A VARIABLE FLOW RATE SPRINKLER FOR SITE–SPECIFIC IRRIGATION MANAGEMENT

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ABSTRACT. *A variable flow rate sprinkler applicable to center pivot and lateral–move irrigation systems was constructed and tested in the laboratory. Sprinkler nozzle size was reduced a fixed amount using a retractable concentric pin in the nozzle bore. Cycling insertion of the concentric pin in the sprinkler nozzle bore provided a time–averaged variable flow rate over a range of 36% to 100% for the nozzle sizes tested. The application pattern radius of the sprinkler tested was reduced approximately 15% under variable flow conditions. Sprinkler drop size distribution was also reduced by engagement of the pin in the sprinkler nozzle bore. Measured flow rates compared well with theoretical flow rates below 28 L/min (7.4 gpm). Results from laboratory testing indicate the variable flow rate sprinkler could potentially be used for site–specific irrigation management with center pivot and lateral–move irrigation systems.*

Keywords. *Sprinkler irrigation, Center pivot, Lateral–move, Variable rate application, Drop size distribution.*

Over the past decade, interest in site–specific irrigation management has risen in response to the need for U.S. agriculture to increase production efficiency and to complement successful commercialization of other site–specific application technologies in irrigated agriculture. A holistic approach to site–specific crop management in irrigated agriculture includes water as one of the primary inputs because water availability greatly impacts crop yield and quality.

Center pivot and lateral–move irrigation systems provide a natural platform upon which to develop site–specific irrigation management technologies due to their current use and high degree of automation. Control systems and hardware to implement site–specific irrigation management have been reported in the literature (Fraisse et al., 1995; King et al., 1996; Sadler et al., 1996; Evans et al., 1996; Harting, 1999; Perry et al., 2003). In each instance, spatially variable water application was successfully achieved by either using multiple sprinkler packages to obtain step–wise variable rate water application (King et al., 1996; Sadler et al., 1996) or on–off cycling using an appropriate duty cycle (Fraisse et al., 1995; Evans et al., 1996; Harting, 1999; Perry et al., 2003). Despite these successful implementations, one common element has been the lack of a variable rate sprinkler. Implementation of spatially variable water application could be simplified and potentially more economical with the advent of a variable flow rate sprinkler.

The flow through a sprinkler nozzle varies approximately proportional to the square root of differential pressure. Thus, to vary the flow rate through a sprinkler nozzle by a factor of four requires the pressure to be varied by a factor of 16. Providing and controlling such a large range in pressure on an individual sprinkler basis is possible but not very feasible. The adverse effect on application pattern would likely be substantial. Furthermore, this approach would be inconsistent with the current emphasis of reducing operating pressure requirement of irrigation systems to minimize energy requirements and hence operating costs. Thus, controlling nozzle cross–sectional flow area would be the desired parameter to vary from a theoretical viewpoint. However, to be practical this would need to be achieved in a manner that is easily controlled, repeatable, and does not adversely affect the sprinkler application pattern.

One potential approach to reduce the cross–sectional area of a sprinkler nozzle without adversely affecting sprinkler application pattern is to insert a concentric pin into the nozzle bore. Cycling a retractable concentric pin in and out of the orifice in a controlled manner could potentially achieve a time–averaged variable flow rate (King et al., 1998). Rinkewich (1991) proposed using a similar approach to increase the wetted diameter of an impact–type sprinkler. The objective of this study was to investigate the feasibility of using a concentric pin in a sprinkler nozzle to effectively achieve a variable flow rate from a medium pressure–type sprinkler typically used on center pivot and lateral–move irrigation systems.

