa	138 kPa
Senninger I-Wob, Black Plate, 9 grooves			
5.55	16.6	19.8	22.8
7.94	33.1	39.5	45.6
Senninger Xi-Wob, Black Plate, 6 grooves, 15° trajectory			
5.55	16.6	19.8	---
7.94	33.1	39.5	---
Nelson N3000, Green Plate, 9 grooves, 21° trajectory			
5.75	17.5	21.4	---
8.14	35.5	43.4	---
Nelson S3000, Purple Plate, 6 grooves, multi-trajectory			
5.75	---	21.4	---
8.14	---	43.4	---
Nelson R3000, Red Plate, 6 grooves, 12° trajectory			
5.35	---	---	21.2
7.54	---	---	42.7
Nelson R3000, Brown Plate, multi-trajectory			
5.35	---	---	21.2
7.54	---	---	42.7

*Flow rates based on manufacturer's data.

measured using a graduated cylinder. Application rate was calculated based on the diameter of the catch cans and the duration of each test.

Kinetic energy per unit sprinkler discharge (area-weighted kinetic energy per unit drop volume), KE_d (J L^{-1}), was computed as:

$$KE_d = \frac{\sum_{i=1}^{R} \left(\frac{\sum_{j=1}^{ND_i} \frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000 \sum_{j=1}^{ND_i} \frac{\pi d_j^3}{6}} \right) A_i}{\sum_{i=1}^{R} A_i} \qquad (1)$$

where R is the number of radial measurement locations, ND_i is the number of drops measured at the ith radial location, ρ_w is the mass density of water (kg m^{-3}), d_j is the measured diameter

(m) of the *j*th drop, v_j is the measured velocity (m s^{-1}) of the *j*th drop, and A_i is the wetted area (m^2) associated with *i*th radial location. Wetted area was computed as $A_i = 2\,\pi\,S\,r_i$ where *S* (m) is the radial distance between adjacent radial measurement locations and r_i (m) is the radial distance from the sprinkler to the *i*th measurement location. The resulting value represents the average kinetic energy per liter of drop volume applied over the wetted area.

Specific power, *SP* (W m^{-2}), is a function of the radial measurement location and was computed as:

$$SP_i = \left(\frac{\sum_{j=1}^{ND_i} \frac{\rho_w \pi d_j^{\,3} v_j^{\,2}}{12}}{1000 \sum_{j=1}^{ND_i} \frac{\pi d_j^{\,3}}{6}} \right) \cdot \frac{AR_i}{3600} \qquad (2)$$

where AR_i is the average application rate (mm h^{-1}) associated with the *i*th radial location. *SP* represents the rate at which kinetic energy is transferred to the soil surface as a function of radial distance from the sprinkler. *SP* is sometimes referred to as droplet energy flux (Thompson and James, 1985). A sprinkler radial *SP* distribution is analogous to a sprinkler radial water application rate distribution. The depth of water applied by a center-pivot sprinkler irrigation system can be determined by integrating the composite overlapped sprinkler application rate perpendicular to the sprinkler lateral with respect to time. Similarly, the kinetic energy applied by a center-pivot irrigation system can be determined by integrating the composite overlapped sprinkler *SP* distribution perpendicular to the sprinkler lateral with respect to time.

A model written in Visual Basic was used to simulate composite water application rate for a 0.3-m spaced square grid orientated perpendicular and parallel to the lateral. The composite application rate was computed by overlapping the radial water application rate distributions from successive sprinklers spaced at 3 m increments along the center pivot lateral. An average composite application rate distribution perpendicular to the sprinkler lateral was computed as the average of simulated application rates over a distance a 3 m distance parallel to the center pivot lateral centered about a sprinkler. Sprinkler application rate distributions determined indoors were used in the simulation model. Sprinkler application rate distributions were interpolated to 0.3 m radial increments using cubic spline interpolation between catch can measurements.

Water application depths were determined by numerically integrating the average composite application rate distributions over time. The time required for the center-pivot lateral to pass over a location when applying 25 mm of water was determined by adjusting the integration period (center-pivot lateral travel speed). Average center pivot application rate was calculated as the numerical average of the average composite application rate distribution perpendicular to the sprinkler lateral.

The composite center pivot *SP* distribution perpendicular to the center-pivot lateral was computed as the sum of the *SP* from sprinklers applying water to a fixed point on the soil as center pivot system travels over the fixed point using the simulation model. Sprinkler *SP* distributions (eqn 2.) were interpolated to 0.3 m radial distance increments using cubic spline interpolation of TCLPM measurements. An average composite SP distribution was calculated as the average of simulated SP over a distance a 3 m distance parallel to the center pivot lateral centered about a sprinkler. Average center pivot SP was calculated as the numerical average of the average composite SP distribution perpendicular to the sprinkler lateral.

