VARIABLE-RATE, DIGITALLY CONTROLLED METERING DEVICE

C. R. Camp, E. J. Sadler, D. E. Evans, L. J. Usrey

ABSTRACT. *During the past decade, there has been increasing interest in applying water and chemicals to crops based on need or yield potential rather than applying uniformly to the entire field. While ground-driven variable-rate chemical application equipment is now being used, most irrigation systems continue to apply nominally uniform water depths. Our objective was to make variable-rate irrigation applications possible by developing a digitally controlled metering device. The device consists of a reservoir that is alternately filled and emptied at a rate determined by a digital pulse from an external source and requires pressurized sources of water and air. The flow rate can be altered by changing the cycle duration and frequency, by changing air and water pressure, or by exchanging the reservoir with one of different volume. Tests with prototypes indicate reproducible flow rates for a range of operating pressures and discharge cycle durations. Various sprinklers or nozzles may be attached to the outlet if specific distribution patterns are desired. Additionally, the metering device can be used in a wide variety of applications with a variety of fluids or gases for variable-rate flow or injection of a fluid into either another fluid or gas.*

Keywords. *Irrigation, Sprinkler, Site-specific, Precision agriculture, Injection.*

With increasing use of crop yield monitoring equipment, it is now more feasible to measure spatial crop response to variable water and nutrient applications. During the past decade, there has been increasing interest in applying water and chemicals to crops based on need or yield potential rather than applying uniformly to the entire field. While ground-driven variable-rate chemical application equipment is now being used, most irrigation systems continue to apply nominally uniform water depths. Some of the traveling irrigation systems have the capability to vary application depths by changing travel speed but only for large areas constrained to swaths along the system structure. For site-specific crop management to be acceptable to growers, variable application depths must be available in smaller, arbitrary areas, which requires that each sprinkler or nozzle be capable of variable flow rates.

The flow rate of a sprinkler or nozzle can be regulated by the pressure drop of the fluid across the orifice, the fluid viscosity, and the orifice size. Dynamic control of flow rate using pressure is difficult in irrigation systems because of the limited pressure range available, the dependence of water droplet size and application pattern size uniformity on pressure, and the difficulty in changing pressures throughout an entire system. In irrigation systems, flow rate control using fluid viscosity is generally not possible because water is being discharged into the atmosphere and the viscosity of either water or air is not easily altered. Consequently, using different-sized orifices is the most common design method used to obtain different flow rates, especially in irrigation systems, where water pressure is relatively constant within a system. However, small orifice sizes (needed for low flow rates in continuous flow systems) are more susceptible to plugging, which requires either clean fluids or filtration. Control of flow rates using orifice size is most often achieved in a discrete rather than continuous manner, during the design phase rather than in operation.

Dynamic variable-rate applications can be achieved in a step-wise manner using either combinations of individual sprinklers at a single location or combinations of manifolds, each with fixed, continuous flow rates. Multiple manifolds with sprinklers or nozzles delivering combinations of fixed flow rates have been used to achieve variable-rate irrigation applications on moving irrigation systems (Roth and Gardner, 1989; W. M. Lyle, 1992, personal communication; Omary et al., 1997; Camp et al., 1998). Stark et al. (1993) patented a control system (McCann and Stark, 1993) to provide site-specific application of water and chemicals for both linear and center pivot irrigation systems. This system consisted of three conventional sprinklers at each location, each controlled by a microprocessor, and sized 1/4, 1/4, and 1/2 of full flow, to provide 1/4, 1/2, 3/4, and full irrigation rates.

Variable application rates through nozzles and sprinklers can be achieved in a more continuous manner by pulsing the water flow, either for individual devices or for manifolds with several devices. In these cases, flow rates are influenced by the characteristic of the solenoid valve, pump, or other metering device controlling the fluid. This technology has been used in many applications, including