MATERIALS AND METHODS

Two prototype versions of a variable rate sprinkler were constructed and tested in the laboratory. The first prototype (fig. 1), referred to as Prototype I, was constructed using a 19–mm (0.75–in.) threaded PVC pipe tee. A linear actuator

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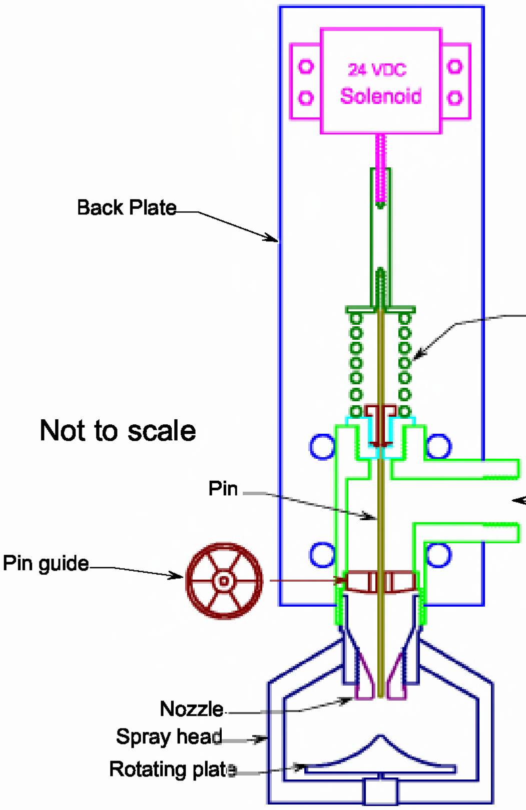

Figure 1. Design of Prototype I variable rate sprinkler.

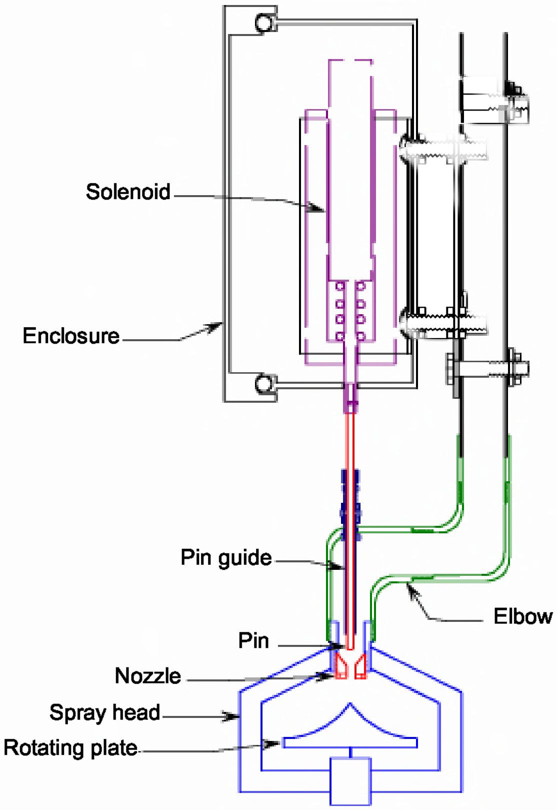

Figure 2. Design of Prototype II variable rate sprinkler.

for moving the concentric pin was aligned axially in a fixed position relative to the pipe tee. The linear actuator was equipped with a spring to automatically retract the pin from the sprinkler nozzle in the inactive state. A streamlined pin guide was friction fit into the bottom of the threaded tee. A medium pressure sprinkler head (Nelson R30, Nelson Irrigation Co., Walla Walla, Wash.) was attached below the insert. The flow path dimensions of the sprinkler head used are very similar to current commercial sprinkler heads of this manufacturer (the R30 used two support bars for the plate bearing and a brass nozzle, while the newer R3000 uses three support bars, and plastic nozzles). Thus, the results reported here are expected to be similar to those measured with a new production model sprinkler head if the tests were repeated. The concentric pin length and diameter were sized to fit the sprinkler head and nozzle sizes tested and provide a predetermined reduction in flow when the pin was inserted in to the sprinkler nozzle. The end of the pin was cut off square to the pin axis and any remaining burrs removed with emery cloth. Effects of pin end profile were not investigated in this study. The pin was of uniform cross–section along its entire length.