Total kinetic energy from an application of 25 mm of water was determined by numerically integrating the average composite *SP* distribution using the same integration period required to apply 25 mm of water. Total kinetic energy applied per unit volume of water, KE_a (J m^{-2} mm^{-1}), was determined by dividing the total kinetic energy by the depth of water applied (25 mm). Total kinetic energy per unit depth of water with units of J m^{-2} mm^{-1} is used because it is more intuitive than J L^{-1} and is numerically equivalent to kinetic energy per unit volume applied (J L^{-1}) (1 mm of water over 1 m^2 equals 1 L).

Results and Discussion

Results of the computation of KE_d and KE_a for the sprinklers used in the study are shown in table 2. For the larger nozzle sizes, KE_d ranged from 11.98 to 13.76 J L^{-1} for the Xi-Wob and I-Wob sprinklers, respectively, at 103 kPa. Similarly, KE_a ranged from 8.60 to 12.15 J m^{-2} mm^{-1} for the Xi-Wob at 103 kPa and the R3000 red plate sprinkler at 138 kPa, respectively. The correlation between KE_d and KE_a is shown in figure 1. The linear regression is significant ($P < 0.001$) with an R^2 of 0.63 indicating that only 63 percent of the variation in KE_a is represented by KE_d. Note that kinetic energy per unit discharge (KE_d) is consistently greater than applied

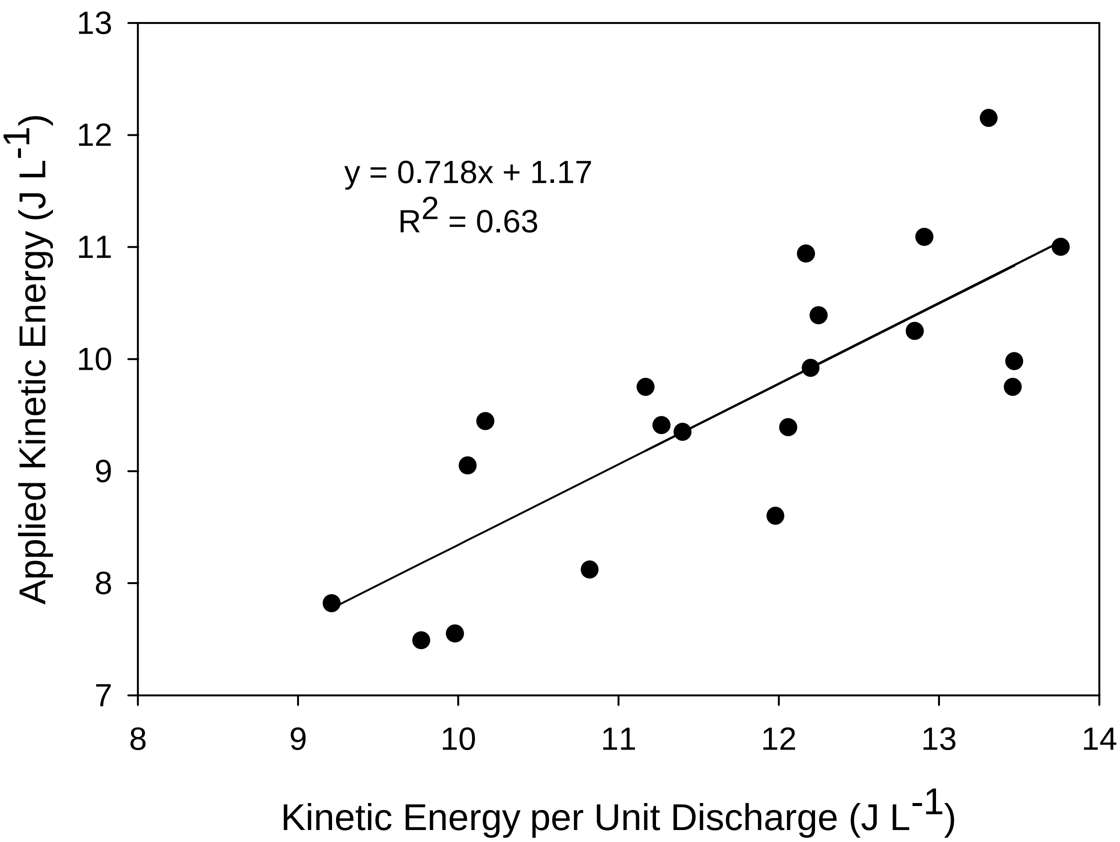

Figure 1. Linear correlation between kinetic energy per unit discharge (KE_d) and kinetic energy applied per unit depth of water application (KE_a) for sprinklers used in this study

Table 2. Kinetic energy per unit discharge (KE_d), applied kinetic energy per unit irrigation depth (KE_a) and average composite specific power and average composite water application rate computed by overlapping distributions from sprinklers spaced 3-m apart along the lateral.