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fuel injection for engines, various devices for injection of a fluid or additive into another fluid, and in agricultural systems. Duke et al. (1992) and Fraisse et al. (1992) modified a linear irrigation system to provide variable water and nutrient application using pulsed sprinklers mounted on discrete manifolds (21 m in length) along the truss. The application rate was determined by the frequency at which the water supply to each manifold was pulsed via switching the solenoid valves on and off for varying portions of a base time period, usually 1 min. In a similar manner, a precision chemical application system that used pulse-width modulation of solenoid valves on individual nozzles was developed for tractor-transported equipment (Giles et al., 1996). Flow rates in this system were much lower than those required for irrigation but varied over a continuous 10:1 range for fixed pressure. Variable pressure extended the range to 30:1 and allowed control of droplet size. This approach is feasible for tractor-transported chemical application equipment, but the flow rates are too low for irrigation applications and the cost for components to provide the higher flow rates needed for irrigation would be prohibitive. A variable-rate sprinkler for water and nutrient applications in field-scale irrigation systems was developed by King and Kincaid (1996) and King et al. (1997). The application rate was varied by moving a pin into the sprinkler orifice to reduce its area, and thus flow, to 40%. Alternatively inserting and removing the pin provided a time-averaged application rate ranging from about 40 to 100% of maximum sprinkler flow rate.

Each of the above methods of providing variable flows has certain disadvantages. Multiple manifolds are more costly and heavier than single manifold systems. Pulsing of water to a manifold with multiple sprinklers typically has long cycle times and thus requires a large wetted radius to achieve acceptable uniformity with moving irrigation systems. The solenoid valves needed for pulse-modulated control of irrigation systems are larger and more costly than those required for the low flow rates in a pesticide application system. This is aggravated by the number required. The pin insertion method, though continuously variable from 40 to 100%, cannot provide rates below 40% of full flow. While this may be acceptable in arid areas, lower application rates (near zero in some cases) would be needed for precision water and nutrient management in humid areas. To provide variable flow rates for a wide variety of needs, a variable-rate metering device was developed. A U.S. patent application for the metering device is pending (Sadler et al., 1998).

Design and Operation

The digitally controlled, variable-rate metering device is a positive displacement device that alternates between charge and discharge phases and requires pressurized sources of either two fluids or a fluid and a gas. In this application, water and compressed air are the fluid and gas. Although flow rate may be reduced, depending upon emitter size, various types of emitters or nozzles may be attached to the outlet to provide a desired distribution pattern. During the charge phase, a reservoir fills with water from a pressurized source. During the discharge phase, water is expelled through the outlet by a pulse of air at higher pressure, with a check valve preventing backflow of water. A digital controller generates electronic signals to control the duration and frequency of the charge and discharge phases. During design, the reservoir may be sized to provide a range of volumes, which increases the range of available flow rates for the device.

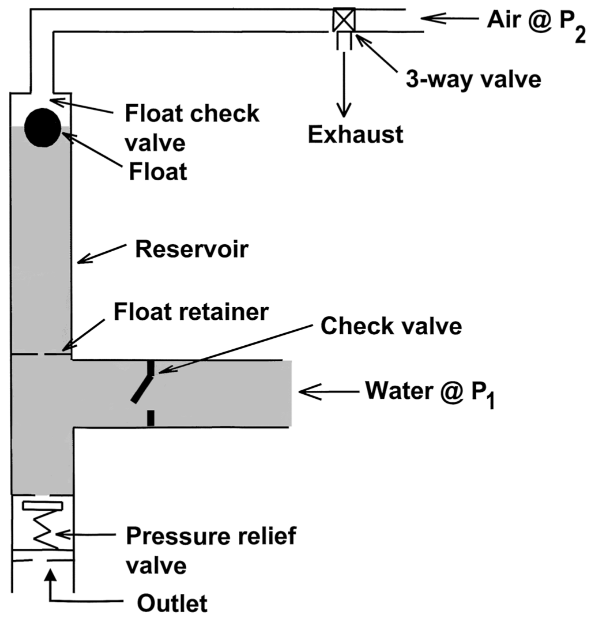

Figure 1–Schematic diagram of variable-rate metering device showing necessary auxiliary equipment.

A schematic diagram of the variable-rate metering device is shown in figure 1. During the charge phase, water at pressure P_1 enters the device through the entry port to fill the fixed-volume reservoir. The pressure relief valve at the outlet retains the water in the reservoir, air in the reservoir is vented to the atmosphere via the three-way valve on the air supply line, and the floating ball closes the valve at the top of the reservoir as the reservoir fills. After the charging phase is completed, the check valve in the water entry port closes to prevent water flow back into the supply line. The discharge phase is initiated by the digital controller, which provides an electrical pulse to the three-way valve that controls air at pressure P_2 ($P_2 > P_1$). When the valve opens, air enters the top of the reservoir, opening the float-operated valve. As the water pressure in the reservoir exceeds the relief valve pressure ($> P_1$), the outlet pressure relief valve opens and the water is rapidly expelled from the reservoir. When the electronic pulse value drops to zero, the air supply valve closes, pressure in the reservoir returns to atmospheric pressure, and a new charge phase is initiated.