A second prototype (fig. 2), referred to as Prototype II, was constructed to overcome difficulties with pin alignment and binding encountered with Prototype I and make construction simpler for multiple field units. Prototype II was constructed starting with a 19–mm (0.75–in.) threaded PVC 90° elbow. The elbow was modified by drilling a hole in the outside bend of the elbow axially aligned with the female threaded end of the elbow. An alignment guide for the concentric pin was made from a brass hose barb inserted into the female end of the elbow with the threaded end of the hose barb extending through the hole drilled in the elbow bend. The inside diameter of the hose barb and its attachments were predrilled to allow free axial movement of a predetermined size pin. A Nelson R30 sprinkler head was attached to the female end of the elbow. The pin was installed through the pin guide and extended through a sprinkler nozzle of the same size diameter. The pin guide was then aligned to allow free movement of the pin in the sprinkler nozzle and fixed in place with epoxy glue. This process resulted in good concentric axial alignment of the pin guide with the sprinkler nozzle.

The sprinkler elbow assembly was attached to 19–mm (0.75–in.) PVC piping by using a second 90° threaded elbow (fig. 2). A metal back plate was affixed relative to the sprinkler elbow assembly by clamping it to the PVC piping. A 24 VDC push–type solenoid housed in a plastic enclosure was attached to the back plate directly above the sprinkler elbow assembly. The solenoid was bolted to the back plate through slots that allowed axial alignment of the solenoid plunger with the pin through the sprinkler elbow assembly. The push solenoid was equipped with a spring to return the solenoid plunger and attached pin to the retracted position in the inactive state.

Indoor laboratory tests of sprinkler flow rate and radial application pattern were performed on both prototype sprinklers. Tests on Prototype I were conducted at the USDA ARS Northwest Irrigation and Soils Research Laboratory. Tests on Prototype II were conducted at the University of Idaho Aberdeen Research and Extension Center. Tests on Prototype I focused on investigating concept feasibility while tests on Prototype II included a wider range of nozzle and pin diameters to identify a pin and nozzle size combination suitable for field scale testing.

A 2–min duty cycle was used in all tests meaning that the duration of pin engagement in the nozzle bore was identically repeated at 2–min intervals during the tests. A single line of catch cans with 0.33–m (1.1–ft) spacing, starting at 0.67 m (2.2 ft) from the sprinkler and extending to 10 m (33 ft) from the sprinkler, were used to measure water application rate radially from the sprinkler. Catch can opening was 152 mm (6 in.) and height was 178 mm (7 in.). The prototype sprinkler was housed in a 56–cm (22–in.) diameter enclosure equipped with a drain in the bottom, open top, and a 20–cm (8–in.) wide rectangular side opening. The side opening was aligned with the catch cans to measure radial application pattern. Metal strips, with one edge radially aligned with the center of the enclosure and the other edge attached to the vertical edges of the enclosure side opening, were used to prevent spray pattern splash near the opening from interfering with the spray exiting the opening. The enclosure was lined with window screen over 25–mm (1–in.) thick evaporative cooler pads to minimize spray splash within the enclosure. The enclosure was used to allow indoor testing within the indoor laboratory space available at both locations. The prototype sprinkler was rotated within the enclosure to effectively measure radial application patterns at different angles relative to the sprinkler head splash plate support bars. The radial application patterns for four different angles were averaged. The sprinkler was located at a height of 2 m (6.6 ft) above the catch cans and the test durations were 30 min each.

Pressure was monitored at the inlet to the chamber housing the pin guide for each prototype. An adjustable pressure regulator was used to provide near constant water supply pressure to the prototype sprinklers during testing. A compressed air column connected between the pressure regulator and sprinkler was used to absorb fluctuations in pressure to the prototype sprinkler when flow through the pressure regulator changed as the pin was engaged and retracted from the sprinkler nozzle bore. The air column replicated the head of a large water reservoir allowing near constant water supply pressure to be maintained. The adjustable pressure regulator and compressed air column combination allowed a ±3.4–kPa (±0.5–psi) range in test pressure to be maintained as flow rates though the prototype sprinkler changed.

Time–averaged flow rate was measured by blocking the enclosure side opening to force all water from the prototype sprinkler to drain through the bottom of the enclosure. Three or more minutes later, water draining from the enclosure over a 4–min interval was captured. For Prototype I testing, the volume of water captured was determined by placing it in a cylinder of known diameter and height and using a point gauge to measure the distance to the water surface in the cylinder. This measurement along with known diameter and height of the cylinder was used to compute volume of water captured. For Prototype II testing, the volume of water captured was determined by weighing. Flow measurements were repeated three or more times and averaged.