Nozzle Size (mm)	Pressure (kPa)	KE_d ($J\ L^{-1}$)	KE_a ($J\ m^{-2}\ mm^{-1}$)	Specific Power ($W\ m^{-2}$)	Application Rate ($mm\ hr^{-1}$)
Senninger I-Wob Black Plate 9 grooves					
5.55	69	9.21	7.82	0.067	26.0
5.55	103	10.82	8.12	0.065	28.0
5.55	138	9.98	7.55	0.071	31.7
7.94	69	12.85	10.25	0.146	47.2
7.94	103	13.76	11.00	0.159	51.9
7.94	138	12.2	9.92	0.155	56.3
Senninger Xi-Wob Black Plate 6 grooves 15˚ trajectory					
5.55	69	11.27	9.41	0.074	28.2
5.55	103	9.77	7.49	0.076	30.1
7.94	69	12.25	10.39	0.150	50.6
7.94	103	11.98	8.60	0.130	54.3
Nelson N3000 Green Plate 9 grooves 21˚ trajectory					
5.75	69	10.17	9.45	0.070	26.5
5.75	103	11.40	9.35	0.078	30.2
8.14	69	12.91	11.09	0.156	50.7
8.14	103	13.47	9.98	0.168	60.7
Nelson S3000 Purple Plate 6 grooves multi-trajectory					
5.75	103	11.17	9.75	0.076	28.4
8.14	103	12.17	10.94	0.188	61.7
Nelson R3000 Red Plate 6 grooves 12˚ trajectory					
5.35	138	10.06	9.05	0.071	28.2
7.54	138	13.31	12.15	0.175	51.0
Nelson R3000 Brown Plate multi-trajectory					
5.35	138	12.06	9.39	0.069	29.1
7.54	138	13.46	9.75	0.129	47.6

kinetic energy (KE_a). Applied kinetic energy can vary by 28% depending upon the sprinkler (Xi-Wob vs I-Wob with 7.94 mm nozzle at 103 kPa). Thus, sprinkler selection influences the kinetic energy applied from center pivot irrigation more than indicated by KE_d. Kinetic energy per unit discharge does not accurately represent sprinkler selection choices. It is strongly influenced by drop size because larger drops have greater kinetic energy and travel further from the sprinkler representing a larger portion of the wetted area (eqn. 1).

In general, KE_d and KE_a both increase with nozzle size because drop sizes increase with flow rate (data not shown). Both KE_d and KE_a decrease with pressure because drop sizes decrease with pressure (data not shown). However, changes in the radial application profiles with flow rate can lead to exceptions such as for the I-Wob at 103 kPa vs 69 kPa.

