

# AUTOMATION OF DELIVERY DEVICE FOR CHLORINE DIOXIDE DISINFECTION

S. Vedachalam, J. P. Schmiedeler, K. M. Mancl

**ABSTRACT.** *Although water reuse has been practiced in many countries for centuries, severe water scarcity in many parts of the world has aroused renewed interest. In addition, it is imperative to destroy the dangerous pathogens transmitted by the fecal-oral route by adequately disinfecting wastewater. Though chlorine has been used widely as a disinfectant, its inability to inactivate certain viruses and protozoan parasites and its reaction with certain contaminants to form carcinogenic trihalomethanes has made imperative the search for alternatives. Chlorine dioxide has been found to be an effective USEPA-approved replacement, though it poses safety issues, being explosive at concentrations of 10% (w/w) or more, sensitive to pressure, and somewhat toxic to juvenile fish. Small packets of precursor chemicals are now commercially available to generate small quantities of chlorine dioxide onsite. The aim of this research was to develop an automated delivery device for dispensing this disinfectant in the form of a packet, which would strongly mitigate the safety issues and make the dispenser user-friendly. The automation of the delivery device involved the design of a 30-slot Geneva mechanism to drop the packet into a reaction chamber. This packet-dropping mechanism was designed for use both in a manual mode, requiring no electricity, and an automated mode, powered through electricity. A fully functional prototype was built to demonstrate the automation of a disinfection delivery device. Disinfected water is safe for discharge on open lawns and gardens since the chlorite ion, a byproduct, is present in low concentration. However, wastewater discharge and reuse may be subject to local or state regulations.*

**Keywords.** *Chlorine dioxide, Disinfection, Geneva mechanism, Wastewater reuse.*

The evolution of wastewater reclamation, recycling, and reuse has its roots in the early water and wastewater system characteristics of the Minoan civilization in ancient Greece (Angelakis and Spyridakis, 1996). Although water reuse has been practiced to a small extent in many countries for centuries, renewed interest in water reuse is surging (Asano and Levine, 1996). Water reclamation and recycling have been prominently used or are being considered in the arid and semi-arid parts of the world such as West Asia (Al-A'ama and Nakhla, 1995), Mediterranean Europe (Kantanoleon et al., 2007), parts of Africa (Bahri and Brissaud, 1996), and Australia (Eden, 1996) and in countries such as China, where demand for clean water outstrips supply (Yang and Abbaspour, 2007). In the United States, water reuse for non-potable or indirect potable purposes is being practiced in arid regions of Arizona, California, Colorado, and Texas and in humid regions of Florida, Georgia, Puerto Rico, and the U.S. Virgin Islands in

which the surging water demands of rapidly growing human populations are threatening the water resources needed for agriculture and for natural ecosystems (Hartley, 2006).

The motivation for reusing and recycling wastewater is fueled mostly by the realization that human water consumption in many countries has increased beyond sustainable levels, resulting in extended periods of drought, depletion of environmental flows in natural water systems, and the decrease in the wholesomeness of drinking water reservoirs, including groundwater systems (Dolničar and Schäfer, 2006). In addition, there is an imperative need to prevent the fecal-oral transmission of pathogens by adequately disinfecting wastewater as one of the highest priority health measures. Disinfection is the selective destruction of disease-causing microorganisms, as opposed to sterilization, which is the destruction of all living organisms (Crites and Tchobanoglous, 1998). Nevertheless, a disinfectant for treating wastewater must have sufficiently broad spectrum of action to destroy bacteria [*Vibrio cholerae* (cholera), *Salmonella typhi* (typhoid), *Shigella*, *Escherichia*, *Staphylococcus*, etc.], viruses (poliovirus, Coxsachievirus, hepatitis A, human rotavirus, etc.), protozoa (*Giardia*, *Cryptosporidium*, *Entamoeba*, etc.) and helminths (*Ancylostoma*, *Ascaris*, *Trichuris*, *Taenia*, etc.)