For Prototype I, a nozzle diameter of 4.56 mm (0.180 in.) and pin diameter of 3.18 mm (0.125 in.) were used in the tests. This nozzle and pin–size combination provided a 48% reduction in cross–sectional area of the nozzle bore when the pin was engaged in the nozzle bore, and theoretically a 48% reduction in flow rate. A four–groove rotator plate and six–groove spinner plate were used in the tests. Tests were conducted at both 138 and 207 kPa (20 and 30 psi).

For Prototype II, nozzle diameters of 5.95, 7.14, and 8.73 mm (0.234, 0.281, and 0.344 in.) were tested with a 4.76–mm (0.188–in.) diameter pin. All tests used a six–groove rotator plate and 138–kPa (20–psi) operating pressure. Drop size distributions measurements were performed at the California State University Center for Irrigation Technology using the laser method as described by Kincaid et al. (1996) for the 5.95–mm (#0.234–in.) diameter nozzle with the pin both engaged and retracted from the nozzle. Sprinkler test height was 3 m (9.8 ft) and drop size distributions were measured at 2–m (6.6–ft) radial distance increments.

Results and Discussion

Results of radial leg application rate tests for Prototype I with a four–groove rotator plate are shown in figures 3 and 4 for operating pressures of 138 and 207 kPa (20 and 30 psi), respectively. With the pin retracted from the nozzle bore, the application rate pattern included two peaks, one at approximately 4 m and the second near the extent of the wetted radius. A 68.9–kPa (10–psi) increase in operating pressure increased the wetted radius about 1 m. When the pin was engaged in the nozzle bore at 207–kPa (30–psi) operating pressure, the wetted radius was reduced about 1 m (10% to 15%) compared to when the pin was retracted. Kincaid (1982) showed that a typical sprinkler pattern radius varies roughly with the nozzle discharge to the 0.2 power. Applying

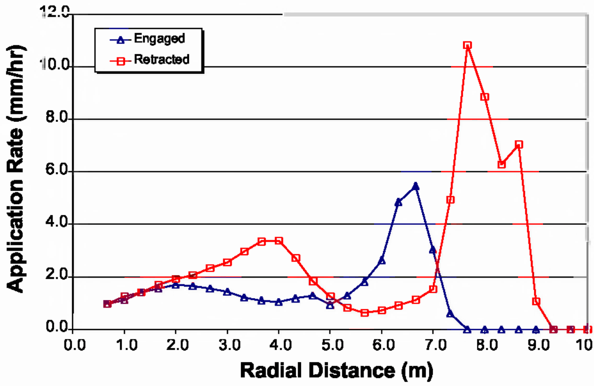

Figure 3. Prototype I application rate patterns for 4.56–mm nozzle with 3.18–mm pin at 138–kPa operating pressure with four–groove rotator plate for pin retracted and pin engaged into nozzle bore.

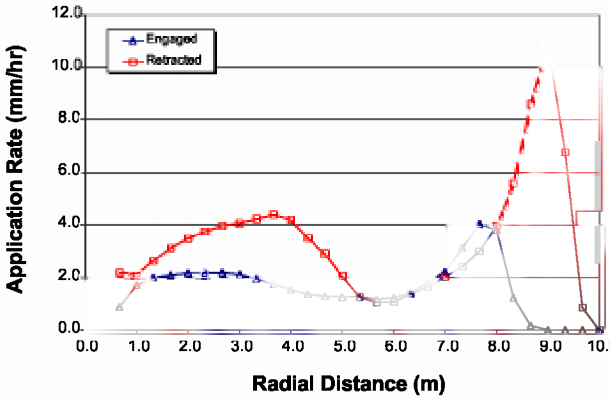

Figure 4. Prototype I application rate patterns for 4.56–mm nozzle with 3.18–mm pin at 207–kPa operating pressure with four–groove rotator plate for pin retracted and pin engaged into nozzle bore.

this to the present case, the reduced flow is 52% of the full flow, so the reduced flow pattern radius should be approximately 88% of the full flow radius ($0.52^{0.2} = 0.88$). This is a reduction of about 1.1 m at 9 m. Thus, the influence of the pin on wetted radius was as expected considering the reduction in flow rate (unfortunately, we did not conduct a test with an equivalent small nozzle). The presence of the pin in the nozzle bore nearly eliminated the application rate peak at 4 m and actually resulted in a more uniform radial application rate pattern. The location of the peak application rate near the wetted radius was reduced nearly in direct proportion to the reduction in wetted radius when the pin was engaged in the nozzle bore. The greatest reduction in application rate occurred at the outer extent of the wetted radius.