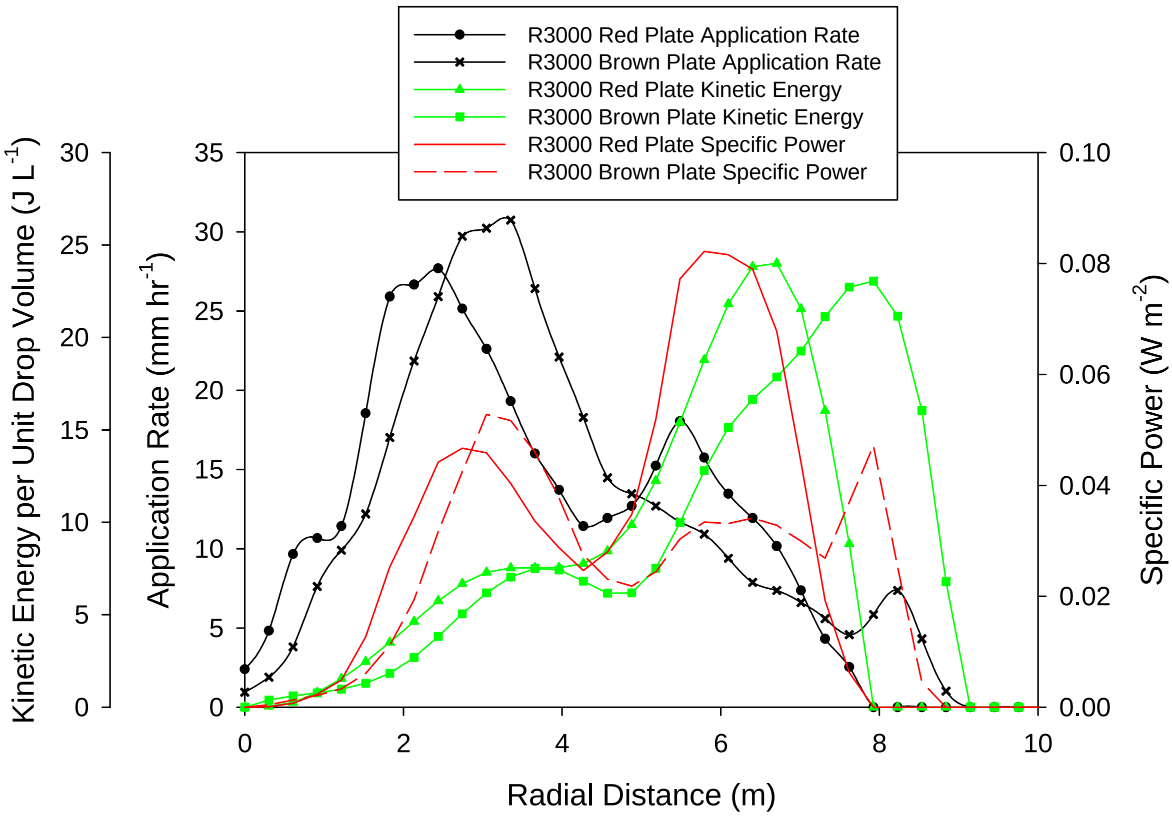

Figure 2. Values of application rate, kinetic energy per unit drop volume and specific power as a function of distance from the R3000 red and brown plate sprinklers

Examining why the R3000 red and brown plate sprinklers with equal nozzle sizes and operating pressures have a 25% difference in kinetic energy per unit of water applied provides some insight into designing center pivot sprinklers to produce less kinetic energy. The application rate patterns of these sprinklers are shown in figure 2. The R3000 sprinkler with the brown plate has approximately 1.3 m greater wetted radius than with the red plate. The peak application rate occurs at 2 to 3 m from the sprinkler for both plate combinations. The red plate produces a secondary peak at approximately 5.5 m from the sprinkler while the brown plate sprinkler has a much smaller secondary peak at approximately 8.5 m. Kinetic energy per unit drop volume as a function of distance from the sprinkler is similar for both sprinklers (fig. 2). Peak kinetic energy per unit drop volume is about equal for the two sprinklers with the peak occurring at approximately 6.5 m with the red plate and at approximately 8 m for the brown plate. Kinetic energy per unit discharge (table 2) is slightly greater for the brown plate option because it has a greater wetted radius and kinetic energy per unit discharge is independent of application rate pattern (eqn. 1). Specific power as a function of radial distance calculated by multiplying application rate and kinetic energy per unit drop volume (eqn. 2) is vastly different for the two plate choices (fig. 2). The red plate has a peak specific power at approximately 6 m from the sprinkler that is approximately 65% greater than for the brown plate. When this higher peak specific power from several sprinklers is added (overlapped) the resulting kinetic energy applied is greater than for the brown plate sprinkler with an equal water application depth.

One method of minimizing applied kinetic energy is to design a sprinkler with monotonically decreasing specific power with distance from the sprinkler. This will require a monotonically decreasing application rate with radial distance as any peak in application rate at large radial distances will result in a peak in specific power. Kinetic energy per unit drop volume will always