The device flow rate is dependent upon several factors, including reservoir volume, air and water pressure, and cycle duration and frequency. Initially, we expected the device to operate so that the cycle duration was long enough to permit complete filling and emptying of the reservoir. In this case, the flow rate is determined by the reservoir volume and the cycle frequency. Later, we determined that the device could operate reliably with partial filling and emptying of the reservoir. In this case, the flow rate is a linear function of cycle duration.

The digital control system must supply a pulse (typically square wave) of proper magnitude for the three-way valve to switch the air supply line from atmospheric venting to compressed air supply. The duration of the pulse depends upon the mode of operation, with the maximum being that required to discharge all water from the reservoir without excessive discharge of air through the outlet. The period between pulses depends upon the mode of operation and the desired flow rate. If the device is operated in the first mode (reservoir fully charged), the minimum period is that required to fill the reservoir completely. Otherwise, the period can be almost any value. The digital control system should be capable of producing pulses for a wide range of characteristics (duration and timing) and should provide a straightforward method for selecting the desired pulse characteristics.

Because the metering device requires pressurized sources of water (or other fluid) and air (or other fluid or gas) to operate, auxiliary equipment may be required to pressurize the fluid or gas, e.g., an air compressor. Specific requirements (pressures, flow rates, storage, etc.) for this equipment depend upon specific metering device configurations (number of devices, reservoir volume, design flow rates, etc.). A power source will also be required for the digital control system and for some of the auxiliary equipment.

Although this metering device may be used with a wide range of fluids and/or gases, there are some restrictions. The two fluids or a fluid and a gas must be either non-mixing or of no consequence if they do mix. The floating element in the reservoir that closes the valve at the top of the reservoir must have an intermediate density so that it floats or is suspended on the controlled fluid. If the controlling fluid or gas cannot be safely vented into the atmosphere, it must be captured at the three-way valve during the charge cycle and properly stored.

Prototype Construction and Testing

Individual Devices

Prototype metering devices were constructed using standard manufactured components, some of which were modified. Standard polyvinyl chloride (PVC) pipe and fittings were used for most of the prototype body. A standard check valve attached to a PVC tee connection served as the water inlet when connected to a pressurized water supply. The reservoir was constructed from a length of clear PVC pipe, which allowed alteration of the volume by changing the pipe length. A standard vacuum breaker with a floating ball was attached to the top of the reservoir to serve as a check valve during the charge phase. The compressed air source was connected to the inlet (atmospheric) side of the vacuum breaker. A small screw was installed in the tee connection so that it protruded into the interior opening (bottom of reservoir) far enough to retain the floating ball within the reservoir. An adjustable pressure relief valve attached to the opposite side of the tee connection served as a check valve during the charge phase and opened during the discharge phase when water pressure in the reservoir exceeded the valve relief pressure.

The prototype metering device was tested to determine the effect of air pressure, discharge duration, cycle duration, and repetition on discharge volume. In most of these tests, the cycle duration was so short that the reservoir did not fill or empty completely. Consequently, the discharge volumes (flow rates) were proportional to the charge and discharge duration as a fraction of the duration required for full charge and full discharge. If the reservoir was fully charged and fully discharged each cycle, the discharge volume (flow rate) was proportional to the cycle frequency. During these tests, the pressure relief valve was adjusted so that it would open at a pressure slightly greater than the water pressure (P_1). Discharge volume was determined using graduated cylinders to measure the volume collected from ten cycles of individual metering devices.

Effect of Air Pressure on Discharge Volume. The first test was conducted to determine the effect of air pressure on discharge volume. During this test, water pressure was 70 kPa (10 psi), cycle duration was 1.5 s, and discharge duration was 0.6 s, which allowed neither complete charging nor complete discharging (for most air pressures) of the reservoir. Discharge volume ranged from 43 to 103 mL/cycle (1.5 to 3.5 oz./cycle) as air pressure varied from 140 kPa (20 psi) to 240 kPa (35 psi) for three replications (fig. 2). Error bars indicate very low variation among measurements. The maximum discharge volume in this test was about 100 mL (3.4 oz.), which is about 70% of the maximum reservoir volume (determined in a later test). One would assume that further increasing of air pressure would eventually cause complete discharge of reservoir contents, and the curve would reach an upper limit.