Accompanying figures 5 and 6 show uniformity coefficients calculated for various sprinkler spacings using the data from figures 3 and 4, with the pin retracted, engaged, and engaged 50% of the time. Engagement of the pin did not substantially reduce the uniformity for most spacings, and the highest application uniformity occurred with the combined pattern for most spacings. These results indicate that the use of the concentric pin can be beneficial with respect to uniformity when used with a rotating plate, which produces a markedly donut–shaped pattern, such as the D4 plate used here.

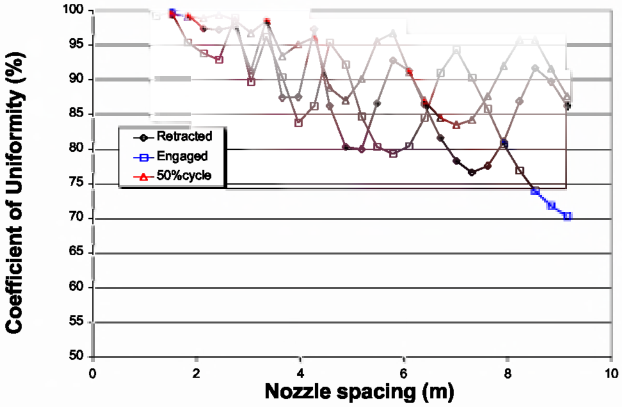

Figure 5. Computed application uniformity for Prototype I with 4.56–mm nozzle and 3.18–mm pin at 138–kPa operating pressure with four–groove rotator plate for pin retracted, engaged, and engaged 50% of the time into nozzle bore.

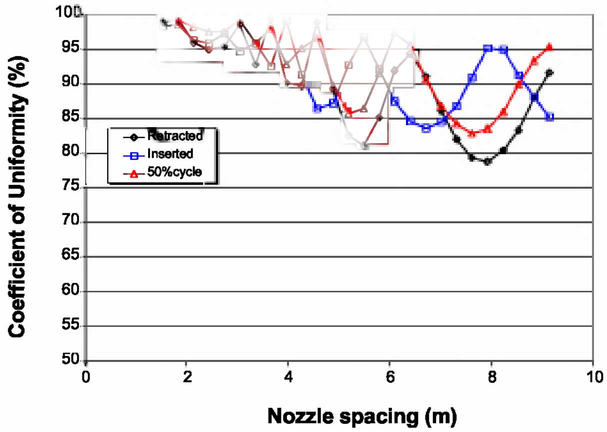

Figure 6. Computed application uniformity for Prototype I with 4.56–mm nozzle and 3.18–mm pin at 207–kPa operating pressure with four–groove rotator plate for pin retracted, engaged, and engaged 50% of the time into nozzle bore.

The effect of cycling the concentric pin to attain a time–averaged sprinkler flow rate on application rate pattern was investigated. Radial leg tests were used to measure the effective application rate pattern for time–averaged flows of 52%, 75%, and 90% with Prototype I. The resulting radial application rate pattern expressed as a ratio relative to the application rate pattern when the pin was retracted from the nozzle bore is show in figure 7 for a six–groove spinner plate at 207–kPa (30–psi) operating pressure. The relative application rate pattern for the time–average flows of 75% and 90% were reduced relatively uniformly over the radial range of 1 to 5 m. Beyond 5 m, the relative application rate peaked and decreased rapidly due to the influence of reduced wetted radius with the pin engaged in the nozzle bore. The relative application rate pattern for a time–average flow of 52%, which represents the pattern when the pin was continually engaged in the nozzle bore, shows that the wetted radius was reduced less than 0.5 m and the radial location of the peak application rate was moved inward with respect to when the pin was retracted.