Chlorine is a widely used disinfectant (Winward et al., 2008). However, its limited ability to inactivate viruses and protozoan parasites; and its role in the formation of carcinogenic trihalomethanes (THMs) and haloacetic acids (HAAs) as by-products of the disinfection process (Kitis, 2004) spurred scientists to look for a better disinfectant. Chlorine dioxide has emerged as one of several viable options endorsed by USEPA because of the numerous advantages it offers. Some of these advantages are

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summarized, along with some challenges, by Gulian-Krishnaswamy and Mancl (2007). A portable delivery system for the dry media chlorine dioxide ( $\text{dmClO}_2^{\text{TM}}$ ), a proprietary product of Avantec Technologies, Inc. (Columbus, Ohio), was developed by Gulian-Krishnaswamy and Mancl (2007). The purpose of this study was to further improve the Gulian-Krishnaswamy and Mancl portable dry media chlorine dioxide packet dispensing device by adding more features and making it automated and more user-friendly.

## SYSTEM CONFIGURATION

The chlorine dioxide dispenser is placed on top of a cylindrical vessel, the reaction chamber, as illustrated in figure 1. The reaction chamber is where the chlorine dioxide is generated when its precursors in the dry medium in the packet react in the presence of water and where chlorine dioxide gas is dissolved in the wastewater.

The reaction chamber is held suspended inside a larger dosing tank, which contains the renovated wastewater being discharged from secondary treatment systems such as ponds or fine media bioreactors. The key issues in designing an automated disinfection system include the design of a packet-dispensing device and the ability to uniformly distribute the chlorine dioxide to facilitate disinfection of the wastewater in the dosing tank. An irrigation pump is placed at the bottom of the dosing tank to pump the treated water out to a lawn or a garden. It is safe to discharge disinfected water on open lawns or gardens (Caldwell et al., 2007); however, wastewater discharge and reuse may be subject to local or state regulations. A study of the effects of using treated wastewater on year round irrigation conducted at the Molly Caren Agricultural Center (London, Ohio) was reported by Caldwell et al. (2007). The year-long study was conducted in 2002, and the irrigation equipment was insulated with winter-resistant material (heat tape, reflective adhesive and foam insulation) to decrease the likelihood of pipes freezing in the winter months. Three study plots, each measuring

210  $\text{m}^2$  (2260  $\text{ft}^2$ ), received 56.8 LPM (15 GPM) of water for less than 20 min per day, keeping the water discharge well below the target irrigation rate of 0.51 cm (0.2 in.) per day. Field-scale trial of the chlorine dioxide device would utilize the irrigation equipment installed by Caldwell et al. (2007).

The chlorine dioxide dispenser, as designed by Gulian-Krishnaswamy and Mancl (2007), consists of two parts: the stationary cartridge with compartments and the rotating bottom plate with an open sector identical to the cross-section of a compartment, as shown in figure 2. The vertically oriented cartridge is closed at the top and on the sides and open at the bottom; the sides are enclosed in an outer tube, which prevents the exposure of the packets to moist air (see Gulian-Krishnaswamy and Mancl, 2007). The cartridge is divided radially into 30 compartments. Each compartment serves to hold one 5- × 5-in. water permeable pouch containing 75 gm of dry powder chlorine dioxide precursors, i.e., sufficient to create a 10-ppm concentration of chlorine dioxide in 945 L of wastewater. The packets are held from falling down by the plate, which has a radial sector-shaped opening matching the size of a compartment on the cartridge. Though the cartridge has 30 compartments to store packets, only 29 of them can be utilized as one compartment is aligned with the opening in the plate at the time of installation. The dispenser, described later in this article, is used to drop the packet vertically into the reaction chamber. The contents in the packet react with the renovated wastewater, releasing chlorine dioxide gas. After completion of the reaction, the spent packets remain at the bottom of the chamber until they are removed when the cartridge is serviced after all the packets have been used. The spent packets are disposed of safely, and a fresh packet is placed in each compartment of the cartridge.