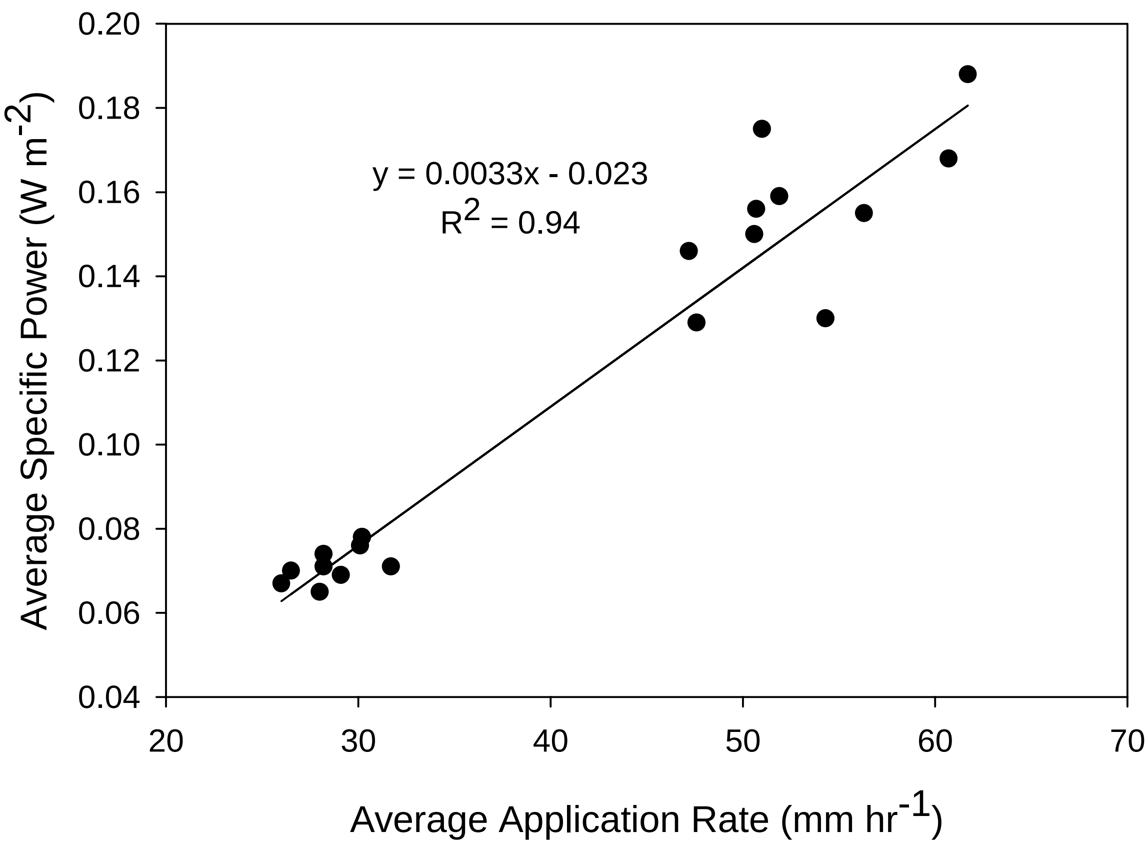

Figure 3. Linear correlation between average composite application rate and average composite specific power calculated using the simulation model for sprinklers used in this study spaced 3 m along the lateral.

increase with radial distance as drops sizes get larger with radial distance. Optimizing kinetic energy per unit drop volume as a function of radial distance to minimize kinetic energy per unit application depth will be the focus of future work.

Average composite water and average composite specific power application rates computed using the simulation program for sprinklers spaced 3 m along a lateral are given in table 2. The correlation between average composite application rate and average composite specific power is shown in figure 3. The linear regression is significant ($P < 0.001$) with an R^2 of 0.94, which was expected as specific power is a linear function of application rate (eqn. 2). The significance of the relationship is that efforts by center-pivot sprinkler manufacturers to develop sprinklers with greater wetted radius to reduce composite average water application rates has also reduced composite average specific power applied. The relationship also shows that some relatively large drops from center-pivot sprinklers needed to increase wetted radius and reduce composite application rate do not necessarily result in greater transfer of kinetic energy to the soil. Average composite specific power is based on the sum of drop size classes and not just a single drop size. Thus, if there are few large droplets the overall kinetic energy applied will not be affected.

Conclusion

Kinetic energy applied by rotating spray-plate sprinklers was characterized using two methods. Specific power represents the rate at which kinetic energy per unit area is transferred to the soil as a function of distance from a sprinkler and is analogous to a sprinkler radial water application rate distribution. Specific power was used to estimate actual kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers equally spaced along a center-pivot lateral. Kinetic energy of irrigation sprinklers has traditionally been characterized using area-weighted kinetic energy per unit drop volume. This method heavily weights the effects of the largest drops, which travel the farthest from the sprinkler and have the largest kinetic energy and does not account for the volume of water applied by each drop size. Sprinkler kinetic energy per unit volume of sprinkler discharge was not well correlated to actual kinetic energy transferred to the soil by the sprinklers. Designing sprinklers that minimize kinetic energy transferred to bare soil will require a monotonic decreasing application rate with radial distance as any peak in application rate at large radial distances will result in a peak in specific power. Kinetic energy per unit drop volume will always increase with radial distance as drops sizes get larger with radial distance. There may be opportunities to optimize kinetic energy per unit drop volume as a function of radial distance to minimize kinetic energy per unit application depth and will be the focus of future work.

Acknowledgements

This research is partially supported by a Cooperative Research and Development Agreement No. 58-3K95-9-1311 with Nelson Irrigation Corp. Walla Walla, WA. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of Nelson Irrigation Corp.

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