The relative application rate patterns for Prototype II using a 5.95–mm (0.234–in.) nozzle and 4.76–mm (0.188–in.) diameter pin operated at 138 kPa (20 psi) with a six–groove rotator plate are shown in figure 8. This nozzle and pin diameter combination provided a 64% reduction in cross–sectional area of flow when the pin was engaged in the nozzle bore. Thus, theoretically with the pin engaged in the nozzle bore flow rate was reduced to 36% of the normal nozzle flow rate. Relative application patterns for time–averaged flows of 36%, 41%, 52%, 68%, 84%, and 95% of normal nozzle flow are shown in figure 8. As with the four–groove rotator plate, presence of the pin in the nozzle bore reduced the wetted radius, in this case by about 1.7 m (5.6 ft) or 18%. However, cycling the pin such that time–averaged flow was 68% or greater, the wetted diameter was not reduced. This indicates that the wetted radius of the sprinkler may be maintained over a greater range of flow if the pin is sized to provide a large reduction in flow when the pin is engaged in the nozzle bore.

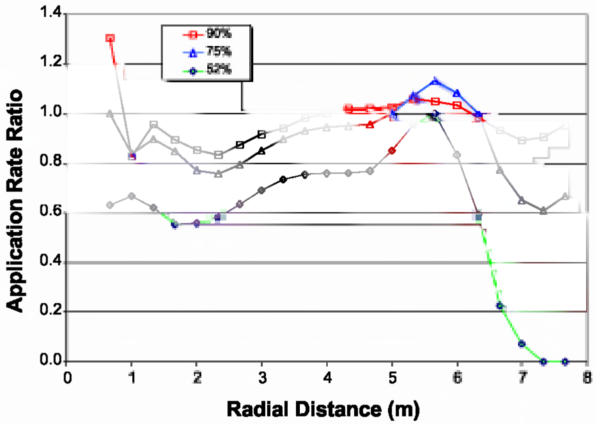

Figure 7. Prototype I application rate patterns for 4.56–mm nozzle with 3.18–mm pin at 207–kPa operating pressure with six–groove spinner plate. Application rate is expressed as a ratio relative to the application rate with the pin retracted from nozzle bore and as a percentage (%) of nozzle flow with pin retracted from nozzle bore.

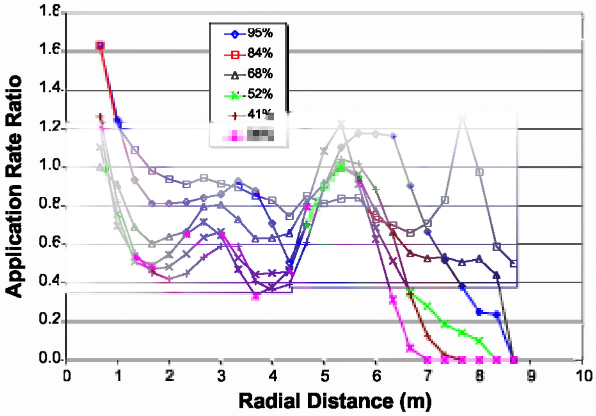

Figure 8. Prototype II application rate patterns for 5.95–mm nozzle with 4.76–mm pin at 207–kPa operating pressure with six–groove rotator plate. Application rate is expressed as a ratio relative to the application rate with the pin retracted from nozzle bore and as a percentage (%) of nozzle flow with pin retracted from nozzle bore.