The following sections in the article describe the system in functional order. Thus, the first section describes the mechanism used to turn and index the plate. One subsection explains the manual mode and another, the automated mode of operation. The second section describes the design dimensions of the Geneva mechanism used for indexing the plate. The third section describes the water take-off

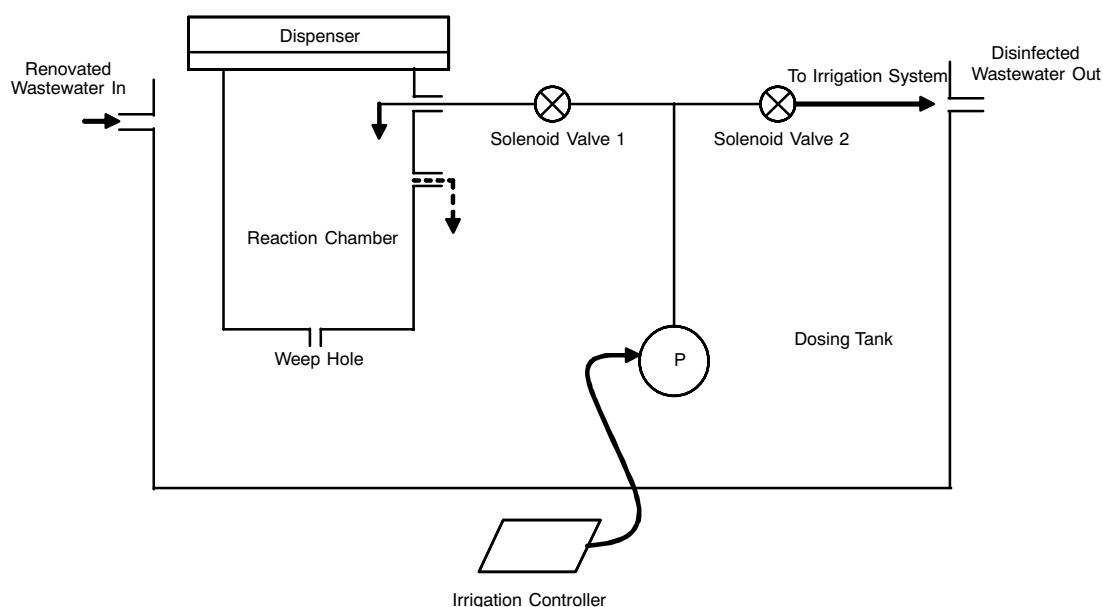


Figure 1. A schematic of the automated delivery device for chlorine dioxide disinfection.

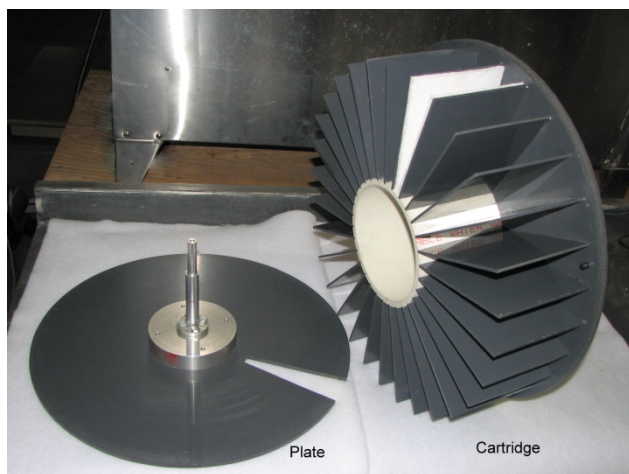


Figure 2. Chlorine dioxide dispenser.

mechanism used for blending the chlorine dioxide into the renovated wastewater. The fourth section discusses the effectiveness of chlorine dioxide as a disinfectant and the chlorine dioxide dispenser in maintaining a uniform concentration in the dosing tank, while the last section consists of a discussion of future research.