Effect of Discharge Duration. The second test was conducted to determine the effect of discharge duration on discharge volume. During this test, water pressure was 70 kPa (10 psi), air pressure was 210 kPa (30 psi), and cycle duration was 3 s. The reservoir was completely charged each cycle. Discharge volume ranged from 57 to 150 mL/cycle (1.9 to 5.1 oz./cycle) as the discharge duration varied from 0.4 s to 1.2 s for three replicates (fig. 3). Again, the error bars indicate very low variation among measurements. It appears that approximately 1 s was required for complete reservoir discharge with the parameters in this test.

Minimum Charge Duration. The third test was conducted to determine the minimum charge duration.

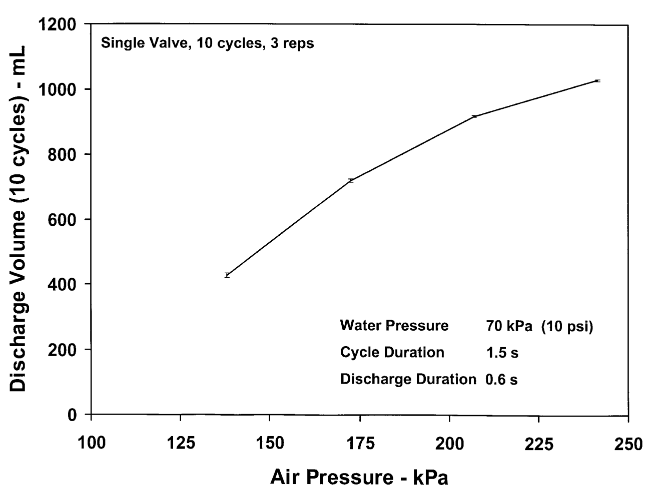

Figure 2–Single metering device discharge volume (10 cycles) for a range of air pressures. Each value is mean of three observations. Water pressure = 70 kPa (10 psi), cycle duration = 1.5 s, and discharge duration = 0.6 s. Measurement variation is indicated by error bars.

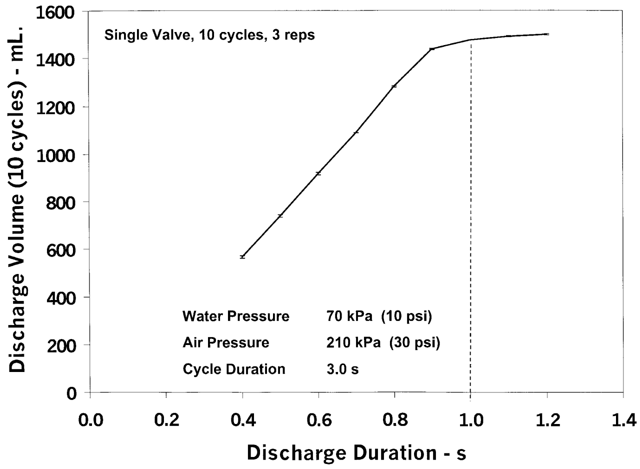

Figure 3–Single metering device discharge volume (10 cycles) for a range of discharge durations. Each value is mean of three observations. Water pressure = 70 kPa (10 psi), air pressure = 210 kPa (30 psi), and cycle duration = 3 s. Measurement variation is indicated by error bars.

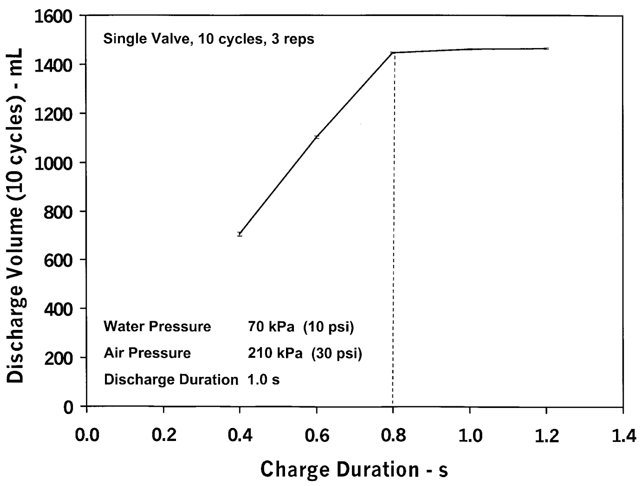

Figure 4–Single metering device discharge volume (10 cycles) for a range of charge durations. Each value is mean of three observations. Water pressure = 70 kPa (10 psi), air pressure = 210 kPa (30 psi), and discharge duration = 1 s. Measurement variation is indicated by error bars.