Measured time–averaged flow rates for both prototypes compared to theoretical time–averaged flow rates are shown in figure 9. Theoretical flow rate with the pin retracted was taken as the sprinkler manufacturer's published flow rate. For Prototype I with a 4.56–mm (0.180–in.) nozzle at 138 and 207 kPa (20 and 30 psi) operating pressures, the manufacturer's flow rates were 15.6 and 19.0 L/min (4.12 and 5.03 gpm), respectively. For Prototype II operated at 138 kPa (20 psi) with 5.95–, 7.14–, and 8.73–mm (0.234–, 0.281–, and 0.344–in.) nozzles, the manufacturer's flow rates were 26.3, 37.6, and 55.3 L/min (6.95, 9.92, and 14.6 gpm), respectively. The theoretical flow rate with the pin engaged in the nozzle was calculated as the theoretical flow rate with the pin retracted multiplied by the fractional area of flow with the pin engaged in the nozzle bore. For example, with Prototype I the fractional area of flow with the pin engaged in the nozzle bore was 0.52, thus the resulting theoretical flow rate was 8.1 L/min (2.14) at 138 kPa (20 psi). Consequently, if the pin was engaged in the nozzle bore 50% of the time, the theoretical time–averaged flow of Prototype I was 11.8 L/min (3.13) for 138 kPa (20 psi) operating pressure. The measured and theoretical flow rates compared very well up to approximately 28 L/min (7.4 gpm). At higher flow rates, the measured flow rates were less than theoretical flow rates. This result suggests that the guide for the concentric pin may begin to act as an obstruction, increasing internal pressure loss and reducing the actual pressure drop through the nozzle.

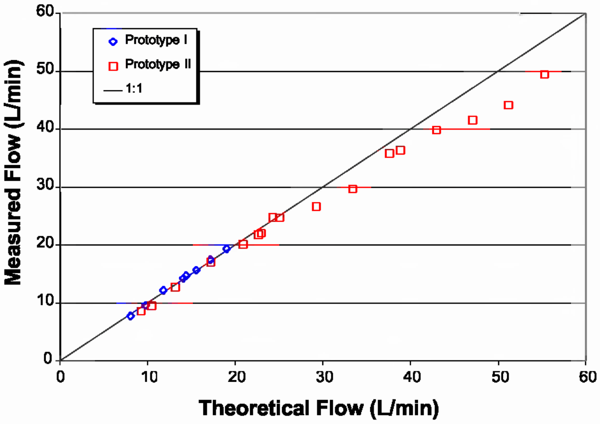

Figure 9. Comparison of theoretical time–averaged flow rates against measured time–averaged flow rates for Prototype I with 4.56–mm nozzle and 3.18–mm pin at 138– and 207–kPa operating pressures and for Prototype II with 4.76–mm pin and 5.95–, 7.14–, and 8.73–mm nozzles at 138–kPa operating pressure.

The measured drop size distributions for Prototype II with a 5.95–mm (0.234–in.) nozzle and 4.76–mm (0.188–in.) diameter pin operating at 138 kPa (20 psi) are shown in figure 10. Engaging the pin into the nozzle to reduce flow rate caused a substantial reduction in the number of droplets greater than 3 mm and essentially eliminated droplets greater than 4 mm in diameter. This result is consistent with the reduction in wetted radius with the pin engaged in the nozzle bore which indicates that drop size is reduced with elimination of the largest droplets which travel the farthest. This is also consistent with the results of Kincaid et al. (1996), which found that reducing nozzle size reduced the size of the largest droplets the most. Comparison of Prototype II drop size distributions with those available for a Nelson R30 sprinkler and six–groove rotator plate with similar nozzle sizes and pressure are shown in figure 11. The drop size distribution with the pin engaged in the sprinkler nozzle is similar to that of a Nelson R30 with a 4.76–mm (0.187–in.) nozzle at 207 kPa (30 psi) (Kincaid et al., 1996). The drop size distribution with the pin retracted is similar to that of a Nelson R30 with a 6.35–mm (0.250–in.) nozzle at 104 kPa (15 psi), which indicates that the presence of the concentric pin assembly in the flow chamber above the sprinkler nozzle has little effect on drop size distribution.

Controlling the time–averaged flow rate of a sprinkler by cycling a concentric pin as accomplished with both sprinkler prototypes used in this study has some advantages and disadvantages. The notable advantages relative to multiple sprinkler packages used by King et al. (1996) and Sadler et al. (1996) include reduced cost through reduced wiring, piping, pressure regulators, and sprinklers, free drainage for freeze protection in cold climates, and irrigation system functionality in the event of failure of a sprinkler, valve or control system since normal sprinkler flow occurs when the pin is retracted which is the inactive state. The notable advantages relative to on–off pulsing of diaphragm valves used by Fraisse et al. (1995), Evans et al. (1996), Harting (1999), and Perry et al. (2003) include limited variations in system flow and pressure since flow is not reduced to zero, which also facilitates chemigation since flow variations