## TURNING AND INDEXING THE DISPENSER

In the chlorine dioxide dispenser designed by Gulian-Krishnaswamy and Mancl (2007), the plate was rotated by a shaft coupled to a motor. While redesigning the mechanism, the following features were considered necessary:

- Precision in the rotation of the plate such that its open sector comes to rest precisely beneath the next compartment in the cartridge to enable the packet to drop into the reaction chamber.
- The mechanism should not be energy-intensive.
- It should be easy to retrofit a hand-powered mechanism on the existing system to accommodate varying infrastructural and economic circumstances of the users.

After considering several options, a Geneva mechanism was chosen to index the dispenser due to the simplicity of the mechanism in both design and construction and its precise positioning motion (Hasty and Potts, 1966). Historically first used in watches and then in movie projectors, the Geneva mechanism translates a continuous rotation into an intermittent rotary motion. It consists of two components: a *drive pin*, which is a small rotating disk with a pin, and a *Geneva wheel*, which is a larger rotating disk with slots (usually four to eight) into which the pin slides. The drive pin also has a raised circular blocking disc that locks the Geneva wheel in position between steps. In the most common arrangement, the Geneva wheel has four slots and thus advances by one step of  $90^\circ$  for each rotation of the drive wheel. If the Geneva wheel has  $n$  slots, it advances by  $(360/n)^\circ$  per full rotation of the drive pin. The Geneva mechanism is placed above the dispenser, and the Geneva wheel secured to the top of the cartridge through a circular shaft fixed to the plate as shown in figure 3. The nature of the design problem required a Geneva wheel with 30 slots. This number was chosen to match the number of compartments within the cartridge, as designed by Gulian-Krishnaswamy



Figure 3. The Geneva mechanism placed above the dispenser.

and Mancl (2007). On a related note, if one packet is consumed every day, the cartridge would last approximately one month. The number of compartments and the number of slots on the Geneva wheel can be modified based on the frequency of disinfection and size of the packets. The Geneva mechanism can be operated in two modes.

### MANUAL MODE

Operation in the manual mode is most suited for locations where a continuous supply of electricity may not be guaranteed. Though the objective of complete automation is not realized in this mode, it compensates by achieving a reduction in the equipment and operational costs. The primary advantage of using a Geneva wheel in the manual mode is that the user need not be concerned about the precise positioning of the plate. A complete rotation of the drive pin would advance the position of the opening in the plate exactly from under one compartment to under the next. A minimal hand torque is applied on the drive pin, and the Geneva wheel rotates due to the interlocking mechanism until the pin makes its way out of the slot. At this point, the Geneva wheel stops turning, while the drive pin is rotated until it comes back to its original position. This way, one full rotation of the drive wheel causes a  $1/30^{\text{th}}$  rotation of the Geneva wheel. The plate, connected to the Geneva wheel through a keyless bushing, rotates by an equal amount, thus positioning the open sector of the plate directly under the adjacent compartment of the cartridge to allow the packet to drop down into the reaction chamber.

### AUTOMATED MODE

The primary objective of the automated mode is to ensure minimal human intervention by using an automatic control mechanism for indexing the dispenser. The automated mode uses a motion controller and a DC stepper motor (NEMA Size 23) to actuate the drive pin of the Geneva mechanism. The stepper motor is placed above the Geneva mechanism using a specially designed mounting fixed on the cartridge and is connected to the drive pin using a setscrew. The motion controller can store programs and is programmable through the USB port of a computer. Once the program is stored on the controller, the stepper motor and controller can be used in a stand-alone mode without requiring the use of a computer. The timing of this automation process for indexing can be regulated using a commercially available irrigation controller.