During the test, water pressure was 70 kPa (10 psi), air pressure was 210 kPa (30 psi), and discharge duration was 1 s. The discharge volume ranged from 70 to 146 mL/cycle (2.4 to 4.9 oz./cycle) as the charge duration varied from 0.4 to 0.8 s (cycle durations of 1.4 to 1.8 s) for three replications with no additional increase as charge duration increased to 1.2 s (fig. 4). Thus, a charge duration of 0.8 s completely charged the device to the reservoir capacity of about 150 mL (5.1 oz.) for these conditions. Variation among measurements was very low as reflected by the error bars.

Discharge Volume Repeatability. The fourth test was conducted to determine the repeatability of discharge volume for each cycle. Discharge volume of five individual cycles was measured while water pressure was 70 kPa (10 psi) and air pressure was 210 kPa (30 psi). The mean volume of each cycle ranged from 150 to 91 mL (5.1 to 3.1 oz./cycle) for a variety of charge and discharge durations (table 1). The coefficient of variation was less than or equal to 1.6% for all tests.

Table 1. Discharge volume delivered by a single cycle of the metering device for a range of cycle and discharge durations

Cycle Duration (s)	Discharge Duration (s)	Water Volume/Cycle* Mean† mL (oz.)	Water Volume/Cycle* CV‡ %
2.00	1.00	149.8 (5.1)	1.6
1.75	0.80	128.2 (4.3)	0.9
1.20	0.60	91.2 (3.1)	1.4

* Test conditions were water pressure of 70 kPa (10 psi) and air pressure of 210 kPa (30 psi).
† Values are means of five observations.
‡ CV = coefficient of variation.

These results show that repeatable discharge volumes (flow rates) can be obtained when the device is operated with either full or partial charges. In the first case, the reservoir is completely filled and emptied each cycle. In the other case, the reservoir does not completely fill and/or empty each cycle.

Prototype Devices on a Manifold

Six additional prototype metering devices were constructed, similar in size to the first prototype, but with improved check valves. Three devices were mounted on each of two manifolds for simulated field tests. The two manifolds were controlled independently so that they could operate either alone or alternately. Discharge volume of each device was measured for a range of discharge durations and number of cycles in both operating modes (tests 1-4). Discharge volume was also measured for a range of charge durations with the manifolds operating in the alternating mode (test 5). For all tests, water pressure was 50 kPa (7 psi) and air pressure was 140 kPa (20 psi). The charge duration was 7 s except for test 5 when it varied from 1 to 4 s to determine the minimum charging duration. Discharge volume was determined using graduated cylinders to measure the volume collected from individual metering devices for two cycles.

Minimum Discharge Duration—Single Manifold. Test 1 was conducted to determine minimum discharge

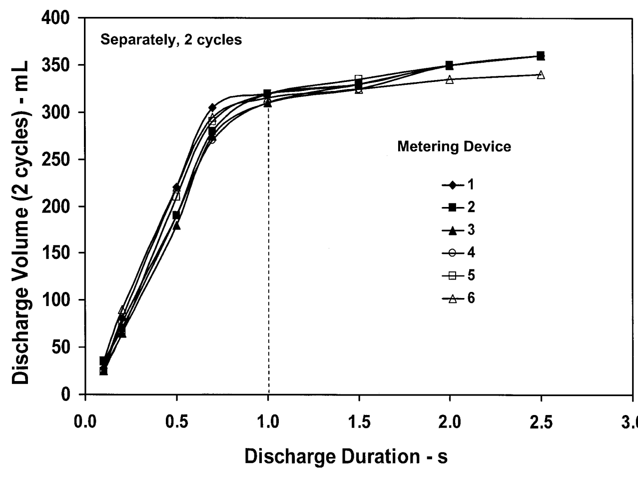

Figure 5–Individual metering device discharge volume (two cycles) for a range of discharge durations with two manifolds operating separately (three devices per manifold). Water pressure = 50 kPa (7 psi), air pressure = 140 kPa (20 psi), and charge duration = 7 s.