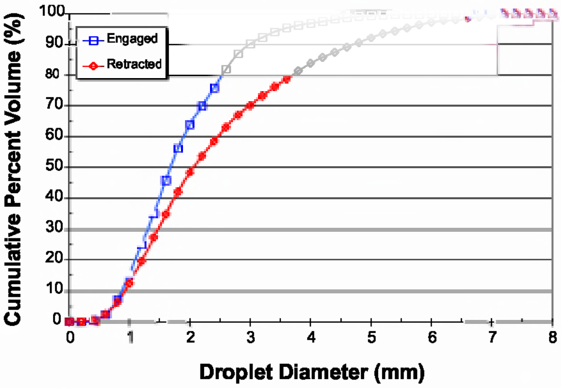

Figure 10. Drop size distributions for Prototype II with 5.95–mm nozzle and 4.76–mm pin at 138–kPa operating pressure for pin engaged and retracted from nozzle bore.

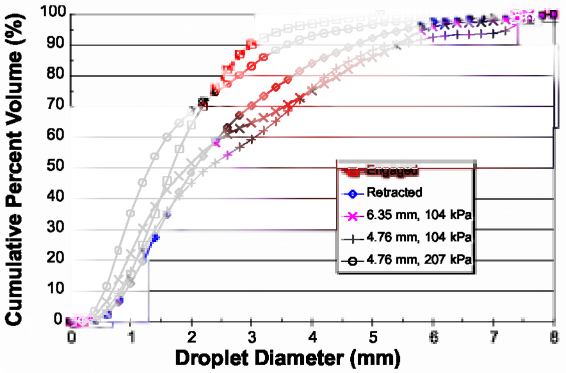

Figure 11. Drop size distributions for commercial Nelson R30 sprinkler with six–groove rotator plate with 6.35– and 4.76–mm nozzles operated at 104 kPa and 4.76–mm nozzle operated at 207 kPa compared with drop size distributions of Prototype II with 5.95–mm nozzle and 4.76–mm pin at 138–kPa operating pressure for pin engaged and retracted from nozzle bore.

are limited, and potentially provides improved application uniformity for medium pressure sprinklers with small wetted diameters and donut shaped application patterns. Also, the life of pressure regulators may potentially be increased since pressure variations are reduced at the sprinkler. The primary disadvantages relative to current approaches for obtaining variable rate water application include no allowance for zero flow without additional components (King et al., 1998), usage of a limited number of moving components that may increase failure rates since they are subject to wear and corrosion, and the fact that the concentric pin needs to be matched to the sprinkler nozzle size which changes along the length of a center pivot system. The advantages provided by use of a concentric pin to control sprinkler flow rate relative to current approaches to variable rate water application warrant continued research and evaluation.

CONCLUSIONS

The results of laboratory tests on both prototype variable rate sprinklers indicate that cycling a concentric pin into a sprinkler nozzle bore to control flow rate is feasible. Engaging the pin in the sprinkler nozzle bore effectively reduced flow rate without substantial adverse effect on the sprinkler radial application pattern. The wetted diameter of the sprinkler tested was reduced approximately 15% when the concentric pin was engaged in the sprinkler nozzle, which was roughly equivalent to that caused a 68.9–kPa (10–psi) reduction in operating pressure. Size of the largest droplets was reduced by engagement of the pin in the sprinkler nozzle. The reduction in flow and near elimination of larger droplets (>4 mm) is largely responsible for the reduction in wetted radius of the sprinkler tested. The measured time–averaged flow rates of the variable rate sprinkler were nearly equivalent to time–averaged theoretical flow rates up to 28 L/min (7.4 gpm). For greater flow rates, the measured time–averaged flow rates began to fall below theoretical flow rates, which may be due to pressure loss caused by the pin and centering guide obstructing the flow path.

Overall the results of the laboratory tests on the variable rate sprinkler were encouraging. Additional testing with a wider variety of sprinkler styles, nozzles, and plates is needed. Field scale testing of water and chemical application uniformity is also needed.

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