## DESIGN DIMENSIONS OF THE GENEVA MECHANISM

The procedure for designing a Geneva wheel is well documented (Hasty and Potts, 1966; Lee, 1998; Figliolini and Angeles, 2002). Although Hasty and Potts (1966) state that their design procedure can be extended to Geneva wheels with any number of slots (as the case for the 30-slot Geneva wheel in this case), most published descriptions present the design procedure for only a six- or eight-slotted Geneva wheel. The geometric parameters of a typical Geneva wheel and drive pin are shown in figure 4. An effort has been made to keep the design details relatively simple in this section, while the Appendix includes the detailed design procedure. To include 30 slots, the Geneva wheel needed to be as large as possible. However, the diameter of the Geneva wheel was restricted by the diameter of the cartridge and plate [ $\Phi 48.26$  cm (19 in.)] designed earlier by Gulian-Krishnaswamy and Mancl (2007). Setting apart space for the drive pin and some buffer space, the diameter of the wheel was set at 43.18 cm (17 in.), and the rest of the dimensions were based on this parameter. The drive pin diameter ( $d$ ) was chosen to be 1.27 cm (0.5 in.), and the number of slots in the Geneva wheel ( $M$ ) was 30. Assuming the tip thickness ( $t$ ) to be 0.635 cm (0.25 in.), the lock radius ( $a$ ) was calculated to be 1.036 cm (0.408 in.). The radial clearance between the drive pin and wheel at the point of maximum slot penetration ( $C_L$ ) was 0.43 cm (0.17 in.). Based on the wheel diameter and the number of slots, the minimum recommended distance between the center of the Geneva wheel and the slot ( $b$ ) was 15.01 cm (5.91 in.). The maximum value for  $b$  calculated by subtracting the length of the drive wheel from the radius of the Geneva wheel was 19.05 cm (7.5 in.). However, the final value chosen for  $b$  was between the two extremes at 17.78 cm (7 in.). The Geneva wheel was fabricated on a CNC milling machine, but the more intricate drive wheel was generated using wire-cut electric-discharge machining (EDM).

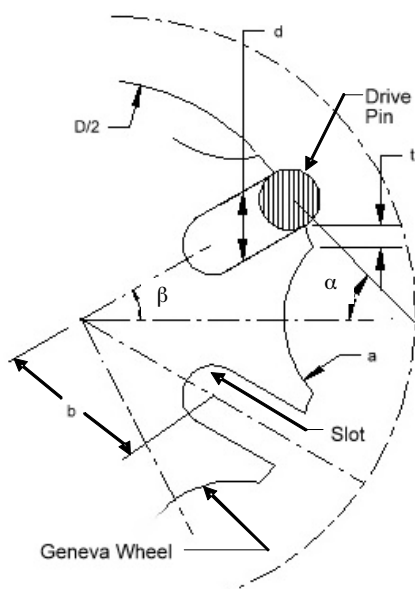


Figure 4. Geometry of the Geneva mechanism.

## WATER TAKE-OFF

Chlorine dioxide is effective as a disinfectant when it dissolves completely in water at the required concentration and is in contact with the pathogens for the duration required to inactivate, say, 99.9% or more of all major pathogenic species. Most pathogens are readily killed with short times of exposure to low concentrations of chlorine dioxide, at pH levels of 5 to 9 regardless of the water temperature. On the other hand, the concentration  $\times$  time (CT) requirements to inactivate parasites, such as the protozoan *Cryptosporidium*, are relatively high, and decline progressively as the water temperature increases. Thus the CT (mg/L  $\times$  min) required to inactivate *Cryptosporidium* at 10°C, 20°C, and 30°C are 609, 174, and 54.2, respectively (New Zealand Ministry of Health, 2001). Dropping the chlorine dioxide packet in water by itself does not guarantee full dispersion of the dissolved gas. Mixing is needed to ensure complete dispersion. A pump could be used to achieve mixing; however, the mixing pump would be in addition to the irrigation pump needed to pump out the disinfected wastewater. To minimize equipment cost, a concept of water take-off is used. Similar to the concept of power take-off (PTO), the irrigation pump is used to deliver part of the water from the dosing tank up to the reaction chamber (fig. 1). The pump is connected to an irrigation controller, which treats the reaction chamber and the outside lawn as two separate zones that can be programmed to run at different times and for different durations. Both “zones” are regulated using solenoid valves. It has been shown that the best time to irrigate the lawn is early morning, since the vadose zone of the earth’s surface retains most of the water until field capacity of the soil is attained. In addition, as soon as sunlight is available, plants take up the water and relay it to the atmosphere through evapotranspiration (Cathey, 2001).