Table 2. Discharge volume delivered by a single cycle for six metering valves mounted on two manifolds, each manifold operating separately

Valve Number	Water Volume/Cycle* Mean† mL (oz.)	CV‡ %
1	160.0 (5.4)	5.6
2	158.3 (5.4)	5.2
3	152.5 (5.2)	31.4
4	151.7 (5.1)	6.8
5	158.3 (5.4)	16.2
6	156.7 (5.3)	3.3

* Test conditions were water pressure of 50 kPa (7 psi) and air pressure of 140 kPa (20 psi).
† Values are means of six observations.
‡ CV = coefficient of variation.

duration with the manifolds operating separately (three metering valves on each manifold). All devices provided similar discharge volumes as the discharge duration varied from 0.1 to 2.5 s. The breakpoint indicated a discharge duration of about 1 s was required to essentially empty the reservoir (fig. 5).

Discharge Volume Repeatability—Single Manifold. Test 2 was conducted to determine discharge volume repeatability for each cycle with the manifolds operating separately (three valves on each). All metering devices produced similar discharge volumes for each of six cycles (table 2). Coefficient of variation values ranged from 3.3 to 31.4%. The greatest variation (device no. 3) resulted from a low discharge volume for the second cycle and a high volume for the third cycle (data not reported), but the mean value for the two cycles was similar to other mean values. This may indicate equipment malfunction or experimental error.

Minimum Discharge Duration—Alternate Manifolds. Test 3 was conducted to determine the minimum discharge duration when manifolds were operating alternately (three metering devices on each manifold). Variance in discharge volume among the six devices was greater for short discharge durations (0.5 to 0.9 s) than for longer discharge durations (0.9 to 1.3 s). The plateau in discharge volume indicates that the minimum discharge duration for completely emptying the reservoir is 0.9 to 1.0 s (fig. 6).

Discharge Volume Repeatability—Alternate Manifolds. Test 4 was conducted to determine discharge volume repeatability for each cycle with the manifolds operating alternately (three metering devices on each manifold). Discharge volume among the six metering devices was again very similar (table 3). The coefficient of variation values for the six valves ranged from 4.0 to 12.1% for six cycles, indicating very good discharge volume uniformity. As in Test 2, the variation was greatest for device no. 3, which may indicate improper operation of this device.

Minimum Charge Duration—Alternate Manifolds. Test 5 was conducted to determine minimum charge duration for metering devices on manifolds (three devices on each) operating alternately. Variance in discharge volume was considerably greater for short charge durations (1 to 2 s), especially for device no. 4, but was low for longer charge durations (3 to 4 s) (fig. 7). The plateau in discharge volume indicates that the minimum charge duration for these conditions was about 2.5 s.

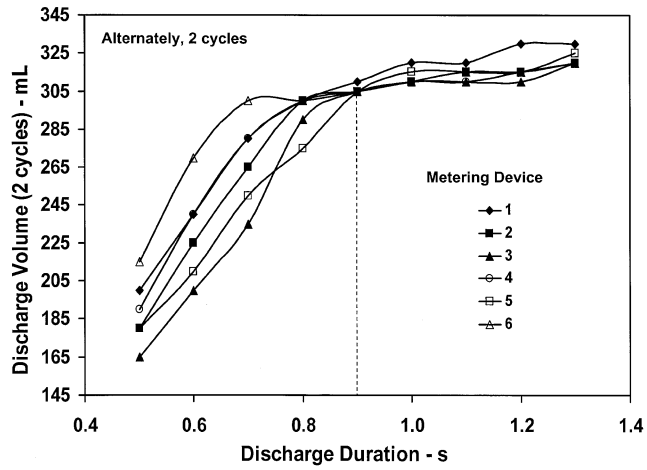

Figure 6–Individual metering device discharge volume (two cycles) for a range of discharge durations with two manifolds operating alternately (three devices per manifold). Water pressure = 50 kPa (7 psi), air pressure = 140 kPa (20 psi), and charge duration = 7 s.