The irrigation controller is programmed such that the packet drops into the reaction chamber early in the morning just before sunrise. A minute or two later, the solenoid valve connected to the reaction chamber (Solenoid 1) is turned on, while the solenoid valve connected to the lawn (Solenoid 2) is turned off. The pump turns on and the water from the dosing tank is sent only to the reaction chamber. The reaction chamber has outlets on the sides and a weep hole at the bottom, so all the water eventually drains back to the dosing tank. The falling water agitates the water in the dosing tank such that the chlorine dioxide is uniformly distributed. This cycle is repeated several times until complete generation of chlorine dioxide in water, and sufficient inactivation of pathogens have been achieved (Gaur and Mancl, 2007). The exact duration of this process would depend on the concentration of the chlorine dioxide precursors in the packet, the volume of the wastewater and the estimation of the concentration  $\times$  time required to inactivate the most resistant parasites of concern. At this point, Solenoid 1 is turned off, Solenoid 2 is turned on, and the disinfected wastewater is discharged to the lawn. As the level of water in the dosing tank decreases, so does the float connected to the pump. When the water level reaches a critical point, the pump switches off automatically. The irrigation controller is programmed to turn off based on the time required to pump out the dosing tank filled to capacity. This time may vary depending on the system configuration, such as the capacity

of the pump, size of the dosing tank, etc. A functional prototype of the automated delivery device is shown in figure 5.

## EFFECTIVENESS

This section describes the effectiveness of chlorine dioxide as a disinfectant and the chlorine dioxide dispenser in maintaining a uniform concentration of chlorine dioxide in the dosing tank.

## DISINFECTION

A study by the United States Geological Survey investigated the effectiveness of chlorine dioxide as a disinfectant (Kephart and Stoeckel, 2009). Two 10-L volumes of wastewater were collected at the outlet of the wastewater stabilization pond at the Molly Caren Agricultural Center (London, Ohio) with one volume serving as the control. Wild enrichments of five test organisms (*Escherichia coli*, *Enterococcus spp.*, *Clostridium perfringens*, somatic coliphage, and F-specific coliphage) were cultivated from raw sewage collected from the Olentangy Environmental Control Center located in Powell, Ohio. Each test organism was added to the 10-L volumes and mixed thoroughly. A 1-L sample from the mesocosm was extracted, yielding the initial microorganism count. Chlorine dioxide was added to the test mesocosm and allowed to mix for 30 s. Then, 100-mL samples were collected to analyze microorganisms after 5, 10, 30, 60, and 120 min.

*C. perfringens* and coliphage counts are strong indicators of the inactivation and removal of viruses in water. Payment and Franco (1993) suggested the use of *C. perfringens* and somatic coliphages as surrogates for virus and parasite testing of drinking water. The study conducted by Kephart and Stoeckel found an average reduction over three trials of more than 4 log<sub>10</sub> within 10 min for *C. perfringens* and within 5 min for somatic coliphages.