Table 3. Discharge volumes delivered by a single cycle for six metering valves mounted on two manifolds, each manifold operating alternately

Valve Number	Water Volume/Cycle* Mean† mL (oz.)	CV‡ %
1	155.0 (5.2)	5.4
2	152.5 (5.2)	4.0
3	150.8 (5.1)	12.1
4	150.0 (5.1)	8.4
5	154.2 (5.2)	5.2
6	150.0 (5.1)	4.7

* Test conditions were water pressure of 50 kPa (7 psi) and air pressure of 140 kPa (20 psi).
† Values are means of six observations.
‡ CV = coefficient of variation.

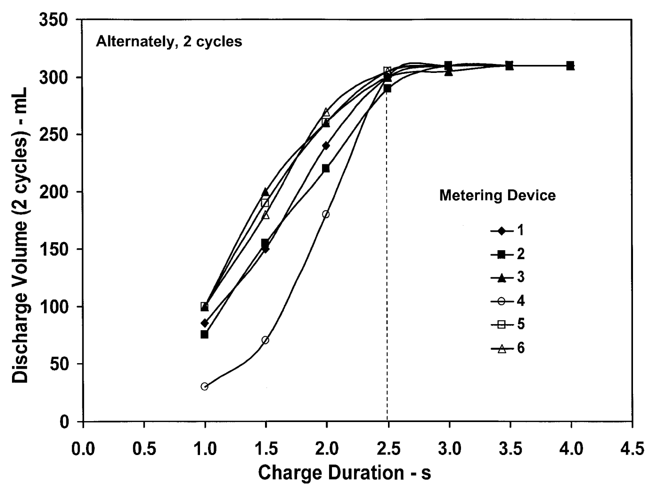

Figure 7–Individual metering device discharge volume (two cycles) for a range of charge durations with two manifolds operating alternately (three devices per manifold). Water pressure = 50 kPa (7 psi), air pressure = 140 kPa (20 psi), and discharge duration = 0.9 s.

From this series of tests, we concluded that the minimum charge duration for the improved prototype metering valve was 2.5 s and that the minimum discharge duration was 0.9 to 1.0 s, giving a total cycle duration of about 3.5 s. Two manifolds working in alternate charge and discharge phases provided satisfactory performance, which permits reduced sizing of the equipment and distribution system for auxiliary resources (air and water) and provides a more nearly constant demand for these resources. Metering valve discharge uniformity was good.

Potential applications of this metering device include those where a wide range of flow rates are needed, especially where a smaller, dynamic range (cycle changes) of flow rate is needed within a larger, fixed range (reservoir size) of flow rates. It should have application especially where relatively low flow rates are needed but the fluid may include particulate matter that would plug small orifices required in conventional systems. The device can be used with a wide range of fluids and/or gases, subject to the restrictions of fluid mixing and compatibility of the controlling fluid or gas with the atmosphere.

Summary and Conclusions

A variable-rate, digitally controlled metering device was developed to permit variable flow of a fluid. The device consists of a reservoir that is alternately filled and emptied at a rate dependent upon a digital pulse from an external source. When the duty cycle is long enough for the reservoir to completely fill and empty, the device flow rate is determined by the reservoir volume and cycle frequency. When the reservoir is not allowed to completely fill and/or empty, the device flow rate is determined by the fluid pressure and duration of the charge and discharge phases. The metering device can be used in a wide variety of applications for a variety of fluids. The primary use described here is for variable-rate irrigation applications using water and air. The addition of a sprinkler or nozzle to provide a desired pattern may reduce flow but not as much as the smaller orifices used for similar continuous application rates without the valve.

Two prototype versions were constructed, one for initial testing of a single device and a second, improved version, for testing of three devices mounted on each of two manifolds (total of six devices). Results of these tests indicate that repeatable flow rates can be obtained with either complete or partial filling and emptying of the reservoir each cycle. For the prototype and operating conditions of these tests, the minimum charge duration was about 2.5 s and the minimum discharge duration was about 1 s so maximum aggregate flow is 2.5/3.5 or 71% of unimpeded flow. Consequently, the water delivery rate to the system will have to be about 1.4x normal to achieve application rates similar to those without the metering valve. Operation of the device is independent of the sprinkler or nozzle, but flow will be reduced depending upon orifice size.

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