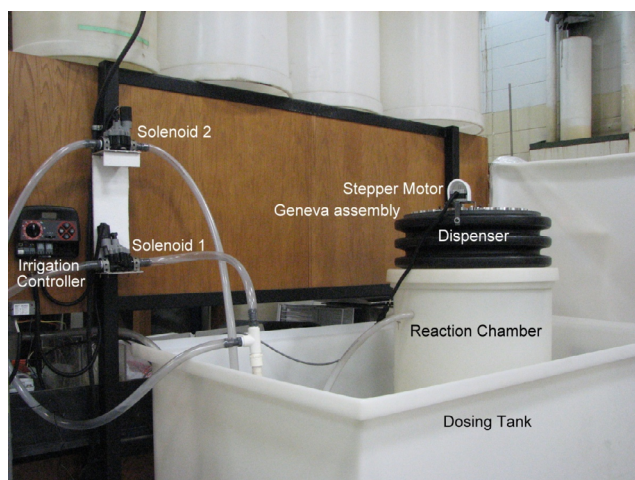


Figure 5. A functional prototype of the automated delivery device for chlorine dioxide disinfection.

## DISTRIBUTION OF CHLORINE DIOXIDE

The effectiveness of the chlorine dioxide delivery device in uniformly distributing the disinfectant throughout the dosing tank was established by collecting water samples at five locations in the dosing tank and measuring the chlorine dioxide concentration using a spectrophotometer. The dosing tank contained approximately 719.2 L (190 gal) of water at room temperature, and one packet containing ClO<sub>2</sub> precursors, weighing 79 g, was used for disinfection. The first sample was collected from the reaction chamber (time = 0) just before the reaction chamber was filled to capacity and water was about to overflow into the dosing tank. Subsequent samples were collected at 5, 10, 20, 30, 45, 60, 75, 90, 105, and 120 min at five locations in dosing tank (fig. 6).

During the course of this experiment, Solenoid 1 was kept 'on', while Solenoid 2 was turned off. This allowed the chlorine dioxide to mix completely in the water contained in the dosing tank. After Solenoid 1 was turned off at 120 min, the water in the reaction chamber completely drained into the dosing tank. This process took 35 min, and another set of samples from the five locations was collected at this time. All the samples were analyzed in a spectrophotometer at a wavelength of 360 nm. The concentration of chlorine dioxide in the samples (in mg/L) was obtained from the absorbance values (in absorbance units) using a conversion factor of 58.6 in the Beer-Lambert law.

Figure 7 shows the plot of chlorine dioxide concentration (mg/L) at the five sampled locations in the dosing tank over time (min). After a steady increase, the concentration values stabilized at 75 min and continued to remain steady until

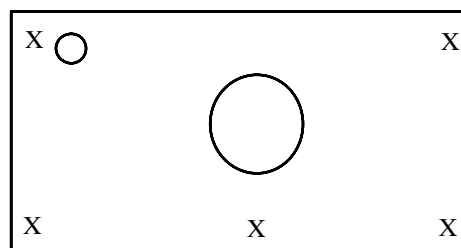


Figure 6. Top view of the dosing tank, with the reaction chamber in the center and the pump in the top left corner. Each sampling location is marked with an 'X' symbol. Locations 1 through 5 are marked clockwise, starting from the bottom left corner.

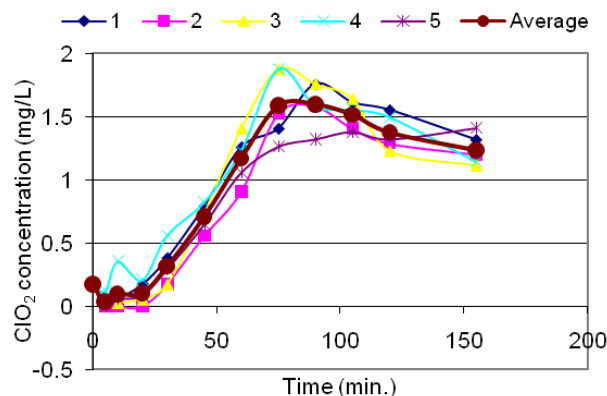


Figure 7. Concentration of chlorine dioxide at the five sampling locations against time.



Solenoid 1 was turned off at 120 min. The small drop in the concentration values at 155 min may be attributed to the off gassing of chlorine dioxide in the air. The concentration at the five sampled locations throughout the experiment indicated uniform mixing of chlorine dioxide in the water. The experiment can be replicated for various volumes and strengths of renovated wastewater to determine the water-take off cycle time needed to dissolve one packet of chlorine dioxide and achieve uniform mixing.

## DISCUSSION AND FUTURE WORK

Automation of the delivery device for chlorine dioxide disinfection was achieved using the Geneva mechanism and the irrigation pump (water take-off). It was shown to be operable in two modes - manual and automated. It is envisaged that solar or waste-powered batteries could be used in the future to power the stepper motor and controller in the automated mode. However, the manual mode still remains an attractive option for places where electricity may not be available around-the-clock to keep the irrigation controller running all day and for people who lack the means to purchase the motor and associated control equipment. Appropriate use of the water take-off mechanism is likely to achieve uniform distribution of chlorine dioxide within the water in the dosing tank.

Future work will focus on safety, additional maintenance aspects and compliance with regulatory requirements. The next model will have a simplified disassembly process during the refilling of the cartridge with fresh packets. It will also address the challenge of keeping the packet fully submerged in the reaction chamber to achieve more rapid and complete delivery. Moisture control inside the dispenser will be assessed to prevent premature generation of chlorine dioxide. Although the current study focuses on conditioning wastewater for irrigation of non-food crops (lawn grasses), the delivery system is also adaptable to meeting drinking water standards. In the United States, the USEPA Stage 1 Disinfectants Byproducts Rules require that the chlorite ion in treated water not exceed 8.0 mg/L (USEPA, 1998), whereas the maximum contaminant level for chlorite ion in New Zealand is 0.3 mg/L (New Zealand Ministry of Health, 2001). It is important to define operating protocols that ensure compliance with requirements of regulatory agencies concerning contaminant levels and efficacy against certain water-borne pathogens. The chlorine dioxide delivery device system is designed to benefit small and rural communities by providing them an effective wastewater disinfection system at an affordable cost. With the addition of these safety and maintenance features, the delivery device would be "smart" - easy to use and requiring little intervention in daily operation. This device, along with the secondary treatment and irrigation equipment, demonstrates reuse of treated wastewater at acceptable safe standards.

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## APPENDIX

The three dimensions that specify an  $M$ -slot Geneva wheel are the wheel diameter ( $D$ ), the drive pin diameter ( $d$ ), and the lock radius ( $a$ ) (fig. 4). For sake of convenience, an alternate set of dimensionless terms was used in the following analysis to specify the wheel geometry, where the normalized pin diameter is defined as

$$d^* = d / D \quad (1)$$

and the normalized tip thickness of the Geneva wheel is given as:

$$t^* = \frac{t}{D} = \frac{\tan(\pi/M) - d^*}{2} - \frac{a}{d} \quad (2)$$

The thickness of the Geneva wheel is not considered an independent parameter, but is chosen to be approximately equal to the pin diameter as described by Hasty and Potts (1966). According to Hasty and Potts (1966), the determination of the wheel diameter is the last step in the wheel synthesis procedure since it is governed by load inertia ( $I_L$ ),  $d^*$ ,  $t^*$ , and  $M$ . However, since the maximum diameter of the wheel was restricted to 43.18 cm (17 in.), the wheel diameter was chosen to be one of the initial design parameters, and the rest of the dimensions were derived from  $D$ . The depth of the slot ( $s$ ) is the difference between the diameter of the wheel ( $D$ ) and the distance between the center of the wheel to the slot ( $b$ ).

$$s = D - b, \quad (3)$$

where

$$b = \frac{D}{2} \left[ \frac{1 - \sin(\pi/M)}{\cos(\pi/M)} \right] - C_L \quad (4)$$

and  $C_L$  is the radial clearance between the drive pin and wheel at the point of maximum slot penetration. It is assumed to be 0.01 in./in. of Geneva wheel diameter.

